

EMERALD e-book for developing of biomimetic mechatronic systems

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EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC
MECHATRONIC SYSTEMS PROJECT

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INTRODUCTION

The „European network for 3D printing of biomimetic mechatronic systems – 21-COP-0019 - EMERALD project, which is part of the Education, Scholarships, Apprenticeships, and Youth Entrepreneurship Programme (ESAYEP) under the EEA Grants 2014-2021, represents a collaborative effort between technical universities coming from Romania (Technical University of Cluj-Napoca and University Politehnica Bucharest), Norway (University of Agder), Poland (Poznan University of Technology), and one private company coming from Slovakia (Bizzcom). This project that is part of the "2021 Cooperation Projects in Higher Education Area," which was implemented in the period 2022-2023 has been focusing on providing educational tools concerning the development of biomimetic mechatronic systems for people with special needs (with amputated arms) by 3D printing technologies. At the core of the EMERALD project initiative stands the creating of a comprehensive e-book which is dedicated to the developing and realizing of such systems.

This e-book is aimed to serve as an educational resource, offering in-depth knowledge and expertise in various related fields to anyone who is interested in getting knowledge and skills for conceiving and developing of biomimetic mechatronic systems that are necessary to support people with special needs (with amputated arms) in the end. Therefore, the e-book comprises a broad range of topics, including Computer Aided Design (CAD), Computer Aided Engineering (CAE), Computer Programming, Virtual Reality / Augmented Reality (VR/AR), Sensors and Electronics, Bio-Mechatronics, 3D Printing / Rapid Tooling methods, Intelligent Materials, and Prescribed / Manufacturing Precision, topics that are highly important for conceiving, developing and testing of biomimetic mechatronic systems, like sensorized orthoses, prostheses or robotic arms realized in a customized way to provide support for real patients with amputated arms taking into consideration their needs.

Each participating institution in the EMERALD consortium has contributed with their unique experience and expertise in the field, ensuring in this way a rich and diverse content in the e-book, accompanied by lot of practical examples and applications that are relevant in this context. This collaborative effort emphasizes the EMERALD project commitment in providing essential knowledge and skills for the conceiving, realizing and testing of biomimetic mechatronic systems, this being a valuable educational resource that is aimed not only to support educational activities, but also to open new doors for future innovations that are still needed to be done in the field of conceiving and developing of biomimetic mechatronics made by 3D printing to support in a customized way patients with amputated arms in the end.

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EMERALD

The Education, Scholarships, Apprenticeships and Youth
Entrepreneurship
EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC
MECHATRONIC SYSTEMS

MODULE COMPUTER AIDED DESIGN

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1. Introduction

Wide possibilities of the still developing methods of additive manufacturing have also been adapted to the needs of medicine. The ability to recreate complex and non-standard lumps and shapes allowed for an individualized approach to a specific patient, both at the stage of planning the operation and educating about the existing problem, by implementing surgical tools and templates dedicated to the patient, ending with individually matched (patient specific) implants or prostheses. In addition, rapid manufacturing methods have been used in tissue engineering as an element of bioprinting using living cells. The continuous development of additive manufacturing methods provides newer solutions in the field of materials used, obtained textures, colors and properties of the final product.

However, before any medical part becomes manufactured, it first must be designed – 3D printing processes require full digital representation of printed objects, in form of 3D models, usually prepared in computer-aided design (CAD) systems. Concerning the non-anatomical 3D printed parts – such as surgical tools, operating room equipment, protection devices and so on – the design can be performed in a standard way, utilizing solid, surface or hybrid modelling methods in selected CAD systems, on the basis of requirements and available ready solutions. This, however, is not a usual use of 3D printing technologies, as they are suited for more individualized and intricate shapes. The task becomes more difficult if a 3D printed part must be based upon real human anatomy, either internal (organs) or external (limbs). It requires gathering the anatomical data, via simple or more sophisticated measurement techniques – e.g. medical imaging. This data must be appropriately processed and used as an input to CAD software, to design individualized medical parts.

The most important trends covered in modern literature are as follows:

- 3D scanning and reverse engineering in medicine [Farhan et al. 2021; Wichniarek et al. 2020; Baronio et al. 2017],
- medical parts design using CAD systems [Dal Maso & Cosmi 2019; Ciocca et al. 2009; Sun et al. 2005; Górski et al. 2022; George et al. 2017],
- automation of CAD modelling [Górski et al. 2020; Portnoy et al. 2020],
- processing of medical imaging for 3D printing [Marro et al. 2016; Huotilainen et al. 2014],

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- design optimization towards 3D printing processes [Wojciechowski et al. 2019; Buonamici et al. 2019; Krishnanand et al. 2016].

This module covers some of the above mentioned problems, presenting basic and advanced knowledge – current state of the art – regarding the design of medical parts for 3D printing.

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2. CAD design of biomimetic devices

2.1 Basic definitions

Design is a set of activities undertaken by engineers in order to create a new product or improve an existing one, fulfilling the requirements of a specific recipient or group of recipients. Design is a first technical stage of product lifecycle (Figure 2.1) and it can be divided into concept preparation and engineering design. This module focuses on the latter, presenting how engineers can work towards 3D printed medical parts.

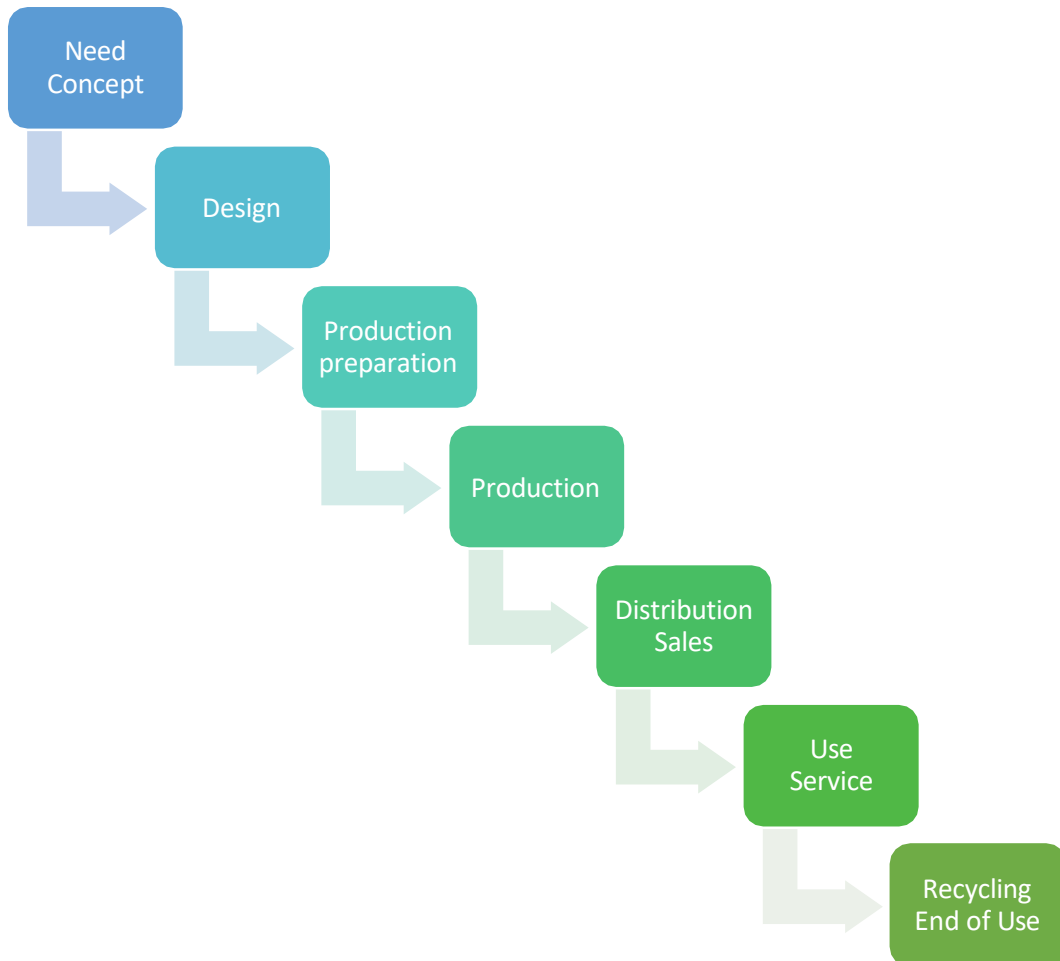


Figure 2.1 Product lifecycle stages including design

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Computer Aided Design (CAD) is use of computer technology to help the engineers prepare a design of a new or improved product. CAD is a part of the whole family of CAx systems, helping engineers and manufacturers to bring a product to life. The other systems are, e.g. CAM (Computer Aided Manufacturing), CAE (Computer Aided Engineering), CAPP (Computer Aided Process Planning) and many others. Popular CAD systems include CATIA, Inventor, SolidWorks, NX, SolidEdge and many others.

3D modelling, for the sake of this module, will be considered as a process realized in CAD software, focusing on formulating a three-dimensional shape of a designed product. The 3D modelling realized in CAD systems is usually parametric, meaning that the shape is governed by a set of dimensional and geometrical constraints, allowing the simplest elements of a given shape to be connected to one another (e.g. a line can have a dimensional constraint of length and a geometrical constraint of being perpendicular to another line). The 3D models also often have history, meaning that all the operations are stored in a linear order, allowing to trace and modify any operation at any given time. Example of parametric 3D model is shown in Fig. 2.2.

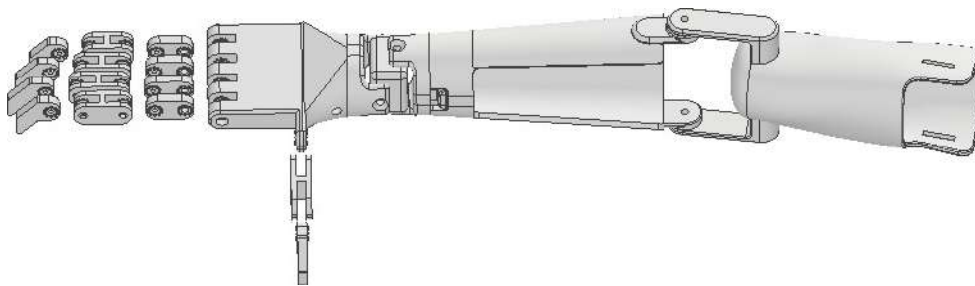


Figure 2.2 Parametric 3D model example – biomimetic arm prosthesis [Komorowska 2022]

In medical engineering, preparation of patient-specific, anatomically adjusted biomimetic devices falls under the range of **Engineering-To-Order (ETO)** and individualized design. Engineering-To-Order is creating a new product directly for a given client (or a group of clients) or patient, in the case of medical design. Individualized design is creating a new variant of an already known product, adjusted to the needs of a given client / patient. Individualization can be based on selectable features – then it can also be named customization. It can also be performed on geometrical (anatomical) level, using patient’s digitized anatomy to create a shape of a product.

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Products of such organic shapes are often named as biomimetic. **Biomimetics** or biomimicry is human-made technology with ideas copied from nature, or directly inspired by it. By this definition, any device with anatomical shapes can be considered as biomimetic, as well as one representing similar working principles, as works of nature (e.g. artificial arm containing joints of the same capabilities as in arm of a living human).

Examples of biomimetic products are shown in Fig. 2.3.



Figure 2.3 Biomimetic product examples [blatchfordmobility.com] [kaylenekau.com]

2.2 3D modelling types

2.2.1 Solid modelling

Solid modelling is a mathematical technique for representing solid objects. Unlike wireframe and surface modeling, solid modeling systems ensure that all surfaces meet properly and that the object is geometrically correct, hence making it the most robust technique for 3D printing (where geometrically incorrect objects cannot be manufactured properly). Solid modeling is the easiest type of 3D modeling to use. With the solid modeler, 3D objects can be made by creating basic 3D shapes: boxes, cones, cylinders, spheres, wedges, and tori (donuts). These shapes can be then combined to create more complex solids by joining or subtracting them or finding their intersecting (overlapping) volume. However, solid are most frequently created by sweeping a 2D object (usually a closed curve, named a sketch in many popular CAD systems) along a path or revolving it about an axis [Kurland 2007].

Parametric 3D solid modelling in modern CAD systems usually consists of the following steps:

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1. Designate a place for a sketch.
2. Draw a sketch.
3. Add 3rd dimension by extrusion or rotation.
4. Add non-sketch modifications or transformations.
5. Repeat until model is ready.

The following operations can be distinguished in solid modelling:

- 1) single sketch based features – extrusion (3rd dimension by linear sweep) or rotation (3rd dimension by angular sweep), both positive and negative effect (add or remove material),
- 2) two or more sketch based features – rib (sweep a 2D closed curve along a 3D curve – closed or open) and multi-section solid (create an advanced shape as blend between many closed curves usually placed on parallel planes), with adding or removing material,
- 3) non-sketch based features – fillet, chamfer, shell (thin-walled solid) and others,
- 4) transformations and multiplications – rectangular array, circular array, symmetry, translation, rotation,
- 5) boolean operations – subtract, add, intersect.

There are also systems, in which the so-called free modeling is available. Starting from a certain primitive shape (cube, sphere, cylinder, cone), steering curves and points can be manipulated in order to obtain a more advanced shape in a so-called digital sculpting process.

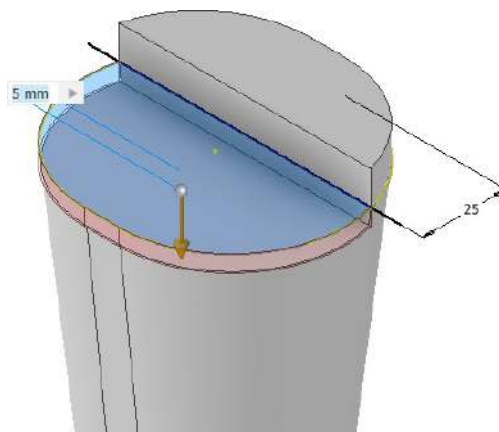


Figure 2.4 Solid modelling – extrusion, Inventor software [Komorowska 2022]

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2.2.2 Surface and hybrid modelling

Surface modelling is a mathematical technique for representing solid-appearing objects. Surface modeling is a more complex method for representing objects than wireframe modeling, but not as sophisticated as solid modeling. Surface modeling is widely used in CAD (computer-aided design) for illustrations and architectural renderings. Although surface and solid models appear the same on screen, they are quite different. Surface models cannot be sliced open as can solid models. In addition, in surface modeling, the object can be geometrically incorrect; whereas, in solid modeling, it must be correct [pcmag.com].

CAD software packages use two basic methods for the creation of surfaces. The first begins with construction curves (splines) from which the 3D surface is then swept (section along guide rail) or meshed (lofted) through. The second method is direct creation of the surface with manipulation of the surface poles/control points. From these initially created surfaces, other surfaces are constructed using either derived methods such as offset or angled extensions from surfaces; or via bridging and blending between groups of surfaces. Freeform surfaces do not have rigid radial dimensions, unlike regular surfaces such as planes, cylinders and conic surfaces; control points of a surface define its shape.

Hybrid modelling is a technique, in which wireframe, surface and solid modelling are combined within a single model. Part of the model can be surface modelled, part can be wireframe and the other part could be solid. This is frequently found in reverse engineering, where measured points and surfaces are imported and a solid model is built upon them. This also applies to medical applications – a surface representing patient’s limb can be used to develop a solid 3D model of a prosthesis or orthosis.

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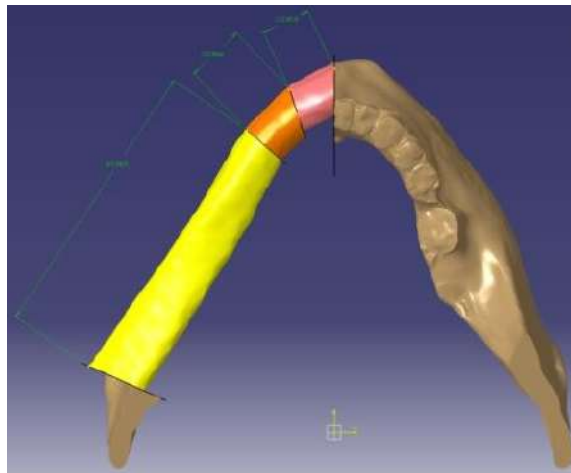


Figure 2.5 Hybrid modelling – CATIA software [Banaszewski et al. 2018]

2.2.3 Wireframe modelling

A **wireframe model** is a skeletal description of a 3D object. There are no surfaces in a wireframe model; it consists only of points, lines, and curves that describe the edges of the object. Wireframe models can be created by positioning 2D (planar) objects anywhere in 3D space. Some 3D wireframe objects are also provided, such as 3D polylines and splines. Because each object that makes up a wireframe model must be independently drawn and positioned, this type of modeling can be the most time-consuming [Kurland 2007].

In wireframe modelling, the following operations are the most commonly used:

- create a point (by coordinates or in relation to other element),
- create a line (as above),
- create a curve (2D or 3D) – spline, circle, ellipse, helix and others,
- create a plane,
- multiply and transform elements: mirror, array, translation, rotation.

Wireframe modelling is usually used as a complementary technique, aiding the surface or solid modelling. For example, to create a spring, helix must be first modelled, then a circular or other shape can be extruded along it, obtaining a solid model.

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2.2.4 Mesh processing

Mesh modeling, or mesh processing, is another type of modeling, not exclusive to CAD systems, but available also in many other software packages, such as MeshLab, GOM Inspect, MeshMixer and many more. The mesh, in this case, is either a point cloud or a triangular mesh, in STL format (the formats are explained in the next chapter). The mesh is usually created as a result of a reverse engineering process (3D scanning or medical image processing). Mesh processing involves selection and manipulation of triangles – manually or semi-automatically, filling holes, smoothing the surface, repairing defects and removing unwanted artifacts etc., basic shaping tools are also available to make certain manipulations and create new geometries (Fig 2.6).

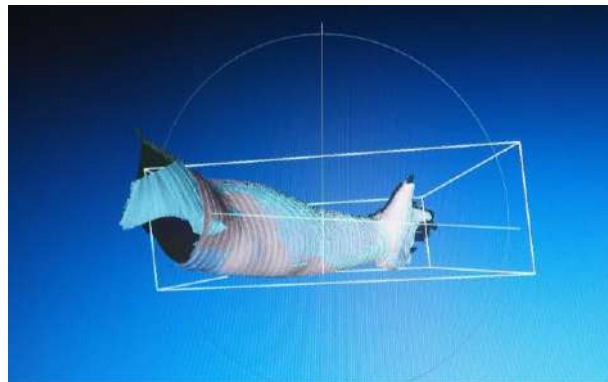


Figure 2.6 Mesh processing – human hand 3D scanned geometry

2.2.5 Assembly

Assembly is a process, in which a complex model of a device is created by putting together models of its components (parts, created by 3D modelling techniques). In order to create an assembly, at least two parts must be inserted into it and linked together by means of geometrical and dimensional constraints.

Assembling parts together in a desired arrangement can be achieved by utilizing the following constraints:

- line/plane contact,
- offset/distance,
- angle,

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- concentricity,
- coincidence (point/line),
- symmetry.

The assembly is usually fully parameterized, so changing values of constraints can allow for controlling the parts arrangement. Assembly is usually a separate module of any given CAD system. Any inserted part can be edited on the spot, adding new features to the part itself (replicated in any assembly where the part is used) or – sometimes – features specific to a given assembly (e.g. a hole through two or more parts or a weld between them).

2.3. CAD Software review

2.3.1. Inventor

Autodesk Inventor is a 3D CAD program used primarily for the mechanical design of parts and assemblies and the preparation of technical documentation based on them (fig. 2.7.). It is focused mainly on creating multi-element assemblies and has an extensive Content Center tool aimed at this eventuality, which enables the effective import of a wide selection of standardized elements. Inventor, due to its competitive price and free access to student versions of the software, has been widely used in the education sector and small and medium-sized enterprises with an engineering profile [bright-project.eu].

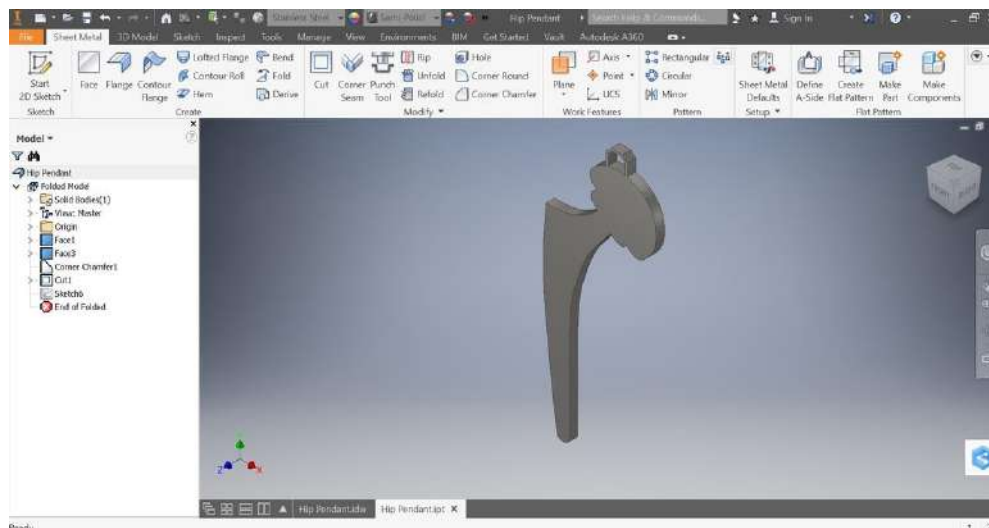


Figure 2.7 Inventor main window – hip implant

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The program has a ribbon structure of the main window with drop-down tabs in the upper part and an operation tree in the form of a block. Some functions are hidden in sub-tabs available after expanding a specific group of commands. In addition to the standard online help and support system, Autodesk Inventor 2014 and higher comes with a set of tutorial videos and educational animations that open when you move the cursor over the tool icon.

Autodesk Inventor can import STL files of any size. In order to convert a mesh to a parametric model, it is necessary to install the Mesh Enabler add-on, which allows you to convert the model in a short operation. The processing time depends on the computational capabilities of the computer and the complexity of the output model.

By design, Autodesk Inventor is not a program dedicated to making complex surface models, but it is nevertheless equipped with tools that allow you to perform basic activities, such as creating surfaces by extrudes.

The software enables automation through the use of product configuration tools, component generators and calculators, and automatic modifications of parts and components. It also has automation tools in the design of assemblies combining mechanical and electrical components, or installation.

The efficiency of work with the program includes the computational capabilities of the computer and the complexity of the design task. Due to the small number of tools for advanced modeling, in some cases it is not possible to complete a design task in full.

2.3.2. SolidWorks

SolidWorks is one of the most popular 3D CAD programs available on the market (fig. 2.8). In addition to standard functions related to 3D modelling, it has tools for technical documentation management, electrical design, FEM simulation and kinematic analysis. It is also widely used in enterprises for the design of technological processes and tools for plastic working and processing of plastics [bright-project.eu].

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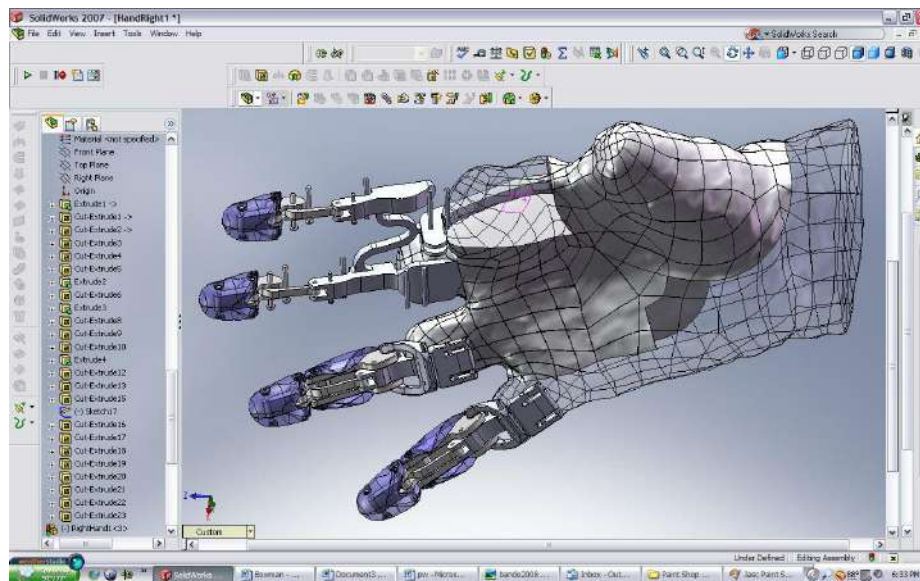


Figure 2.8 SolidWorks window view [solidsmack.com]

The easy-to-use and intuitive interface is one of the main advantages of SolidWorks. All functions are gathered in the main tabs which, when expanded, form ribbons in the upper part of the main window. The operations tree is a separate block that can be expanded or hidden depending on your preferences. The program has a software-level help system as well as a knowledge and instruction base available on the Internet.

Each time, importing a file in the STL format is associated with indicating the type of the output file. You can choose between a graphical model with very limited editing options, surface or solid. At the time of import, the program performs an automatic diagnosis of the file and proposes basic repair actions with the use of a special wizard. The disadvantage of working with STL files in the SolidWorks program is the much greater demand for computer computing power than in other 3D CAD programs.

SolidWorks has a set of tools that allow you to perform a limited number of surface modeling activities. The program enables the creation of simple linear and unfolding surfaces, as well as more complex NURBS (Non-Uniform Rational B-Spline) surfaces [Turostowska 2016].

Automation of model generation in the SolidWorks program is achieved by add-ins, which are a set of macros used to assign specific properties to components. The manufacturer authorized add-on is MacroSolid, which is not an integral part of the software.

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The high demand for computing power in the case of SolidWorks is a problem not only for importing STL files, but also for working with large data sizes or with complex assemblies. As a result, regardless of the user's level of advancement, it is difficult to optimize work with the program, which translates into a decrease in efficiency. The main factor that affects the efficiency of project tasks is hardware capabilities.

2.3.3. Fusion 360

Fusion 360 is a Cloud based collaborative product development program from the Autodesk company [autodesk.com]. It's an all in one package, mainly used for mechanical engineers and product designers, that combines all the phases throughout the entire engineering life cycle, from the planning stage, prototyping, testing all the way to final production. Fusion 360 eliminates the need of utilizing multiple different softwares in the development of new products or upgrade of existing ones. Having all the solutions in one software facilitates the making of various iterations to the design, as no data needs to be transferred to different softwares, and all of the Fusion 360 modules collaborate with each other. This software can be used as a tool for parametric CAD modeling, machining (CAM programming), simulation and analysis (FEM), creation of generative design, visualization (rendering), animation and 3D printing. It also allows real time collaboration between people involved in the same project, updating the models to all the participants [bright-project.eu]. The program is free to use for educational purposes and startups with less than \$100k of revenue per year.

The methodology of working with Fusion 360 is relatively simple, allowing all the standard CAD forms of designing: top-down, bottom-out and middle-out. Being a Cloud based software, the user doesn't have to worry about other models or components outside the main assembly as they can be easily imported and all the changes to the models are implemented in real time. All of the assembly components are stored in one single file, but it is also possible to link multiple files together for even bigger subassemblies and assemblies. Fusion 360 is similar in principles and interface to Inventor software, so users of Inventor can usually easily switch between the two and vice versa.

Some of the advantages of using Fusion 360 are:

- Cloud based program

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- User friendly interface and intuitive command selection
- Fast and easy modeling process
- Easy to make changes
- Simple unit conversion
- Seven different models of work environment (CAD / CAM / FEM / Generative Design / Render / Animation / Technical Drawings)
- Compatible with other CAD softwares

Fusion 360 is frequently used in open source projects for medical 3D printing – e.g. for 3D printed hand prostheses, as demonstrated via representatives of the e-Nable hub (see Fig. 2.9).

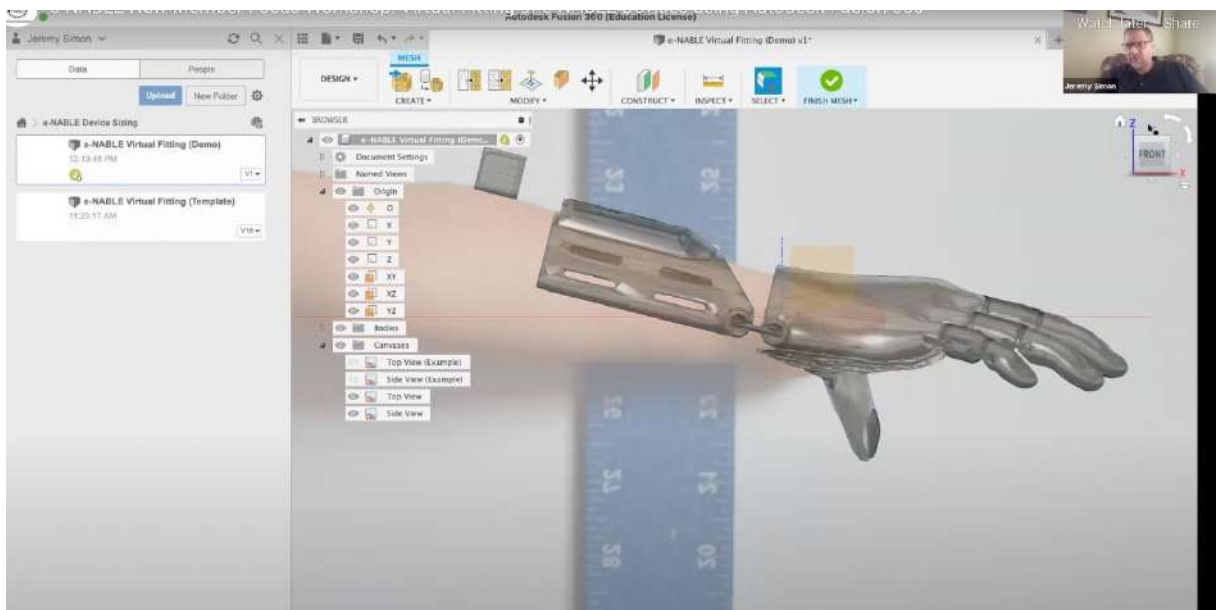


Figure 2.9 Use of Fusion 360 for prosthesis design [e-nable.com]

2.4. Mesh processing software review

2.4.1. MeshLab

MeshLab is an open source software for processing and editing of 3D triangular meshes, as well as point clouds and raster objects. The tool is dedicated to processing large unstructured triangle meshes and includes a set of tools. It allows editing, cleaning, healing, inspecting, rendering, texturing and converting meshes. It processes raw data produced by 3D

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digitization tools/devices and for preparing models for 3D printing [meshlab.net]. The tool is in active development by the Visual Computing Lab of ISTI-CNR (Italy) since 2005. There are new versions released in year 2022.

As a mesh viewing application, MeshLab allows 3D objects (saved in various formats) to be loaded and interactively inspected in a simple way, by dragging and clicking the mesh itself. User can work on a loaded mesh owing to interactive tools or a large set of parametric filters (e.g. Fig. 2.10a), which perform automatic tasks on selected parts or whole meshes. A distinctive feature of MeshLab is a very large range of these filters, allowing to perform very advanced operations, often based on complex mathematic algorithms. A unique feature of MeshLab is automatic recording of the filter usage - auto-creation of macros, which can be saved to a hypertext file and then re-used, both manually (via script interface – Fig. 2.10b) or through console-based tool (originally MeshLab Server, in late versions replaced by PyMeshLab).

Main usage of MeshLab involves the following work:

- 1) Basic align of 3D scanned / medical imaging data in form of point clouds and triangle meshes. MeshLab provides a set of tools for moving the different meshes into a common reference system (Fig. 2.10d). The alignment can be performed on meshes and point clouds coming from several sources, including active (both short- and long-range) scanners and 3D-from-image tools.
- 2) Basic mesh processing: transformation, rotation (Fig. 2.10a), mirror, scaling; selecting and removing vertices, triangles and whole surfaces via manual or semi-automated algorithms; automated mesh error removal and cleaning.
- 3) Advanced cleaning: hole filling, removal of unwanted artifacts, partial or total repair of meshes. Mesh division, simplification, refinement or remeshing.
- 4) Mesh reconstruction. The process of transforming independent acquisitions, or point clouds, into a single-surface triangulated mesh can be fulfilled with different algorithmic approaches. MeshLab provides several solutions to reconstruct the shape of an object, ranging from volumetric (Marching Cube) to implicit surfaces (Screened Poisson – Fig. 2.10e).
- 5) 3D printing oriented features: offsetting (creating inner shells), resampling/remeshing, automatic closing of holes to obtain “waterproof” meshes, flattening the bottom area and more.

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- 6) Measurement and analysis: manual measurement on the mesh surface, automated geometric and topological computations (center of mass, inertia tensor, bounding box size etc.). Planar sections in form of points, polylines or planar surfaces. Comparing different meshes for geometrical and topological differences.
- 7) Conversion and interchange – a number of 3D and 2D formats supported, both for export and import.
- 8) Raster image use – possibility of use of raster layers with 2D imagery or other forms of 2D data.

Figure 2.9c presents an example of an interactive filter. Whereas the engineer drags the mouse over the mesh, the local smoothing is performed on the touched part of the mesh in real time. An example of a rotation operation leading to the matching of two hand scans is shown in Figure 2.10d. The process can run separately or together following a flat approach based on layers [Cignoni et al. 2008].

The rich variety of filters make MeshLab a very important software for mesh-based operations, competing with applications such as MeshMixer or GOM Inspect. It can be utilized with advantage in the medical sector, for processing data from 3D scanning of patients (e.g. limbs) or processing of 3D data extracted of medical imaging (e.g. dental CT scans, MRI and others, after conversion of DICOM into STL, which is done in other software).

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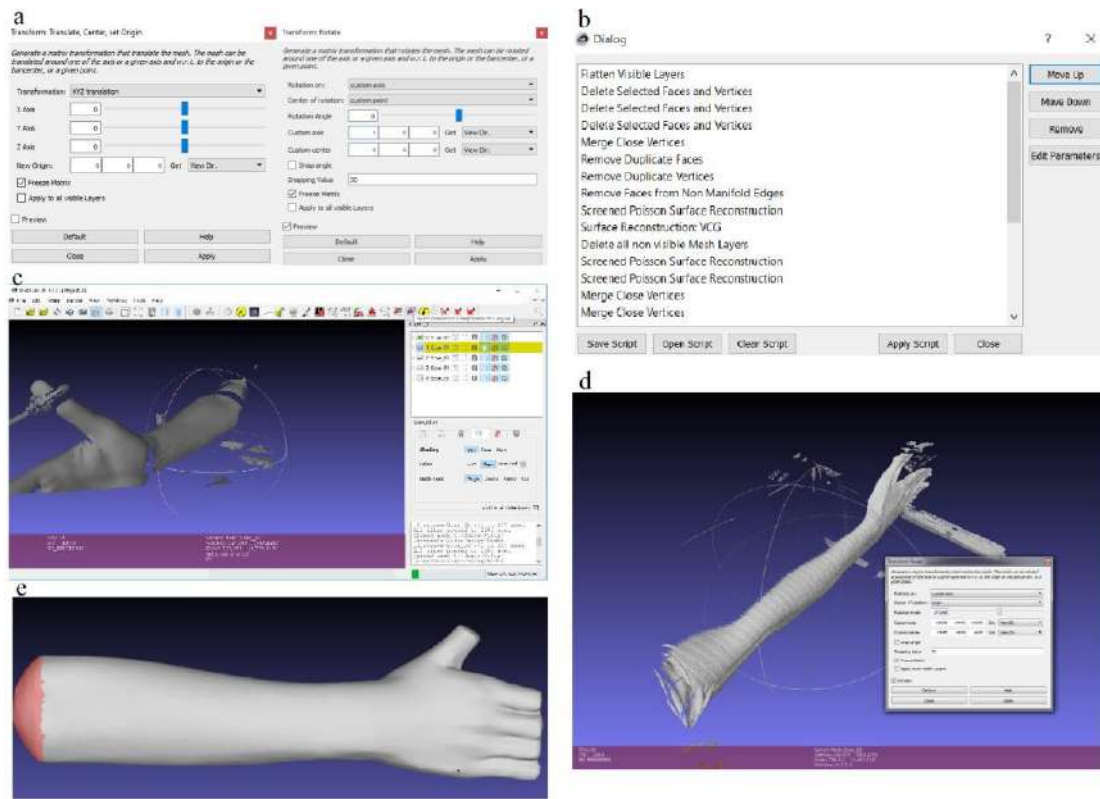


Figure 2.10 MeshLab exemplary features (a) translation and rotation operation, (b) list of operations, (c) mesh processing from the scan, (d) fitting two scans, (e) model after reconstruction [Górski et al. 2020]

MeshLab is operated using a Graphical User Interface, consisting of several windows and toolbars. The main part of the window is 3D viewer, where meshes and other objects can be inspected in 3D space (rotation, zoom and panning operations are available, as well as switch between perspective/orthographic camera, plus a number of possible visualization options – both global and per layer). All the meshes are organized in named layers, usually representing separate files. A project with multiple layers can be saved, referring to multiple files in various formats. Layers can be duplicated, hidden, frozen, renamed and reordered freely.

File, view, align, selection and basic measurement operations are available from the toolbar. All the filters allowing the advanced features are available from the Filters menu. Each of more than a hundred filters has its own interface and unique capabilities (filters are usually contained within external DLL files). The Filters menu also contains simple script editor, allowing preview and basic edition of macros generated by use of filters. Each use of a filter

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creates additional entry to the script, all the entries can be edited – i.e. modified, removed, reordered, duplicated and so on.

MeshLab is generally known for not being a super user-friendly. Its interface is bulky and somehow difficult to get acquainted with. The filters are very advanced, but their descriptions are usually vague and features aren't always intuitive. That is why MeshLab is not recommended as a tool for beginners, unless detailed use instructions are given. However, MeshLab creators, as well as the user community, have prepared a number of video tutorials, instructions and scientific papers on its use, so it is a good start for learning the software. MeshLab main advantages over competing software (MeshMixer, GOM Inspect and others) are:

- Very large quantity of available filters for mesh processing, some of them unique to MeshLab
- Advanced algorithms for mesh measurement, analysis and comparison
- Easy automation of tasks on various level (complete automation possible)
- Open source – free to use, code freely available
- Optimized engine – rapid work, possibility of use on computers with lower computing power
- High range of possible file formats available for import/export

2.4.2 GOM Inspect

GOM Inspect is software for the processing and analysis of 3D data. It enables comprehensive analysis of grids or clouds of points from 3D scanners or computer tomographs. The program allows to generate geometric meshes, with the possibility of smoothing them, filling holes, reducing the number of triangles forming the mesh and optimizing their edges. It also allows to edit the mesh by selecting data to extract a specific structure and remove the rest of the model. In the previous editions, it was a free (also for commercial purposes) version of GOM Professional, delivered in a package with professional devices for 3D scanning and reverse engineering by GOM. Currently, only 14-day free trial is offered [gom.com], but previous versions are still available.

The GOM Inspect software has tools to carry out both rough processing, which consists in cutting the mesh model along the X, Y, Z axis, and fine processing. More precise processing of

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the model consists in removing unnecessary or damaged parts of the mesh by selecting individual triangles.

GOM Inspect allows to carry out work of a similar nature to other mesh processing software (e.g. MeshLab). Due to the origin and original purpose of the program, it contains many tools that facilitate alignment of geometry in relation to each other, assigning coordinate systems and generating inspection reports for e.g. for product quality control, i.e. the compliance of the scan with the model CAD model.

Many different data formats can be imported into the GOM Inspect software - in addition to the standard STL, also incl. STEP representing 3D solids. STL files are transferred to the GOM Inspect program using the dedicated Import tool. Example of an anatomical mesh imported into the software is shown in Fig. 2.11.

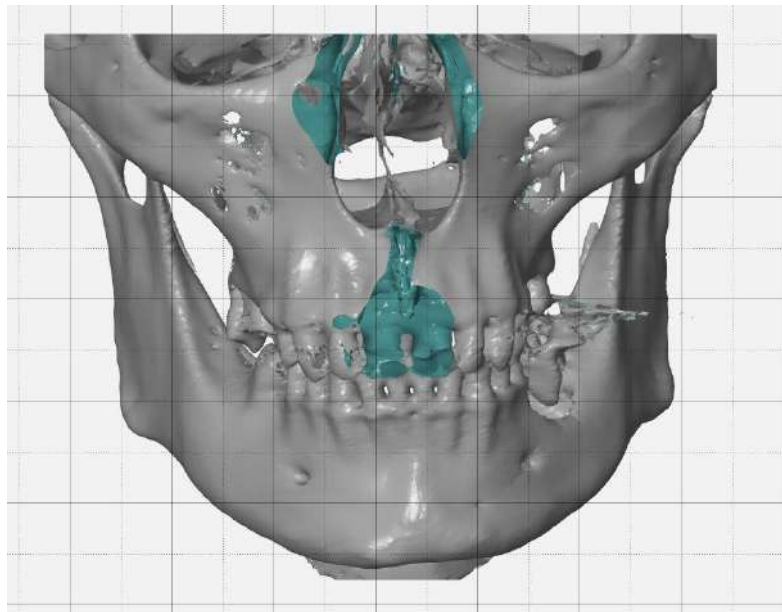


Figure 2.11 GOM Inspect software – anatomical mesh model

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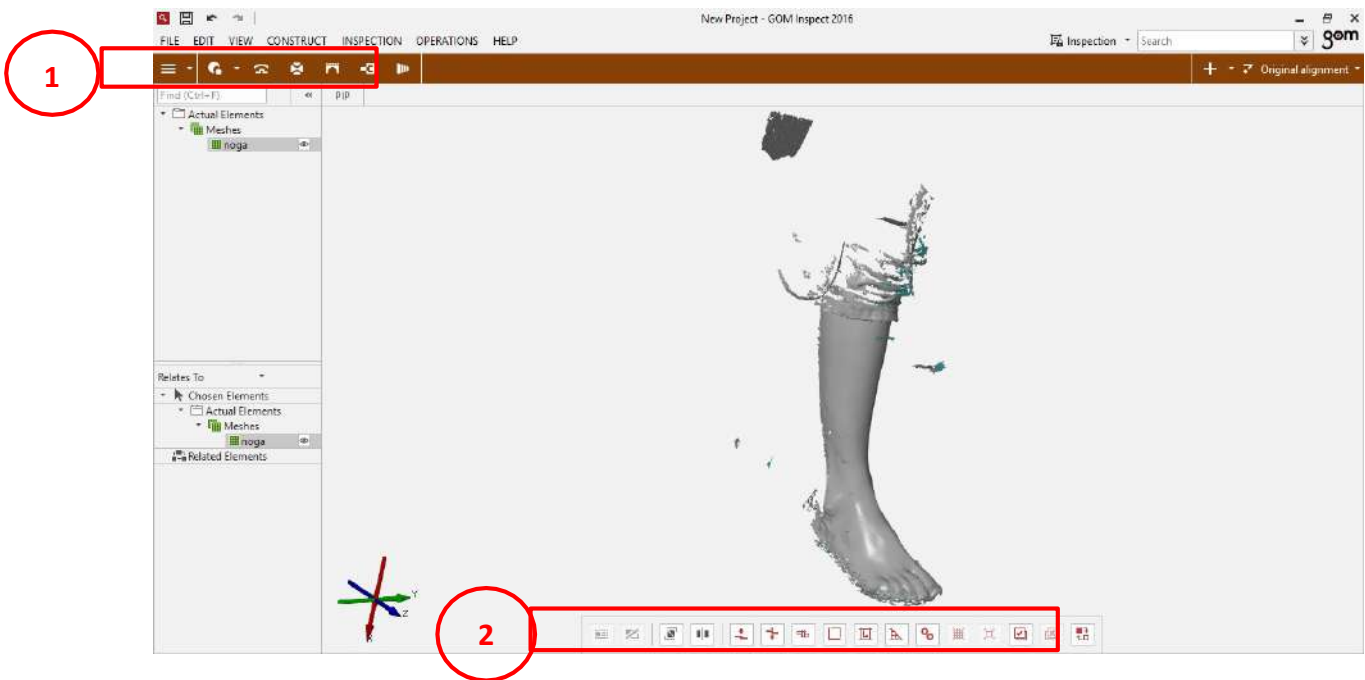


Figure 2.12 GOM Inspect software GUI

GOM Inspect has an intuitive Graphical User Interface (Fig. 2.12), allowing easy selection and performing of some quite advanced tasks. The bar marked as number 1 (available after selecting the Mesh Editing option from the drop-down list) enables the following operations:

- Close Holes - filling holes;
- Smooth Mesh - mesh smoothing;
- Thin Mesh - thinning out the mesh;
- Create Mesh Bridge - creating mesh bridges;
- Repair Mesh - fixing the mesh;
- Refine Mesh - mesh refinement.

Bar number 2 contains options for adjusting the view, selecting a specific area, and manipulating the selection area. Bottom bar tools looking from the left:

- Switch Camera - switch the camera;
- 3D Measuring View Off - turn off the 3D Measuring View;
- Clipping Cube - hide the area beyond the indicated cube;
- Clipping At Plane - hide the area beyond the indicated plane;

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- Select / Deselect On Surface - select / deselect the surface;
- Select / Deselect Through Surface - check / uncheck through;
- Select Patch - select a separate, unconnected item;
- Select Boundary - mark the boundaries;
- Select Along Line - select along the drawn line;
- Select Triangle - select a single triangle;
- Select Reference Points - select reference points;
- Increase Selected Area -increase the selection area;
- Decrease Selected Area -reduce the selection area;
- Select All - select all;
- Deselect All - select all;
- Invert Selection - invert the selection.

In addition to the above-mentioned basic tools for processing triangle meshes, GOM Inspect also has tools for conducting inspections and generating measurement reports (i.e. overlaying meshes from a 3D scan on a nominal CAD model and generating color deviation maps). It is also possible to base meshes on parametrically defined features (line, point, cylinder, plane, etc.), also in relation to imported solid models. The software also enables the diagnosis and automatic repair of damaged (containing errors) meshes, sometimes impossible to open by other software (eg MeshLab). Unfortunately, scripting and automation is impossible in the free version of the software (only available in the Professional version that comes with 3D scanners). The main advantages of the GOM Inspect program over competing programs are listed below:

- clear and friendly interface,
- a lot of options for precise marking of geometry on the mesh,
- quick and effective implementation of basic operations: patching holes, cleaning, reconstruction and repair,
- the ability to generate measurement reports and color deviation maps,
- easy homing and changing the coordinate system.

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3 Methodology of CAD design of 3D printed biomimetic mechatronic devices

3.1. Basic concepts of design of biomimetic products

Basic methodology of design of biomimetic products is a process, which is different to a classical computer aided design of mechanical devices. Biomimetic component of a designed device usually comes from a digital representation of anatomical features of a certain organism (usually – a human one). Also, biomimetic devices are usually medical ones, so they require medical consultation and diagnosis before any engineering work is done. As such, the process includes the following stages:

0. Medical diagnosis / consultation (non-engineering stage). Here the patient is diagnosed and / or prescribed with a certain medical product (orthosis, prosthesis, implant etc.).
1. Measurement / reverse engineering of organic anatomical features. This is usually done by 3D scanning or other form of medical imaging. Acquired imagery is then processed to obtain basic dataset for design engineering.
2. Design – here CAD systems are used to create a 3D parameterized (or non-parametric, in some cases) model of a desired biomimetic device. Very often, all types of modelling are utilized – starting from mesh, through wireframe/surface and finally – solid.
3. Planning of 3D printing processes – here CAD geometry is exported to appropriate file types and NC programs for selected 3D printers are prepared, assuming appropriate parameters of material processing and layer deposition.
4. 3D printing – at this stage, actual layer deposition is performed by 3D printing machines, usually automatically without supervision of a human operator.
5. Post processing, assembly and supply – at that stage, parts are processed (with scope depending on selected 3D printing process and material used) and assembled. Try-on with the patient/user is necessary to obtain feedback and possible re-design guidelines.

The above-mentioned process is presented in Fig. 3.1.

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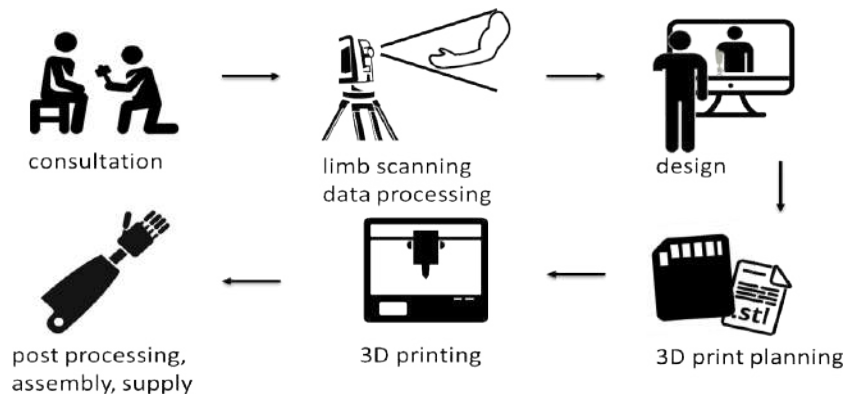


Figure 3.1 Design and manufacturing of 3D printed anatomically shaped devices

If a given biomimetic device is also a mechatronic one, additional sub-process needs to be utilized, with selection, design and programming of appropriate electronic components, mostly Printed Circuit Boards (PCBs). Basics of design of PCBs for medical purposes is described in another chapter.

The design can be based on different premises. On a basic level, there are 2 possible approaches:

- non-parametric ("shell") - conversion of the mesh (e.g. of a hand) into a „dumb” 3D model,
- parametric ("spline") - parametric reconstruction of anatomy in the form of a surface or solid model using a series of closed spline curves obtained as a result of mesh sections.

Data needed in the "shell" approach:

- complete, closed, „waterproof” STL mesh,
- characteristic distances - dimensions, distance range,

Data needed for the "spline" approach:

- a series of selected coordinates of points that control spline curves,
- characteristic distances - distances of planes with curves.

Both design approaches are shown in Figures 3.2 and 3.3. The “spline”, parametric approach is the desired one, allowing quick reconfiguration of a given model basing on different datasets for different patients. In the non-parametric approach, it is difficult to easily change the model for another patient – the whole process must be repeated from the scratch

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on another dataset. As such, the “shell” approach is advisable only in term of “one-shot” problems, where a specific device is unique and created only for one, particular patient, with non-repeatable features.

The “shell” approach converts the 3D scan into a solid, and further work assumes performing offsets, extrusions, cutouts, fillets, holes etc. in this particular solid. As such, it can be considered as “carving” in the anatomical features.

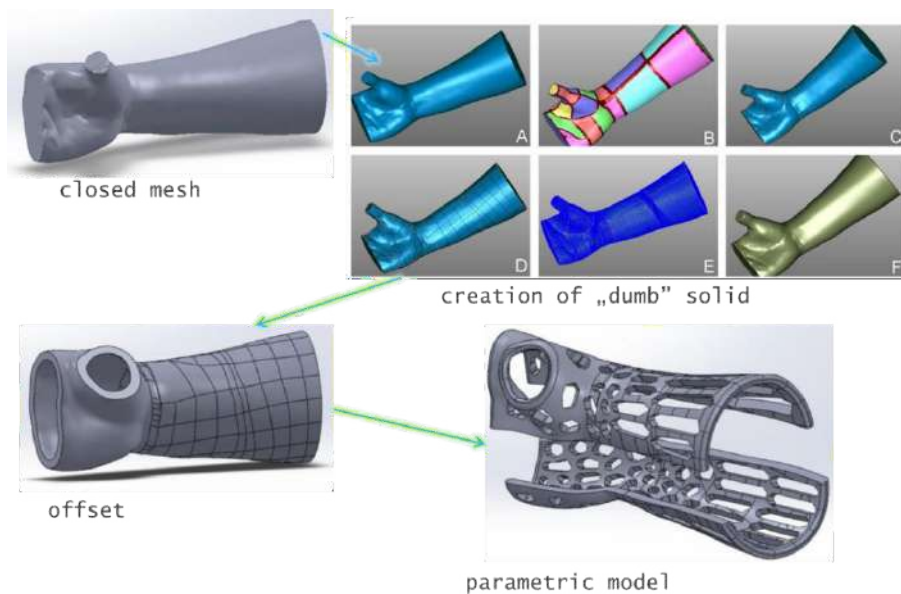


Figure 3.2 “Shell” approach [Górski 2021]

The “spline” approach usually starts with the splines (or other curves), based on points extracted from a mesh model representing anatomical features that need to be recreated in the device model. On the basis of the splines, a multi-extrusion is performed. The basic solid is then appropriately cut, divided and additional features can be added by various techniques of solid and/or surface modelling, if necessary.

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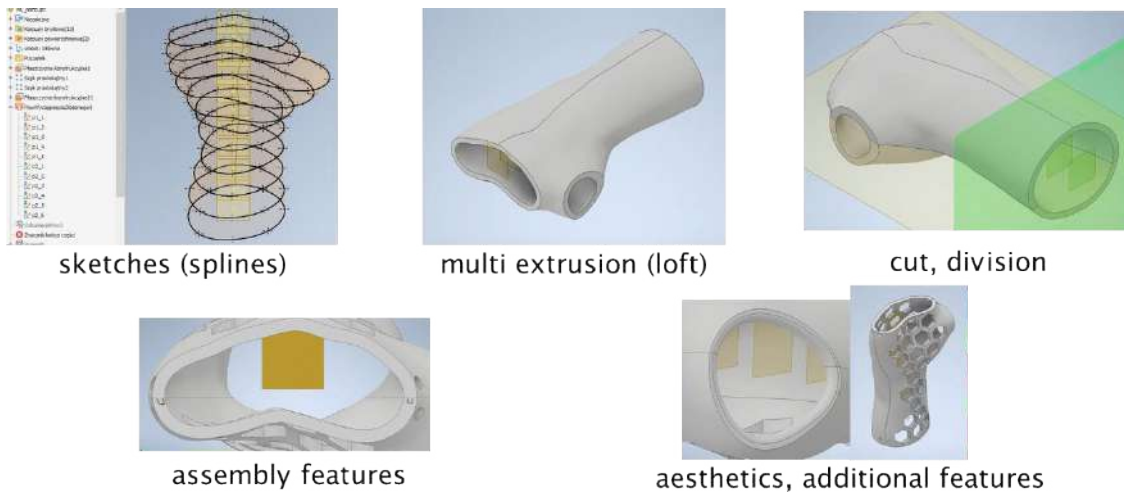


Figure 3.3 “Spline” approach [Górski 2021]

3.2. Automation of design of medical products

Automation of design is a concept introduced alongside the mass customization [Fogliatto et al. 2012]. It assumes that the so-called intelligent CAD models re-configure themselves, on the basis of design parameters entered by the clients. As such, workload of design engineers is significantly reduced, even from weeks to hours or from days to minutes [Chapman & Pinfold 2001, Kulon et al. 2006]. This concept has been successfully introduced in classical mechanical engineering branches, e.g. in automotive [Chapman & Pinfold 2001] or aeronautical [Stokes 2001] engineering.

In design of biomimetic devices, representing anatomical shape of a given human patient, the challenge is much more difficult, as the geometry is usually created of complex shapes, or is non-parametric at all. Aside from that, most of the production of such devices (e.g. limb orthoses or prostheses) still relies on manual processes, in which there is no digital layer. As such, transforming typical design/production process into an automated one, two big steps are required – first introducing the digital process, based on 3D scanning, CAD and 3D printing. This modern process is now known in literature [Cha et al. 2017] but it did not replace the traditional process, mostly because costly and difficult work of technicians has been replaced with also costly work of skilled biomedical engineers. The second big step is automation of design, which is very difficult and possible only in selected cases. Design automation assumes that all the basic stages are performed automatically, or at least without the need of work

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with a specialized software, such as CAD. Main idea of these transformations is presented in Figure 3.4.

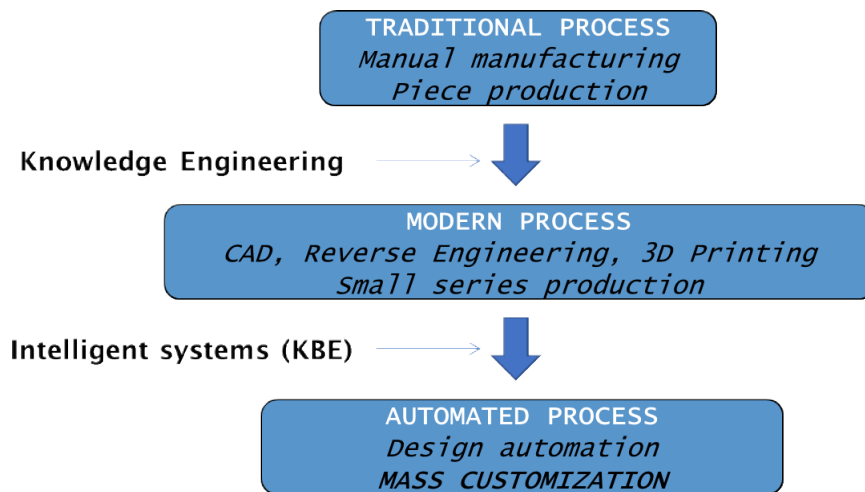


Figure 3.4 Design automation – transformation stages [Górski 2021]

The central component of design automation is usually an intelligent model. Intelligent CAD model is a digital model, in which geometry is enriched with knowledge about:

- functional and structural features,
- relations between these features,
- rules describing selection of these features.

The model is usually linked to an external „design table”. Design table is often an Excel sheet, containing all parameters about a given product variant. In the case of biomimetic devices, it contains anatomical data (e.g. points extracted from mesh, based on 3D scan or medical imagery) mixed with technical data (hole diameters, thicknesses, lengths etc.).

Basic ideas of intelligent CAD models is shown in Figure 3.5. Figure 3.6 contains example of a design table for a biomimetic hand prosthesis, along with a model of such prosthesis.

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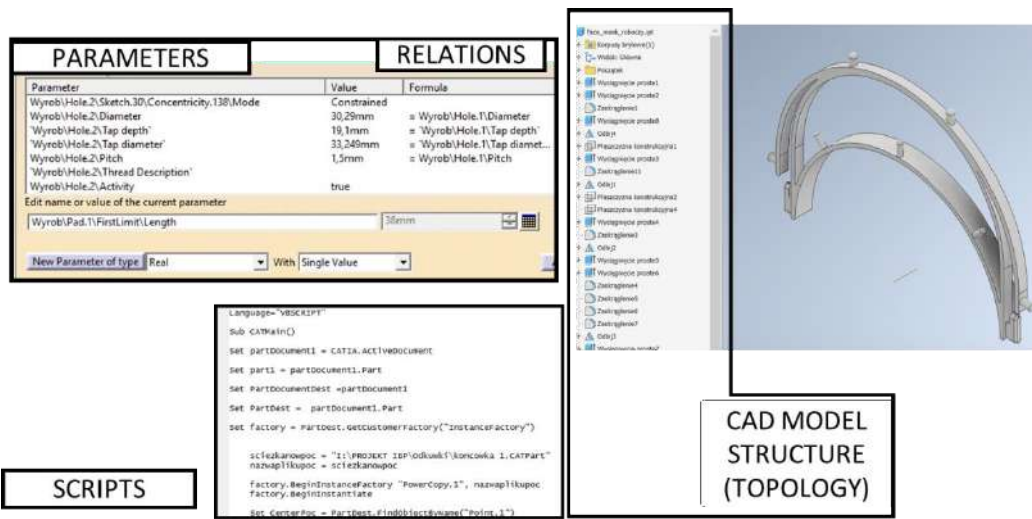


Figure 3.5 Basic ideas of intelligent CAD models [Górski 2021]

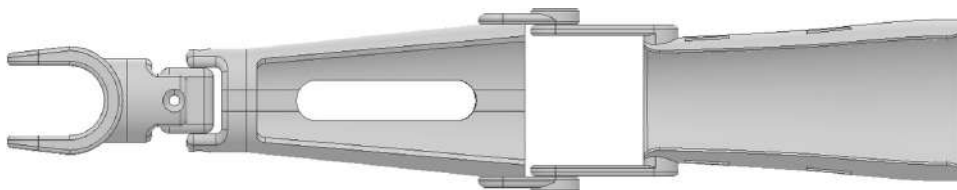
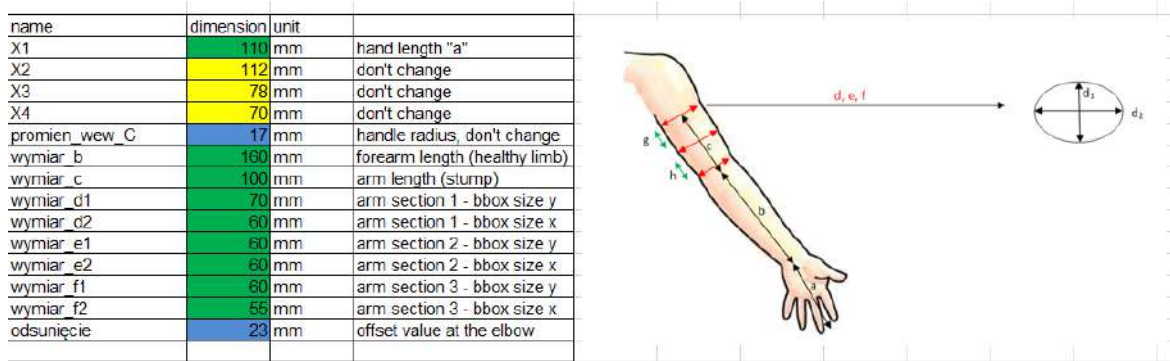


Figure 3.6 Design table of an arm prosthesis [Górski 2021]

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3.3 CAD design of electronic circuits for mechatronic and medical purposes

3.3.1. Basic introduction

Printed Circuit Board is a plate made of insulating material with electrical connections, the so-called tracks and with solder points called pads. Designed for the assembly of electronic components. Different requirements are imposed on them depending on the purpose of electronic systems, e.g. in the automotive industry, electronic systems must have high resistance to vibrations. In the case of medical applications, this may be:

- EMC compatibility,
- no harmful effects of electromagnetic fields, including those of high frequency
- use of lead-free assembly
- no use of harmful ingredients (lead)
- securing the power supply against unauthorized access,
- use of low voltages and currents flowing in the circuits.

At this point, a distinction should be made between systems that are installed directly on the patient's body (or inside) and devices that work independently, for example for medical imaging.

The composition of a PCB involves layering one material on top of another. The thickest, middle part of the board is an insulating substrate (usually FR4). On either side is a thin layer of copper, through which our electrical signals pass. To isolate and protect the copper layers, we cover them with a thin layer of varnish - soldermask, which gives the board its color (green, red, blue, etc.). Finally, to complete the look, we add a layer of screen printing similar to ink, which allows us to add text and logos to the PCB.

PCBs can be divided on:

- single-sided (one copper layer),
- double-sided (two copper layers on both sides of one substrate layer),
- multi-layer (outer and inner layers of copper).

The most important CAD programs for professional and amateur PCB design include:

- Altium Designer (paid license, trial 30 days)
- Eagle Layout Editor (free license for a specific PCB size and non-commercial use, so-called student version)
- Design Spark (free license)

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- KiCAD

The basic types that can be divided into electronic components from the assembly point of view are:

- through-hole components
- SMD components

3.3.2. PCB design procedure

Creating a PCB design in CAD software application is usually a two-step process. In the first stage, we create the so-called electrical schematic (schematic). It defines the elements used in the electronic circuit being created, their parameters and how they are connected to each other. When the electrical schematic is ready, we proceed to design a printed circuit board based on it. The elements used in the schematic will automatically be available in the PCB design. In addition, you will also receive information about the connections of these elements. Thus, it is enough to properly arrange the elements and connect them with paths to get an image of the circuit board, which will then be used to make the board itself. There are companies on the market that accept PCB designs made in Eagle and make professional PCBs based on them. The cost usually depends on the area and number of boards (the more, the cheaper) and ranges from a few tens of dollars upwards. The advantage of entrusting the making of a board to a professional company is that you won't have to bother making it yourself and the result will always be good.

The design procedure steps:

- a) design assumptions - determining the purpose, type of power supply, electrical protection, determining whether the devices should be portable or not
- b) creating a schematic diagram
- c) creating a CAD SCH scheme

Schematic design is a two-step process. First, you must add all the parts to the schematic sheet, and then those parts must be wired together. You can mix these steps - add a few parts, wire a few parts, and then add a few more - but since we already have a reference design, we are able to add parts and wires at once. On figure below example of power supply scheme is presented.

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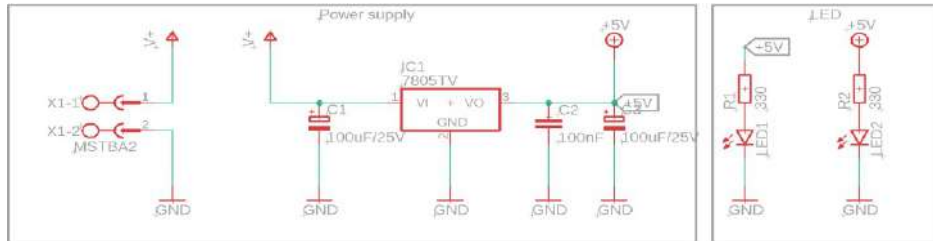


Fig. 3.7 Example of SCH scheme of power supply

d) creation of a BRD scheme

When designing circuit boards, you need to know and understand the basic terminology involved, preferably in English. The basic unit of measurement here is mils (1/1000th of an inch). Electronic circuits developed in Anglo-Saxon countries, and there the non-metric system of measurement is (or was) in effect. 1 inch is 25.4 mm, so 1 mil = 0.0254 mm. On a printed circuit board, paths (tracks) are created along which current flows. These tracks have widths in mils, such as 12, 16, 32, 40.

The thickness of the path depends on the expected electric current that will flow in this path. In the case of digital technology, these currents are usually small and you won't have to be particularly concerned about this. However, in order to comply with formal requirements, I give below a table that determines the widths of paths depending on the current they conduct.

When arranging components on a circuit board, you must take care that there is adequate space between them, otherwise they will not fit. The Eagle program makes it easy for you to do this, because in its database it contains enclosure views for all available electronic components. Here is a sample PCB design, corresponding to SCH schematic:

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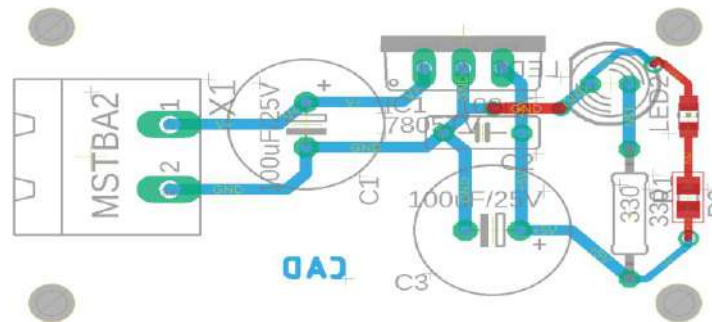


Fig. 3.8 Example of BRD scheme of power supply

- e) PCB making
- f) Assembly of electronic circuits by soldering
- g) System programming (if required)
- h) Function test (power supply, individual modules)
- i) verification of design assumptions and possible return to one of the previous points.

For prototypes, PCBs can be made using one of three methods:

- Thermal transfer
- Phototransfer
- Mechanical milling.
- Most often, however, the tiles are ordered outside (outsourced) and made by external companies

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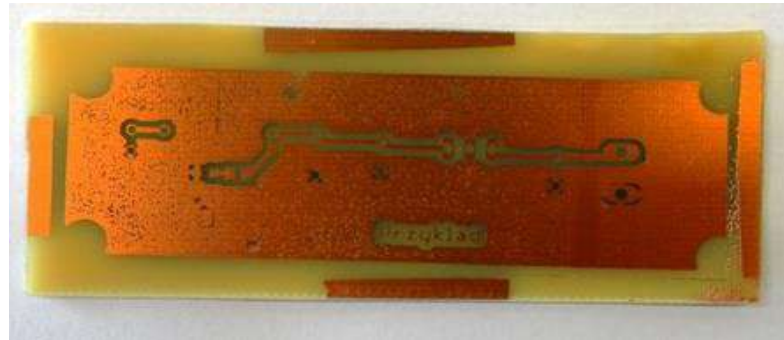


Fig. 3.9 Example of thermal transfer PCB

Example of PCB making using the phototransfer method

Basic rules for the implementation of the BRD layer:

- Before starting work, set the grid on which the elements are to be placed. Due to the dimensioning of the electronic component housings, it is recommended to set inches or mills as the main unit.
- The wire should be as simple and short as possible, especially in analogue and digital circuits, including some communication interfaces, e.g. SPI (impedance and the parasitic effect of connections have a special impact on the operation of the electronic system).

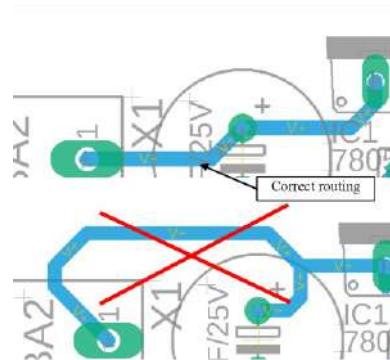


Fig. 3.10 Example of correct and bad routing

- Wires should be routing at an angle of 45 degrees or at an angle of 90 degrees

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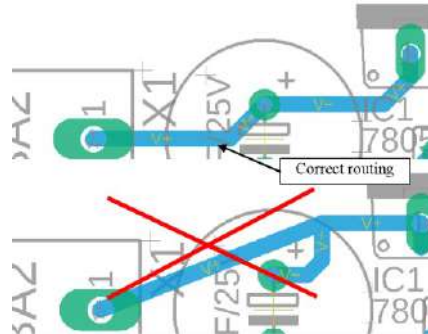


Fig. 3.11 Example of correct and bad angles

- d) Electronic components should be placed differently to the edge of the plate, at an angle of 90 degrees to each other
- e) Remember to add power connectors, which should be placed on the periphery of the PCB, preferably at one edge
- f) The ground plane has several tasks in the case of PCBs: They are:
 - reference for all voltages within the board
 - provides a noise shield and / or heat sink.
 - reduces the inductance of parasitic circuits and increases the capacitance

The basic rule is that it should occupy the largest possible PCB surface - preferably the entire one layer of the PCB. In multilayer boards, the ground plane and the power plane are dedicated to the inner layers, while the signal paths lead to the outer ones. In the case of the much more common two-layer panels, it is recommended that at least 75% of the layer's surface be allocated to the test range.

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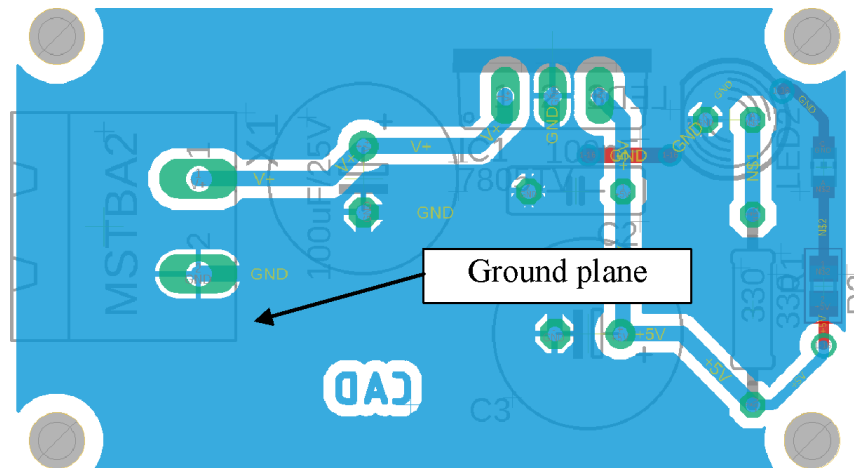


Fig. 3.12 Example of ground plane on bottom layer of PCB

- g) Testing the board for correctness according to predetermined parameters (Design Rule Check). It might look like this:

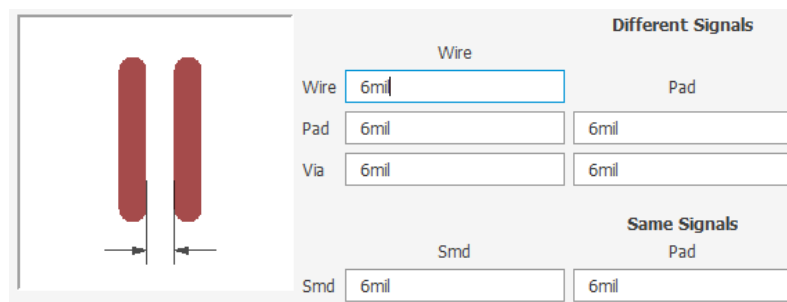


Fig. 3.13 Example of signals settings

- h) Use of information imprints

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Fig. 3.14 Example of text in bottom copper layer

- i) Grouping of cooperating components - dependent elements should be placed as close to each other as possible
- j) Using as many of the same components as possible - this applies especially to passive components, such as resistors, capacitors, etc. Using components with values from the series, including the same housing sizes, the same within the board, simplifies the list of components and facilitates assembly. These elements can also be used in other projects.
- k) Placing test points on the PCB
- l) pay attention to paths that must be symmetrical and of the same length, e.g. paths connecting quartz with a microcontroller

3.3.3. Production files - GERBER format

The standard of printed circuit board production documentation is the so-called Gerber format. It allows to vector save the image of the design layers:

- paths,
- mosaics,
- masks,
- descriptions.

There are two versions of the format:

- older Standard Gerber (RS-274D)
- contemporary Extended Gerber (RS-274X).

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Layer files in the Extended Gerber format (RS-274X) contain the complete set of data for design processing - coordinates and aperture definitions.

Machining parameters such as drilling and milling are most often used in the Excellon format (version 2). A program of this type for CNC drilling or milling operations should include:

- definition of the diameters of the tools used.
- also store information about the format of the coordinates and the units of measurement used.

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3.4 Examples of 3D printed biomimetic devices

3.4.1. Bicycle prosthesis

The first product example is a 3D printable mechanical prosthesis, intended for use with personal transportation devices, such as bicycles or scooters (Fig. 3.15). The prosthesis is a mechanical device, anatomically adjusted to a specific patient by a set of constraints and dimensions. It is intended for patients with transradial amputations or defects (above or at the elbow level), although patients with a short forearm stump could also possibly use it.



Fig. 3.15 [automedprint.put.poznan.pl]

The prosthesis is printable of any material – PLA and PET-G are recommended as being known for proper behavior in contact with user's skin. PLA is suitable for children version, while more durable materials, such as PET-G, are recommended for adult users. ABS and other materials could also be used, provided that there is no direct skin contact (e.g. foam is used) or sterilization is performed before and also after use. 3D printing of the whole prosthesis in children version lasts approx. several hours, depending on the material and printer used. It could be realized simultaneously, as the prosthesis contains few larger parts and several smaller parts. Standard nuts and bolts are used for assembly, along with straps and EVA foam for lining of socket's insides.

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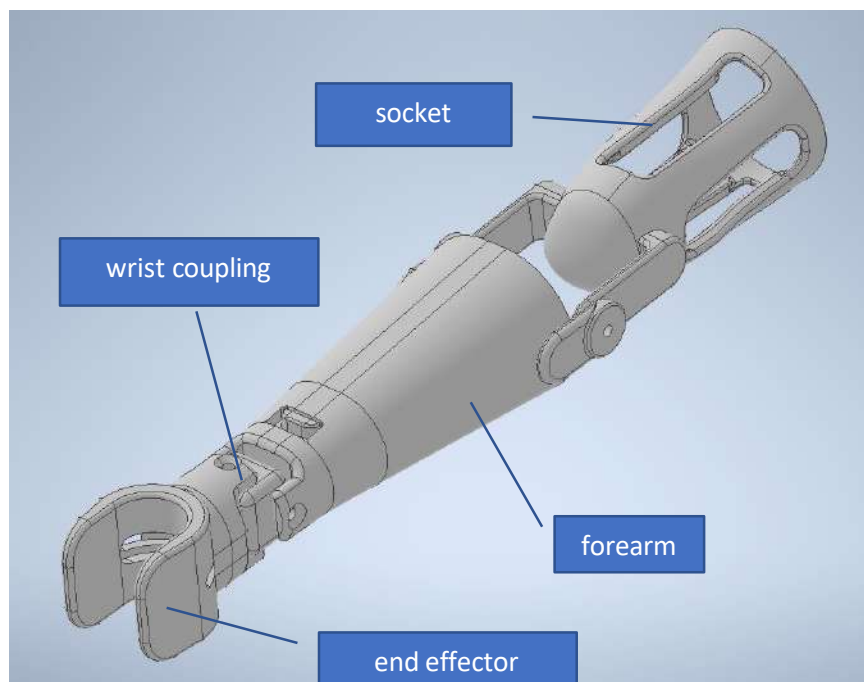


Fig. 3.16 Basic parts of the bicycle prosthesis

The prosthesis consists of basic parts (as visible in the figure above):

- socket (stump part) with elbow coupling,
- forearm part,
- wrist coupling (4 parts),
- elbow coupling,
- end effector.

The prosthesis is a biomimetic device, having two joints resembling human elbow and wrist joint, as well as a customizable socket of anatomic shape, using compression and release of muscle tissue to keep the prosthesis locked on patient's limb. All the basic parts are modular and can be replaced with different parts.

The prosthesis was designed using Autodesk Inventor software. Thanks to use of modularity and implemented iLogic rules, it is possible to obtain a large number of variants for a single patient (examples in Fig. below).

The model is impossible to use without aid of MeshLab software, which is needed to obtain data necessary to feed the model with patient-specific anatomical features. MeshLab software is also used to check fit of the prosthesis after it is generated (Fig. 3.17).

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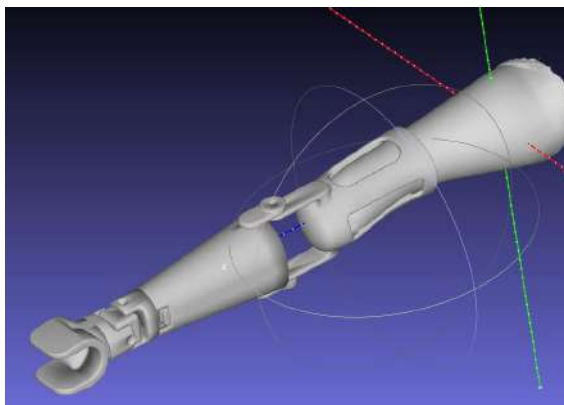


Fig. 3.17 Fitting check in MeshLab software

3.4.2. Therapeutic hand orthosis

The product is an orthosis used for wrist joint stabilization in time after an injury (e.g. Colles fracture) or for patients with conditions that require stabilization (rheumatoid arthritis, muscle atrophy and many others) – Fig. 3.18. The orthosis is openwork, to enable skin access in both comfort and hygienic reasons. Rehabilitation orthosis (used in the event of muscle paralysis, damage to the hand nerves, etc.) is designed to stabilize the hand in a position where active rehabilitation of the hand occurs. In this way, it supports the correct positioning of the hand and allows to perform exercises supporting the patient in the rehabilitation process.



Fig. 3.18 Examples of use of the Wrist Hand Orthosis [automedprint.put.poznan.pl]

The orthosis is customized on the basis of a 3D scan geometry of patient's hand and forearm. It is 3D printed using one of the basic FDM technology materials: PLA, ABS, PET-G and PA-12 (nylon), of which PLA and PA-12 are recommended due to proper combination of mechanical and processing properties, as well as no known issues with skin irritation. The 3D printing takes approx. 3-4 hours for one part of the orthosis, for an adult patient.

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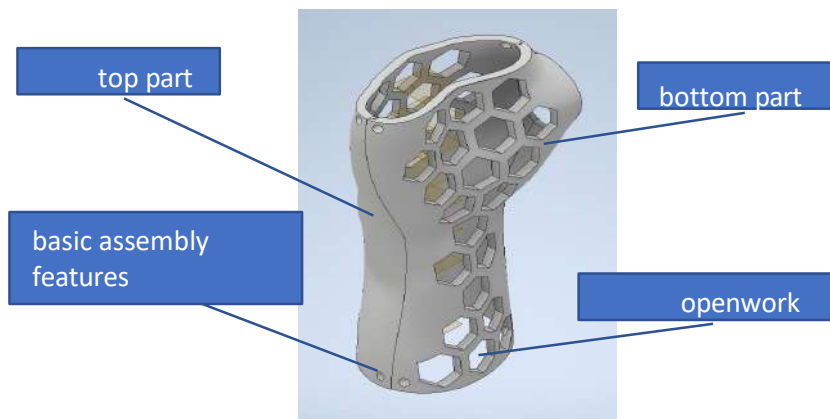


Fig. 3.19 Wrist hand orthosis – basic parts [Górski 2021]

The orthosis consists of basic parts (as visible in the figure above):

- bottom part (in contact with palm),
- top part (in contact with back of the hand),
- optionally – the bottom and top part could be transversally divided if orthosis too long for a given 3D printer (could be 4 parts instead of 2) .

Complete model of a customizable orthosis was made in Autodesk Inventor. The parameters (dimensions) are stored in an Excel spreadsheet (which could be edited using MS Excel with VBA macro support). A new set of anatomical measurements is created for every single patient, using a batch file involving a set of algorithms, based on MeshLab, Excel VBA and a custom application for selection of basic section plane positions. Then, these measurements stored in an Excel file, must be used to customize the orthosis and any errors or inconsistencies must be repaired to obtain a functional orthosis.

If the orthosis is set to be functioning not only as a corrective, but also therapeutic device, it needs to have certain cutouts, to allow grasping movement. Examples of these features are shown in Figure below.

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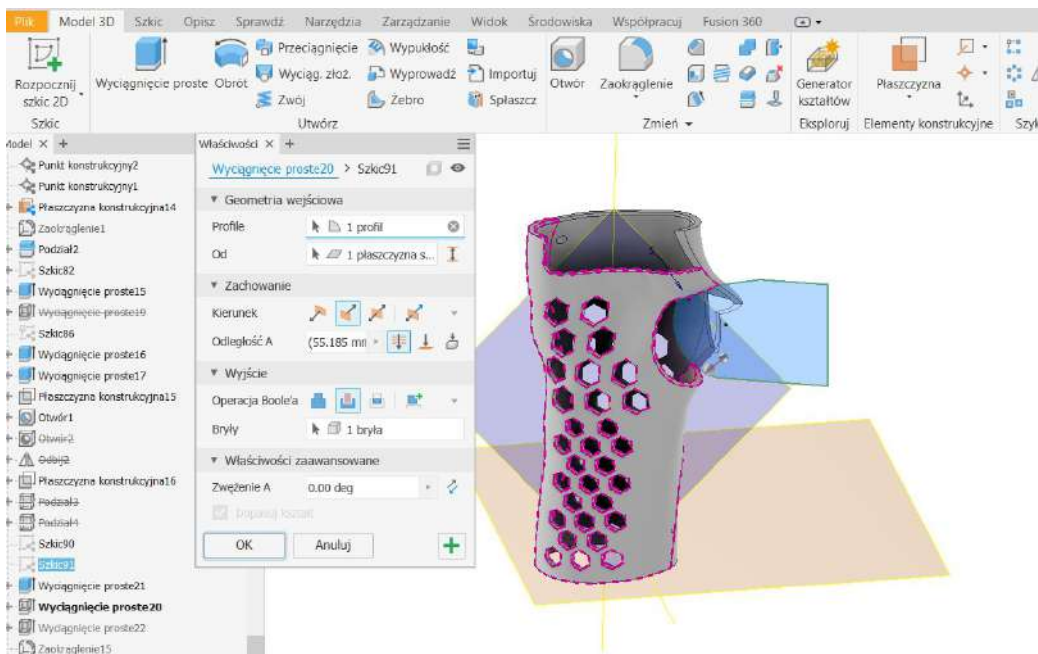


Fig. 3.20 Conversion of standard orthosis into therapeutic orthosis in Inventor

As in the case of the bicycle prosthesis, it is important to use MeshLab software to generate the set of patient data, as well as check proper fitting at a later stage (Fig. 3.21).

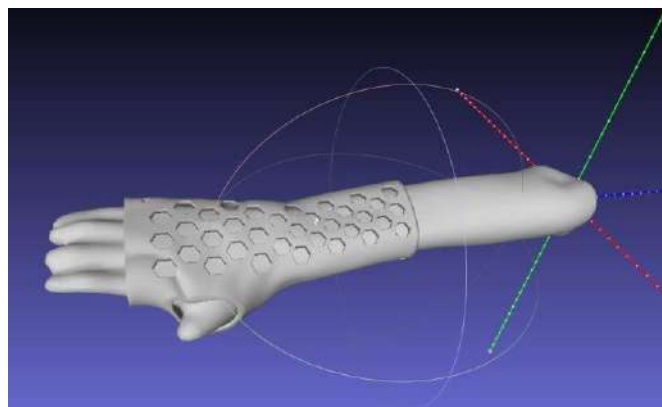


Fig. 3.21 Orthosis fitting check in MeshLab

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4 Summary

In this module, basic knowledge about computer aided design of 3D printed biomimetic mechatronic products for people with special needs was presented. The most important takeaways have been summarized below:

- using digital technologies can make design for medicine much faster and also more robust,
- 3D printing helps faster iteration of design, as well as easier obtaining of organic, anatomical shapes,
- designing individualized medical products requires anatomical data processing in several types of software,
- design for medicine requires participation of doctors at the beginning and often end of the process,
- some, if not most operations in the design process of medical parts can be automated for greater efficiency,
- functional, specialized, biomimetic prostheses can be 3D printed for a fraction of a cost of a traditional, expensive one – but the design can be time consuming,
- design changes can be introduced anytime, as many times as feedback is gathered from patients,
- 3D printed prostheses and orthoses could be converted into mechatronic devices by adding sensors and actuators, helping in therapeutic or daily activities.

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MECHATRONIC SYSTEMS

MODULE COMPUTER AIDED ENGINEERING

Project Title	European network for 3D printing of biomimetic mechatronic systems 21-COP-0019
Output	O1 – EMERALD e-book for developing of biomimetic mechatronic systems
Module	Module – Computer Aided Engineering (CAE)
Authors	Dan-Sorin COMȘA, Emilia SABĂU

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1. Numerical Solution of Engineering Problems

Engineering calculations are essential components of the design process. Any equipment must be designed in such a way that its functionality is ensured while satisfying different requirements related to cost, overall dimensions, manufacturing procedures, reliability, etc. Such requirements often lead to the imposition of some constraints whose fulfillment should be assessed by engineering calculations (for example, not exceeding a maximum stress, strain or deflection level, guaranteeing the fatigue strength, etc.). Engineering calculations provide the information from which the designer can deduce how close the structural components are to the limit states that could compromise the functionality of the whole equipment.

The variety of problems that occur in practice is reflected in the multitude of calculation methods used at present. These methods have been gradually developed, along with the accumulation of technical and theoretical knowledge and, in the last seven decades, simultaneously with the evolution of digital computers. A basic classification of the calculation methods used in engineering distinguishes two large categories:

- Exact (or analytical) methods
- Approximate methods.

Exact methods are applicable only for solving a relatively small number of simple problems. Their use is generally restricted by the geometry of the model under analysis and the type of boundary conditions. Approximate methods are used to solve more complex problems, for which analytical solutions cannot be found.

There is a wide variety of approximate methods for solving engineering problems. Whatever method is adopted by the designer, it must provide a sufficiently accurate solution for the practical problem under analysis. Nowadays, the following approximate methods of numerical type are mainly used in engineering:

- Finite difference method (FDM)
- Finite element method (FEM)
- Boundary element method (BEM).

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At first glance, these methods seem very different from each other. On closer inspection, it can be noticed that they are closely related by their mathematical foundations (all of them rely on notions belonging to the theory of differential equations, calculus of variations, or weighted residual methods). In the following, we will make a brief presentation of these numerical methods, in order to compare them from the point of view of the specific advantages and disadvantages.

Finite difference method (FDM)

The finite difference method is the simplest procedure for solving sets of ordinary or partial differential equations. For the practical application of FDM, the spatial domain occupied by the physical system under analysis is replaced by a rectangular grid consisting of nodes. The differential equations that describe the physical system are approximated with finite differences evaluated at nodes [Tho1995]. In this way, the set of differential equations is transformed into a set of algebraic equations which is then solved using numerical procedures (for example, Gaussian elimination [Dem1981]). The approximate solution is represented by the unknown values associated to the nodes. In general, the accuracy of this solution can be improved by densifying the grid.

The main advantages of FDM are its conceptual simplicity and straightforward implementation in computer programs. FDM still has some shortcomings that restrict its applicability:

- FDM only provides nodal values of the unknowns, without providing information about their distribution between nodes.
- The discretization of complex shaped bodies using only rectangular grids often leads to poor approximations at corners or in the regions where important cross-sectional variations occur.
- FDM has difficulties when complex boundary conditions must be implemented in the numerical scheme.

Because of these disadvantages, FDM is mainly used for solving heat transfer or fluid flow problems, its applicability in the field of solid mechanics being quite limited.

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Finite element method (FEM)

At present, the finite element method is the most frequently used procedure for solving engineering problems expressed by sets of ordinary or partial differential equations. When applying FEM, the spatial domain occupied by the physical system under analysis is divided into a finite number of subdomains. The spatial domain is thus replaced by the so-called finite element mesh [Hen1996, Hut2004, Sab2021, Seg1984]. The differential equations that describe the physical system are approximated at element level.

The mathematical structure of these approximations ensures their continuity across interelement boundaries. The continuity is achieved with the help of some remarkable points associated to the elements (the so-called nodes). In fact, the approximations are controlled by the nodal values of the problem unknowns. FEM produces a set of algebraic equations which is solved numerically for the values of the nodal unknowns. Since the approximations generated by FEM work at element level, they provide information on how the unknowns are distributed over the entire mesh (not only at nodes, as in the case when FDM is used).

The main advantages of FEM are the following ones:

- Flexibility (since it allows meshing complex-shaped bodies and manipulating all types of boundary conditions in the most natural manner)
- Capability of modeling inhomogeneous bodies in terms of their physical properties
- Ease of implementation in general computer programs.

The most important disadvantage of FEM consists in the large amount of input data required for the construction and solution of the numerical model. Most of the input data describes the configuration of the finite element mesh (nodal coordinates and association between elements and nodes). Modern finite element programs relieve the user of the cumbersome task of manual discretization, transferring it to specialized modules that perform this operation in an automatic manner.

Numerous finite element programs have been developed during the last four decades. Most of them are interfaced with computer-aided design software packages so that their use by engineers is relatively simple.

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Boundary element method (BEM)

The boundary element method has been elaborated more recently than FDM and FEM. BEM is based on the idea of replacing the original set of differential equations with an equivalent integral model defined only on the boundary of the analysis domain [Bre1978]. The boundary integral model is advantageous because it no longer needs a mesh generated over the interior of this domain. The number of problem unknowns and the amount of input data are thus significantly reduced. From the point of view of its practical utilization, BEM is very similar to FEM, in the sense that the boundary of the analysis domain is meshed using elements built according to principles similar to those adopted by FEM. BEM also produces a set of algebraic equations that must be solved numerically for the values of the unknowns associated to the nodes of the boundary elements. Once the values of the nodal unknowns are obtained, the distribution of any quantity over the entire analysis domain can be determined using a set of specific formulas.

Besides the previously mentioned advantage, BEM has some other attractive features:

- It can be naturally applied in the case of spatial domains that extend to infinity in one or several directions.
- It can provide accurate solutions at corners or in regions where important cross-sectional variations occur, without requiring an excessive refinement of the mesh (unlike FEM which frequently needs refined meshes in such situations).
- It can be easily accommodated by computer-aided design software packages.

BEM still has some disadvantages that restrict its applicability:

- Serious difficulties in modeling inhomogeneous bodies in terms of their physical properties
- Poor accuracy of the numerical solution in the case of bodies exhibiting major dimensional discrepancies in different directions (e.g., bars, beams, plates, or shells).

However, it must be kept in mind that BEM is still under intense development, so that future research is expected to alleviate these shortcomings.

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The discussion above allows us to understand why FEM is nowadays the most appropriate procedure for the numerical solution of engineering problems expressed by sets of ordinary or partial differential equations. The penetration of FEM in all engineering fields has been facilitated by its generality and flexibility, as well as the large number of finite element programs interfaced with computer-aided design software packages.

The development potential of FEM is far from being exhausted. Many researchers are currently involved in the elaboration of finite elements to meet the needs of the most diverse engineering applications. The finite element programs are also continuously developed with the aim of exploiting the processing capabilities of high-performance computers (e.g., parallel computing), as well as ensuring the most natural integration of the finite element analysis in the computer-aided design process [WWW2022a].

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2. Features of the Finite Element Method

From a mathematical point of view, many engineering problems are expressed by sets of ordinary or partial differential equations. FEM is one of the numerical procedures that can be used to obtain approximate solutions of such problems.

FEM builds the approximation of the exact solution as follows:

- The spatial domain occupied by the physical system under analysis is divided into a finite number of non-overlapping subdomains called (finite) elements.
- Polynomial approximations of the problem unknowns are defined over each element.
- Each polynomial depends on the unknown values associated to a finite set of points called nodes.
- The element approximations are assembled into a global approximation of the problem unknowns.

The global approximation must be understood as a function that depends on a finite set of undetermined parameters. These parameters are the unknown values associated to the nodes of the finite element mesh. By assigning arbitrary values to the parameters, we obtain an infinite set of global approximations that are virtually acceptable for the problem under analysis. This set is usually called family of test functions [Hen1996, Hut2004, Seg1984]. FEM searches among the test functions for the best global approximation of the exact solution.

In fact, FEM provides the most accurate approximation of the exact solution over the entire spatial domain (not only at specific points). With this aim in view, FEM uses a global criterion for minimizing the errors of the numerical solution. The set of partial differential equations cannot be used directly for obtaining such a criterion. This is because differential operators describe only the local behavior of the unknown quantities. The minimum criterion used by FEM is built in the form of an integral defined over the entire domain occupied by the physical system under analysis. It is known that, unlike derivatives, an integral can describe the behavior of one or more functions averaged over the integration domain. Integrals are thus more suitable for obtaining global minimization criteria. In the case of elasticity problems, this criterion is expressed by the theorem of minimum potential energy.

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By enforcing the condition that the numerical solution corresponds to the minimum error, FEM generates a set of algebraic equations. These equations are solved for the nodal values of the problem unknowns. After replacing the nodal values in the expressions of the element polynomials, FEM obtains approximations of the unknowns defined at element level. Finally, the element approximations build together a global approximation of the solution (i.e., an approximation defined over the entire mesh).

In the specific case of elasticity problems, the steps performed when elaborating and solving a finite element model are as follows:

- Selecting the finite element type which is the most suitable for the problem under analysis
- Meshing the analysis domain
- Generating element approximations for the problem unknowns
- Including the element approximations in the expression of the potential energy
- Enforcing the minimum condition on the finite element approximation of the potential energy and assembling the set of equations emerging from this condition
- Applying the boundary conditions by reducing the set of equations
- Solving the set of equations for the nodal unknowns
- Reconstructing the element approximations and assembling them into a global approximation
- Analyzing the numerical results.

In practical applications, when modern finite element programs are used, most of the steps mentioned above are automated. The geometric representation of the analysis domain is generated using a CAD program or the modeling facilities provided by the finite element program itself. The mesh is then generated automatically by the finite element program (the analyst is responsible for selecting the element type and controlling the mesh density). In the next stage, the analyst applies external loads and motion constraints to the finite element model. The finite element program now has all the information needed for generating the set of equations. The assemblage and numerical solution of the set of equations are fully automated steps. Modern finite element programs generally provide tools for the graphical presentation of numerical results. In this way, the analyst is also assisted in interpreting the output data.

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3. Common Types of Finite Elements

The discretization of the analysis domain is the first step that must be performed when using FEM to obtain the numerical solution of a problem. Discretization involves making decisions on the type, number and size of the finite elements to be used. FEM users must find a balance between the quality of the numerical solution and the computational effort needed for obtaining it. In general, increasing the density of the finite element mesh improves the accuracy of the numerical solution. However, an excessively refined mesh leads to a large set of global equations and, consequently, involves an increased computational effort in the solution stage. The analyst must use his/her theoretical knowledge and engineering expertise to refine the mesh only in the regions where steep gradients of the problem unknowns are expected. In the regions where the variation of the unknowns is expected to be smoother, the mesh can be coarsened without affecting the accuracy of the numerical solution.

The quality of the numerical solution is also influenced by the mathematical features of the finite element in use. In general, the analyst must choose an element whose properties (especially the degree of the polynomial approximation) are appropriate to the type of problem to be solved. The importance of choosing the element type should never be underestimated, since a wrong decision in this stage might lead to inaccurate solutions. In practice, most of the poor decisions made by FEM users in the discretization stage are due to the following reasons:

- Insufficient knowledge of the theory behind the problem under analysis
- Lack of information on the mathematical features of the finite elements used for meshing the analysis domain.

Even if the user relies on a high-performance finite element program, he/she is not fully relieved of having such knowledge.

In what follows we will describe a few types of finite elements suitable for solving engineering problems. The limited space does not allow us to present all the finite elements that might be used in applications. References [Hen1996, Hut2004, Seg1984] could be helpful to the reader interested in getting further information about different types of finite elements

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and their usage in practice. The manuals of the finite element programs also provide valuable information about these topics.

3.1. Classification of finite elements

A general classification (but not comprehensive, unfortunately) defines three categories of finite elements differentiated by their dimensionality:

- One-dimensional elements
- Two-dimensional elements
- Three-dimensional elements.

This classification is far from capturing all the finite element features. For example, it does not make any reference to the degree of the polynomial approximation. Under such circumstances, some other criteria can be used to define subclassifications within each of the categories mentioned above. For example, if the degree of the polynomial approximation is considered, the following subcategories of finite elements can be individualized:

- First order (or linear) elements
- Second order (or quadratic) elements
- Third order (or cubic) elements
- ...

Finite elements having a degree of the polynomial approximation greater than three are rarely used in practical applications.

Although this second criterion clarifies an entire series of aspects, it is not exhaustive either. In fact, it is impossible to devise a unique criterion for classifying all the finite elements used in practical applications. There are types of elements that can hardly be included in a particular class, especially those having a higher mathematical complexity.

Despite their limitations, the classification criteria mentioned above are sufficient for our purposes. We will rely on them when presenting some finite element types frequently used for solving engineering problems.

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3.1.1. One-dimensional elements

One-dimensional elements are used when the physical quantity that needs to be approximated depends on a single variable. By consequence, one-dimensional elements are straight or curved lines along which the independent variable of the problem takes values (Fig. 3.1).

The simplest one-dimensional element is a line segment ended by two nodes (Fig. 3.1.a). A first-degree polynomial approximation is associated to this element. This is the reason for calling it first order (or linear) one-dimensional element.

The second order (Fig. 3.1.b) and third order (Fig. 3.1.c) elements are more complex. One may notice that they have both end and internal nodes. The second order elements have three nodes, their polynomial approximation being of the parabolic type. The third order elements have four nodes, their polynomial approximation being a cubic parabola. Both the second and third order one-dimensional elements have curved versions as shown in Figure 3.1.

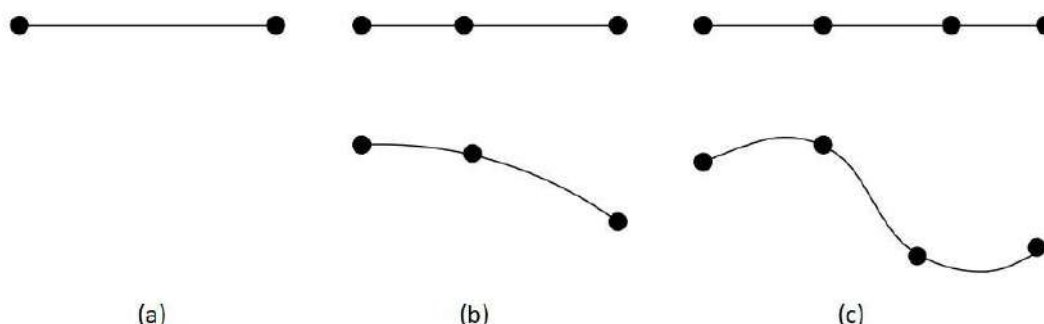


Figure 3.1: One-dimensional finite elements: (a) First order (or linear). (b) Second order (or quadratic). (c) Third order (or cubic)

3.1.2. Two-dimensional elements

Two-dimensional finite elements are used when the physical quantity that needs to be approximated depends on two variables. For example, they can be used for solving two-dimensional elasticity problems (i.e., plane stress, plane strain or axially symmetric problems).

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Two-dimensional finite elements can be subdivided in two large classes distinguished by their shapes:

- Triangular elements (Fig. 3.2)
- Quadrilateral elements (Fig. 3.3).

As their name suggests, triangular elements are planar regions bounded by three sides. The simplest is the triangle with straight sides and three nodes placed at the vertices (Fig. 3.2.a). The approximation associated to the element shown in Figure 3.2.a is a first-degree polynomial in two variables. This is the reason for calling it a first order (or linear) triangular element.

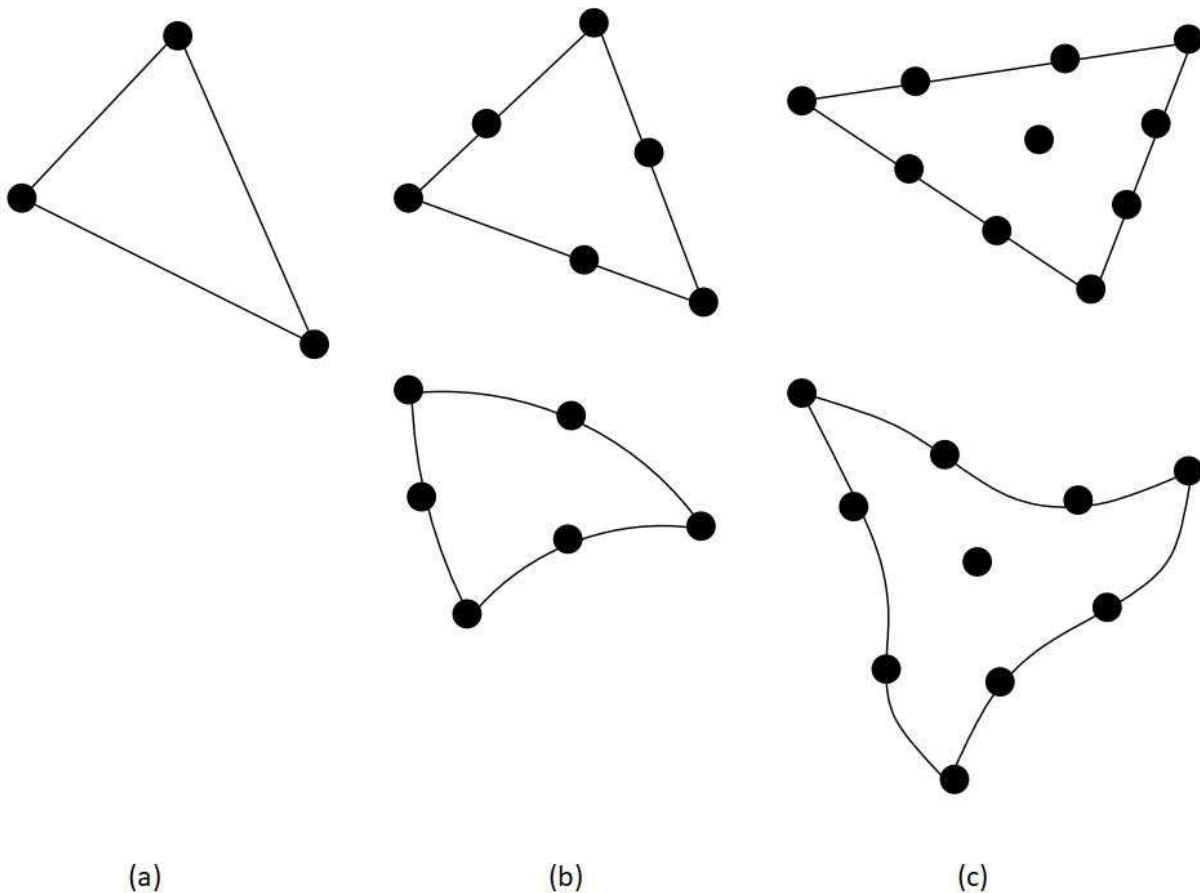


Figure 3.2: Triangular finite elements: (a) First order (or linear). (b) Second order (or quadratic). (c) Third order (or cubic)

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More complex triangular elements are those of the second order (Fig. 3.2.b) and third order (Fig. 3.2.c). They have nodes not only at the vertices but also on the sides. The third order triangular element even has an internal node. The approximations associated to the higher order triangular elements shown in Figures 3.2.b and 3.2.c are complete second-degree and third-degree polynomials, respectively (of course, these polynomials depend on two variables). One may notice in Figure 3.2 that higher order triangular elements have versions with curved sides. The triangular elements having an order greater than two are rarely used in practice, because they are computationally expensive due to the large number of nodes. This remark is also valid for other classes of finite elements. In general, users tend to prefer elements that can ensure a sufficiently accurate approximation defined over a minimal set of nodes.

Quadrilateral elements are planar regions bounded by four sides. The simplest member of this family is the quadrilateral element with straight sides and four nodes placed at the vertices (Fig. 3.3.a). The associated polynomial approximation is a bilinear function.

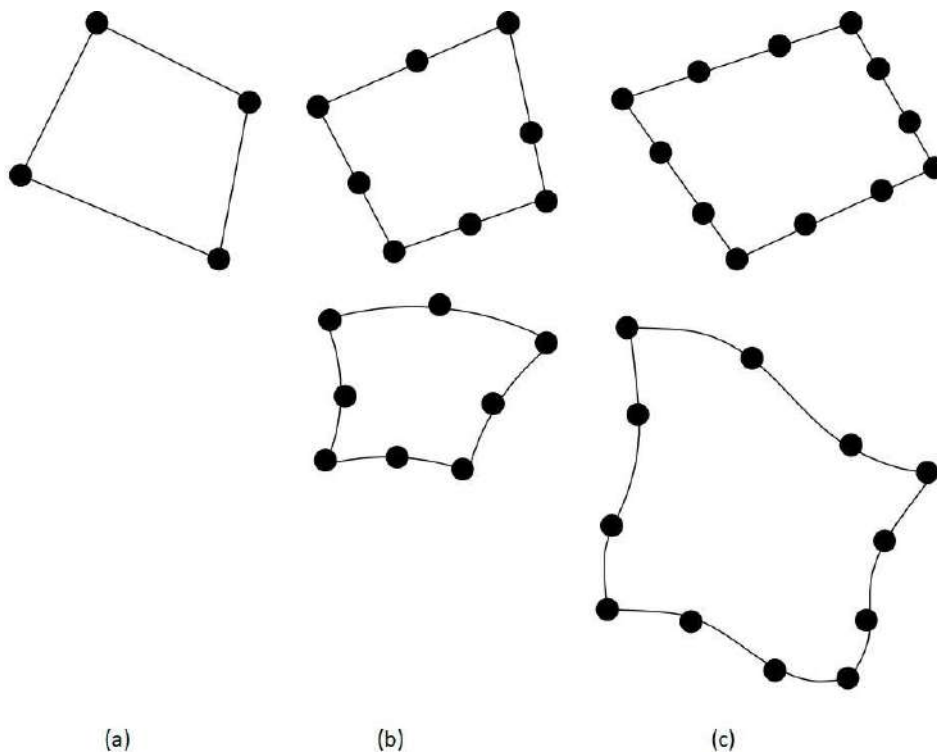


Figure 3.3: Quadrilateral finite elements: (a) Bilinear. (b) Biquadratic. (c) Bicubic

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Figure 3.3.b shows the 8-node quadrilateral element together with its curved version. The associated polynomial approximation is a biquadratic function. Finally, Figure 3.3.c presents both the straight and curved versions of the 12-node quadrilateral element. The polynomial approximation associated to this element is a bicubic function. Many users consider the biquadratic element as having too many nodes. Because of this, the bilinear quadratic element is generally preferred in practical applications.

3.1.3. Three-dimensional elements

Among the numerous types of three-dimensional finite elements, the following ones are frequently used for solving engineering problems:

- Tetrahedral elements (Fig. 3.4)
- Hexahedral elements (Fig. 3.5).

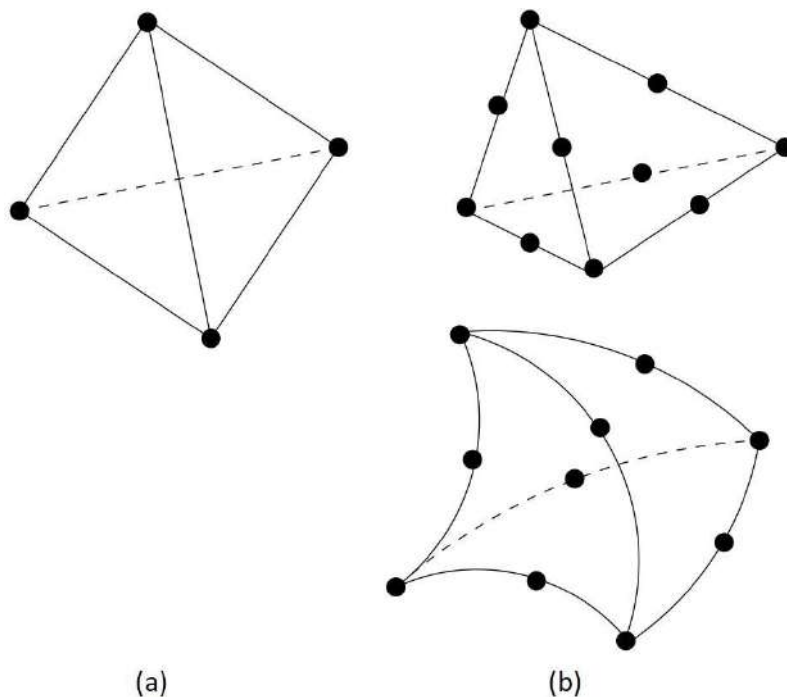


Figure 3.4: Tetrahedral finite elements: (a) First order (or linear). (b) Second order (or quadratic)

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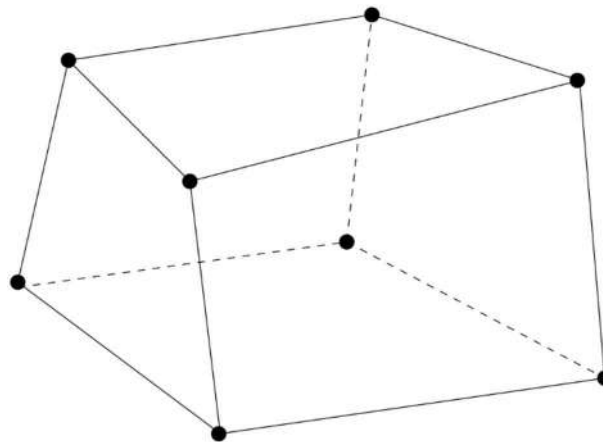


Figure 3.5: Hexahedral finite element of the trilinear type

In the three-dimensional space, a growth of the polynomial approximation degree causes a significant increase of the node number needed for defining such an approximation. Under such circumstances, users tend to limit their choice to the elements having a lower degree of the polynomial approximation. We will also limit ourselves to describing the three-dimensional elements that are frequently adopted in applications.

Figure 3.4.a shows the simplest tetrahedral element. It has planar faces and four nodes placed at the vertices. The approximation associated to the element in Figure 3.4.a is a first-degree polynomial in three variables. This is the reason for calling it a first order (or linear) tetrahedral element.

Figure 3.4.b shows the second order (or quadratic) tetrahedral element in the versions with planar and curved faces. One may notice that, besides the set of four nodes located at the vertices, this element has six extra nodes placed on its edges. The associated approximation is a complete polynomial of the second degree depending on three variables.

Among the hexahedral elements, the one which is almost exclusively used in applications is the 8-node hexahedral element with straight edges shown in Figure 3.5. The associated polynomial approximation is a trilinear function. There are also hexahedral elements of a higher order (with curved versions), but they are rarely used because their polynomial approximations need an excessive number of nodes.

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3.2. General rules to be applied when selecting the finite element type

Finite elements are complex entities individualized by the following features: spatial configuration, number and position of associated nodes, and typology of the polynomial approximations. The number of associated nodes and the typology of the polynomial approximations are closely related, since the nodal values of the unknown quantity define the polynomial coefficients.

In general, higher-degree polynomials ensure more accurate approximations. However, an increase of the polynomial degree causes a significant growth in the number of element nodes. We thus have to find a balance between the accuracy of the numerical solution and the computational effort needed for obtaining it. In practice, the following rules can be applied:

- When solving two-dimensional problems, bilinear quadrilateral elements should be used instead of the linear triangular ones (the former elements, having polynomial approximations of a higher degree, provide more accurate solutions at the cost of a moderate growth in the number of nodes).
- Similarly, in the case of three-dimensional problems, trilinear hexahedral elements provide more accurate solutions than the linear tetrahedral elements (however, this improvement in performance implies a doubled number of nodes at the level of each element).

We therefore keep in mind that finite elements having first-degree polynomial approximations should be avoided as much as possible in practical applications. On the other hand, when selecting the type of finite element to be used, we should also estimate the computational effort needed for obtaining the numerical solution.

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4. Example: Finite Element Analysis of a Wrist Hand Orthosis

4.1. Introduction

This chapter is focused on exemplifying the practical manner in which FEM can be used to evaluate the strength characteristics of a wrist hand orthosis (WHO) by simulating a compression test with the finite element analysis (FEA) module SolidWorks Simulation [WWW2022c] included in the SolidWorks CAD package [WWW2022b]. The principle of the compression test is shown in Figure 4.1. As one may notice, the lower and upper parts of the orthosis are assembled together and placed between two blocks: the support block which is fixed and the pressure block which applies a vertical compression load upon the orthosis. The compression load gradually increases from 0 (zero) to 4000 N. The contact between the lower/upper parts of the orthosis and the support/pressure blocks takes place along perfectly matching surfaces.

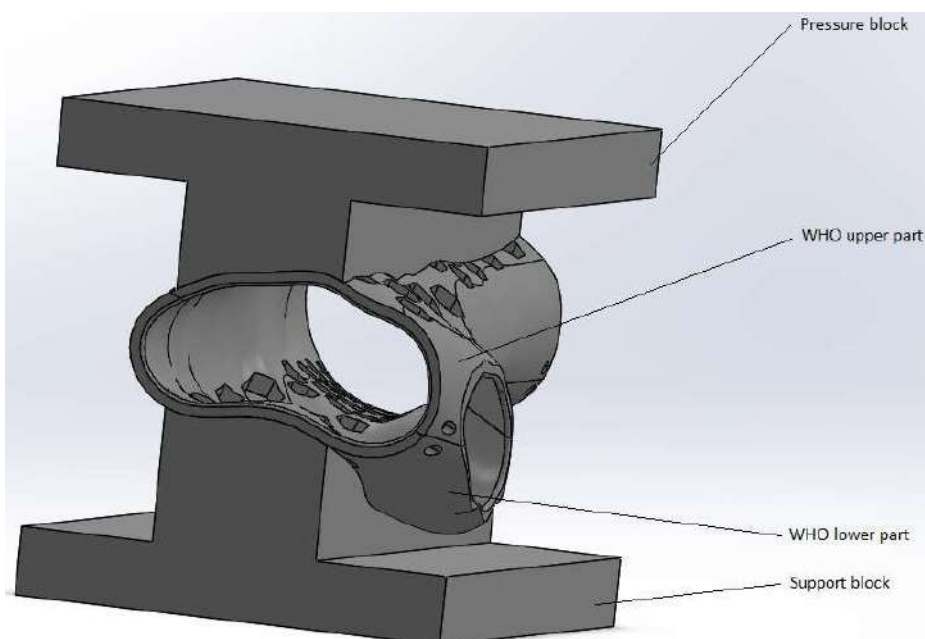


Figure 4.1: Principle of the compression test simulated for evaluating the strength characteristics of the wrist hand orthosis (WHO)

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The following hypotheses are adopted when preparing the finite element model of the compression test:

- The lower and upper parts of the orthosis are made of ABS exhibiting an isotropic linear elastic behavior.
- The support and pressure blocks are perfectly rigid bodies.
- The lower and upper parts of the orthosis are bonded together along their contact surfaces.
- The lower/upper parts of the orthosis and the support/pressure blocks are also bonded together along their contact surfaces.

The contact surfaces of the individual parts are already defined as selection sets in the assembly model:

Selection-Set1(36) Support_block_vs_WHO_lower_part	– surface of the support block along which the contact with the WHO lower part may occur
Selection-Set2(1) WHO_lower_part_vs_Support_block	– surface of the WHO lower part along which the contact with the support block may occur
Selection-Set3(3) WHO_lower_part_vs_WHO_upper_part	– surface of the WHO lower part along which the contact with the WHO upper part may occur
Selection-Set4(3) WHO_upper_part_vs_WHO_lower_part	– surface of the WHO upper part along which the contact with the WHO lower part may occur
Selection-Set5(2) WHO_upper_part_vs_Pressure_block	– surface of the WHO upper part along which the contact with the pressure block may occur
Selection-Set6(31) Pressure_block_vs_WHO_upper_part	– surface of the pressure block along which the contact with the WHO upper part may occur.

The selection sets listed above ease the procedure of defining contact interactions between different parts of the assembly.

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The displacement (deflection), force and stress quantities manipulated by the FEA model are expressed using the following measurement units:

- Displacement (deflection) – millimeter [mm]
- Force – Newton [N]
- Stress – megapascal [MPa] (1 MPa = 1 N/mm²).

4.2. Preparation of the finite element model

The FEA model of the compression test (Fig. 4.1) is developed by performing the following steps:

- a) Open the WHO assembly model in SolidWorks (Fig. 4.2).

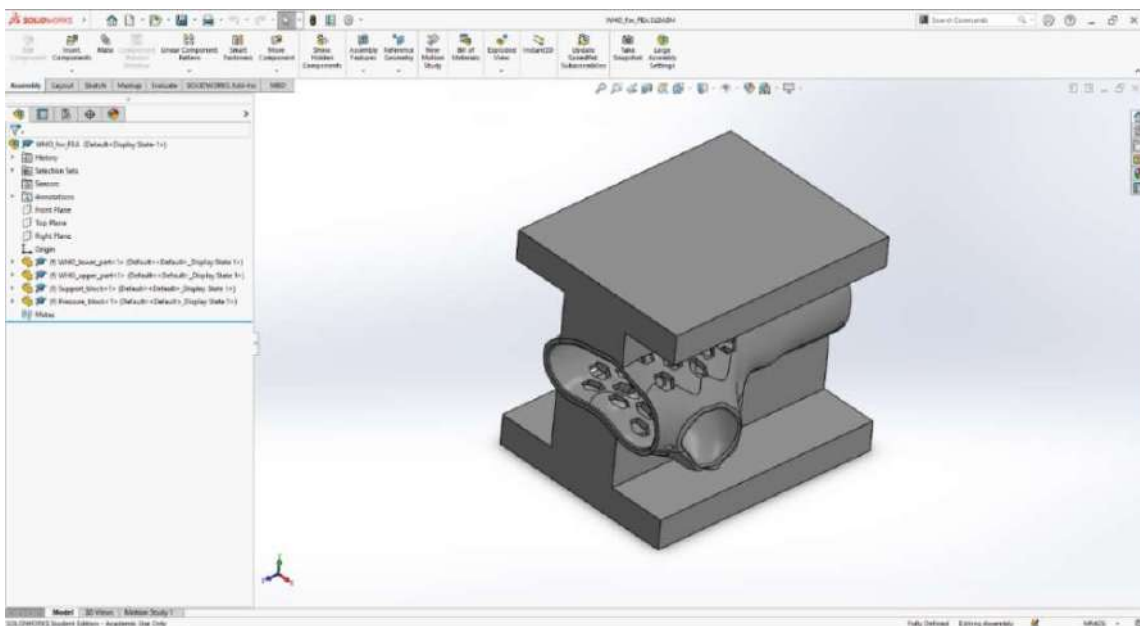


Figure 4.2: WHO assembly model open in SolidWorks

- b) Activate the SolidWorks Simulation module by accessing the “SOLIDWORKS Add-Ins” tab of the “Command Manager” toolbar (Fig. 4.3) and pressing the “SOLIDWORKS Simulation” button (Fig. 4.4). Consequently, the “Simulation” tab is included in the “Command Manager” toolbar (Fig. 4.5).

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- c) Change some working parameters of the SolidWorks Simulation module by accessing the “Simulation” menu and selecting the “Options...” command (Fig. 4.6). Consequently, the “System Options – General” window is displayed. In the “Default Options” panel, select the SI (MKS) unit system, then change the following measurement units: length/displacement [mm] and pressure/stress [N/mm²] (Fig. 4.7).
- d) Enter the “Simulation” toolbar and press the “New Study” button (Fig. 4.8) to create a new FEA model having the following characteristics (Fig. 4.9):
- name of the FEA model: “Static 1”
 - type of the FEA model: “Static”.

Press the “OK” button placed at the upper-left corner of the “Study” window (Fig. 4.9).

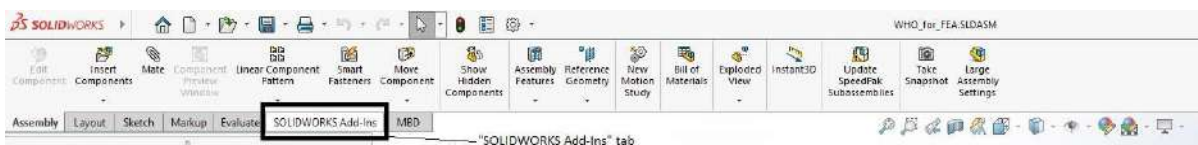


Figure 4.3: “SOLIDWORKS Add-Ins” tab in the “Command Manager” toolbar

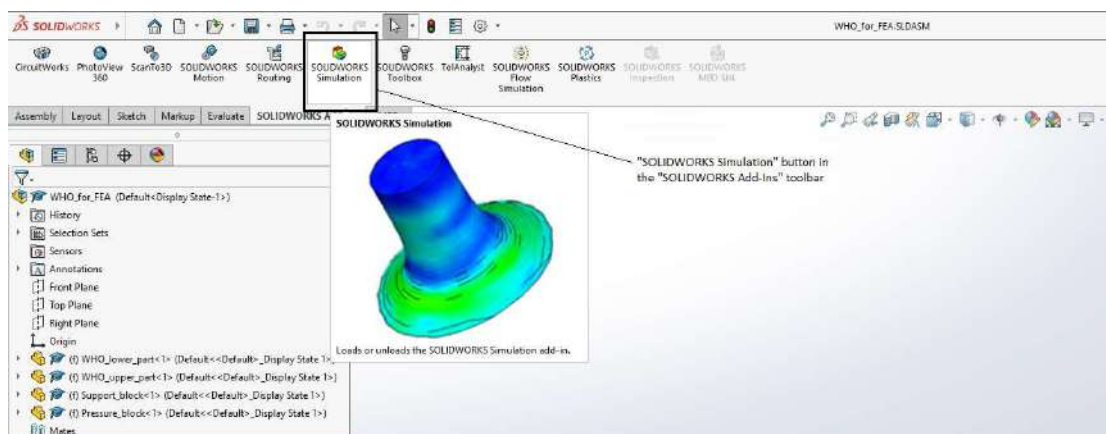


Figure 4.4: “SOLIDWORKS Simulation” button in the “SOLIDWORKS Add-Ins” toolbar



Figure 4.5: “Simulation” tab included in the “Command Manager” toolbar after the activation of the SolidWorks Simulation module

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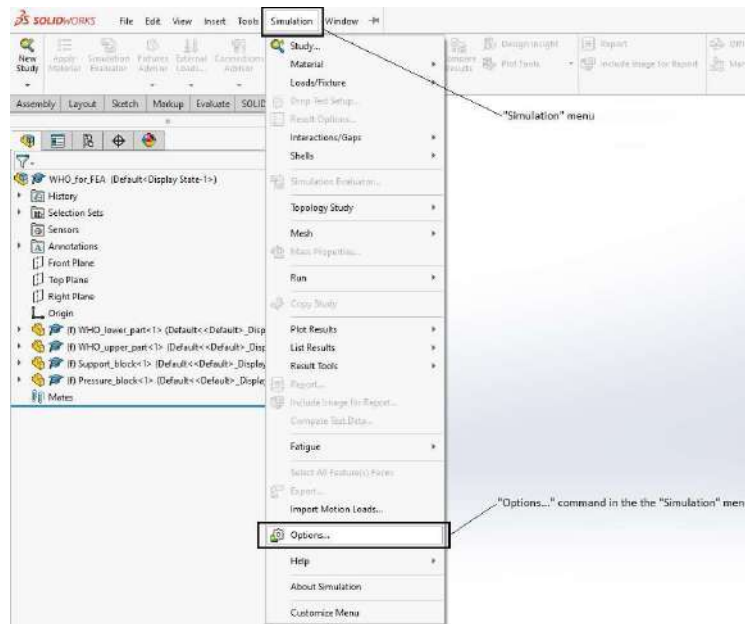


Figure 4.6: "Options..." command in the "Simulation" menu

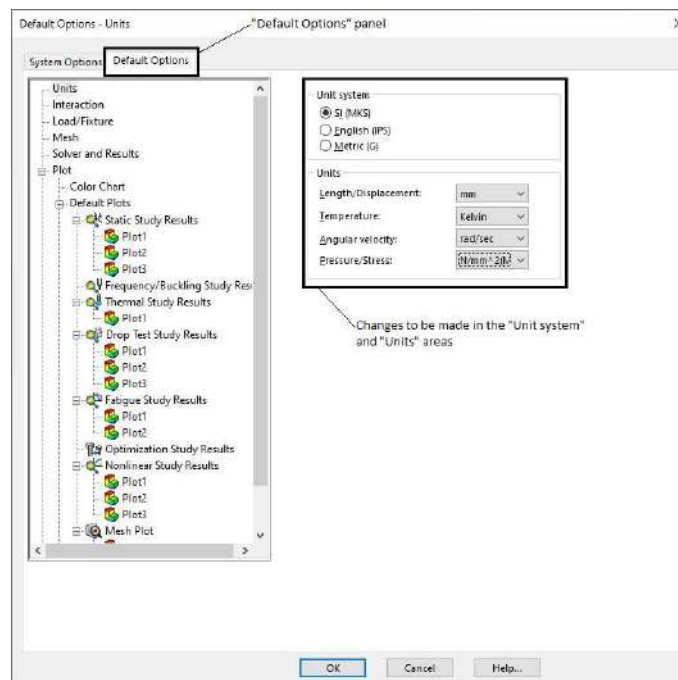


Figure 4.7: Changes to be made in the "Default Options" panel of the "System Options – General" window

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Figure 4.8: Creation of a new FEA model

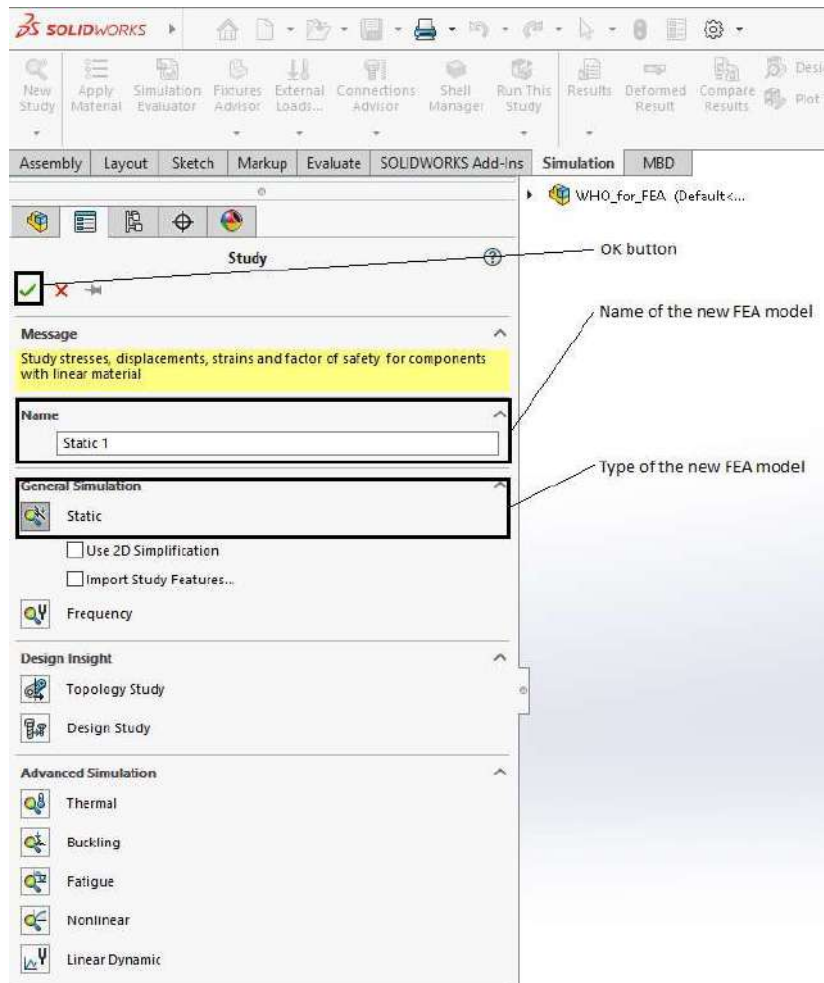


Figure 4.9: Defining the name and type of the new FEA model

- e) Unroll the “Parts” entry of the FEA tree, select the parts called “Pressure_block-1” and “Support_block-1”, press the right button of the mouse on any of them, and select the “Make Rigid” command in the drop-down menu (Fig. 4.10). This action defines the pressure block and support block as perfectly rigid bodies.

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- f) Unroll the “Parts” entry of the FEA tree, select the parts called “WHO_lower_part-1” and “WHO_upper_part-1”, press the right button of the mouse on any of them, and select the “Apply/Edit Material” command in the drop-down menu (Fig. 4.11). Consequently, the “Material” window is displayed (Fig. 4.12). In that window, look for the “Plastics” category of the “SOLIDWORKS Materials” library, unroll it, select the “ABS” material, then press the buttons “Apply” and “Close” placed at the bottom of the “Material” window.

Note: The tensile strength $R_m = 30$ MPa (see the ABS material data listed in Figure 4.12) defines the upper limit of the von Mises equivalent stress that can be supported by the lower and upper parts of the orthosis.

- g) Unroll the “Connections” and “Component Interactions” entries of the FEA tree, press the right button of the mouse on “Global Interaction (-Bonded-Meshed Independently-)”, and select the “Delete” command in the drop-down menu (Fig. 4.13).

Note: If active, the “Global Interaction” option allows the solver to detect the contact surfaces in an automatic manner. Even though it seems convenient to the user, this strategy must be avoided when complex-shaped surfaces are involved in contact interactions, because it dramatically increases the computation time. In such cases, the user should explicitly define the contact surfaces (see the next step).

- h) Press the right button of the mouse on the “Connections” entry of the FEA tree and select the “Local Interaction...” command in the drop-down menu (Fig. 4.14). Perform the following actions in the “Local Interactions” dialogue box to define the contact interaction between the support block and the lower part of the orthosis (Fig. 4.15):
- Select “Bonded” instead of “Contact” in the “Type” drop-down list of the “Local Interactions” dialogue box
 - Press the left button of the mouse in the “Faces, Edges, Vertices for Set 1” selection box of the “Local Interactions” dialogue box
 - Unroll the assembly tree placed at the upper-left corner of the SolidWorks graphics area
 - Unroll the “Selection Sets” entry of the assembly tree
 - Select “Selection-Set1(36) Support_block_vs_WHO_lower_part” in the assembly tree
 - Press the left button of the mouse in the “Faces, Edges for Set 2” selection box of the “Local Interactions” dialogue box

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- Select “Selection-Set2(1) WHO_lower_part_vs_Support_block” in the assembly tree
- Press the “OK” button of the “Local Interactions” dialogue box.

Press the right button of the mouse on the “Connections” entry of the FEA tree and select the “Local Interaction...” command in the drop-down menu (Fig. 4.14). Perform the following actions in the “Local Interactions” dialogue box to define the contact interaction between the lower and upper parts of the orthosis (Fig. 4.16):

- Select “Bonded” instead of “Contact” in the “Type” drop-down list of the “Local Interactions” dialogue box
- Press the left button of the mouse in the “Faces, Edges, Vertices for Set 1” selection box of the “Local Interactions” dialogue box
- Select “Selection-Set3(3) WHO_lower_part_vs_WHO_upper_part” in the assembly tree
- Press the left button of the mouse in the “Faces, Edges for Set 2” selection box of the “Local Interactions” dialogue box
- Select “Selection-Set4(3) WHO_upper_part_vs_WHO_lower_part” in the assembly tree
- Press the “OK” button of the “Local Interactions” dialogue box.

Press the right button of the mouse on the “Connections” entry of the FEA tree and select the “Local Interaction...” command in the drop-down menu (Fig. 4.14). Perform the following actions in the “Local Interactions” dialogue box to define the contact interaction between the pressure block and the upper part of the orthosis (Fig. 4.17):

- Select “Bonded” instead of “Contact” in the “Type” drop-down list of the “Local Interactions” dialogue box
- Press the left button of the mouse in the “Faces, Edges, Vertices for Set 1” selection box of the “Local Interactions” dialogue box
- Select “Selection-Set6(31) Pressure_block_vs_WHO_upper_part” in the assembly tree
- Press the left button of the mouse in the “Faces, Edges for Set 2” selection box of the “Local Interactions” dialogue box
- Select “Selection-Set5(2) WHO_upper_part_vs_Pressure_block” in the assembly tree
- Press the “OK” button of the “Local Interactions” dialogue box.

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- i) Press the right button of the mouse on the “Fixtures” entry of the FEA tree and select the “Fixed Geometry...” command in the drop-down menu (Fig. 4.18). Perform the following actions in the “Fixture” dialogue box to define a full locking boundary condition on the lower face of the support block (Fig. 4.19):
 - Press the left button of the mouse in the “Faces, Edges, Vertices for Fixture” selection box of the “Fixture” dialogue box
 - Select the lower face of the support block in the graphics area
 - Press the “OK” button of the “Fixture” dialogue box.
- j) Press the right button of the mouse on the “Fixtures” entry of the FEA tree and select the “Roller/Slider...” command in the drop-down menu (Fig. 4.20). Perform the following actions in the “Fixture” dialogue box to enforce the vertical sliding of the pressure block (Fig. 4.21):

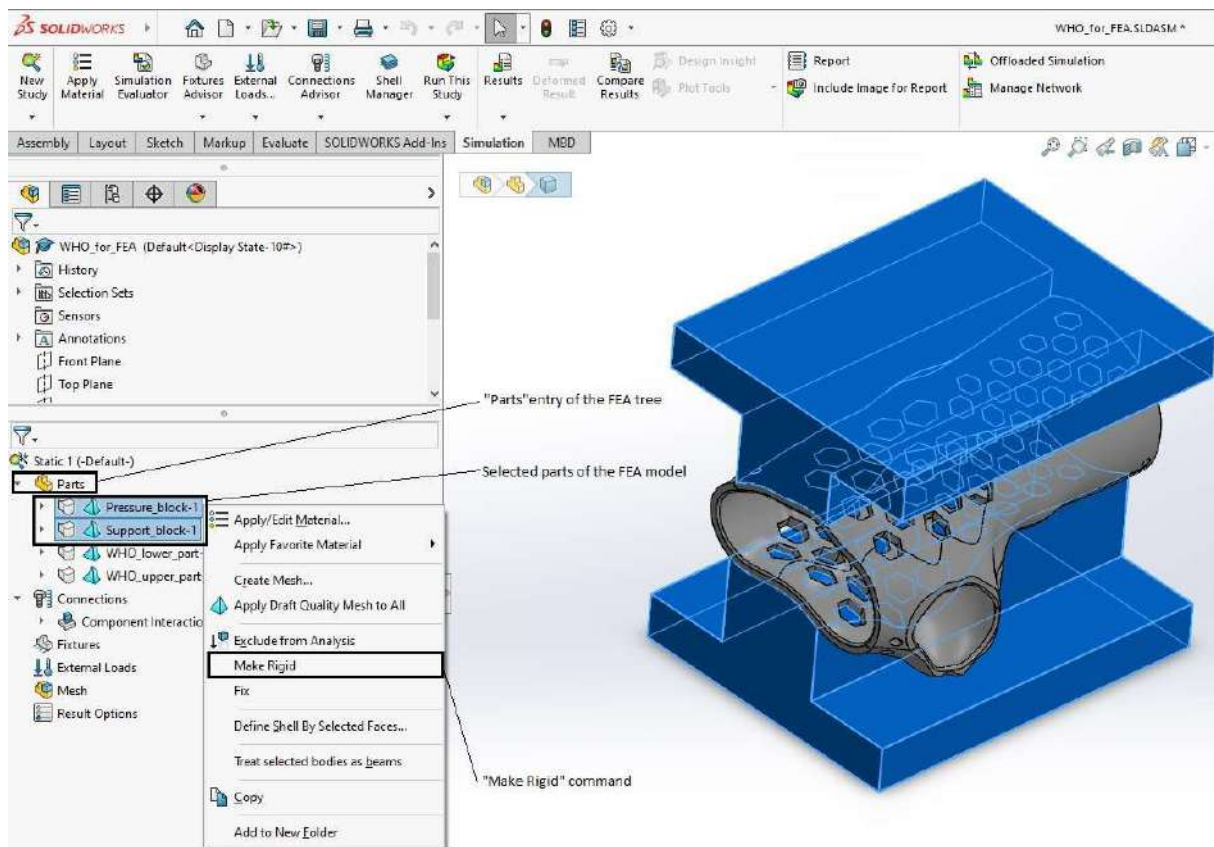


Figure 4.10: Defining the pressure block and support block as perfectly rigid bodies

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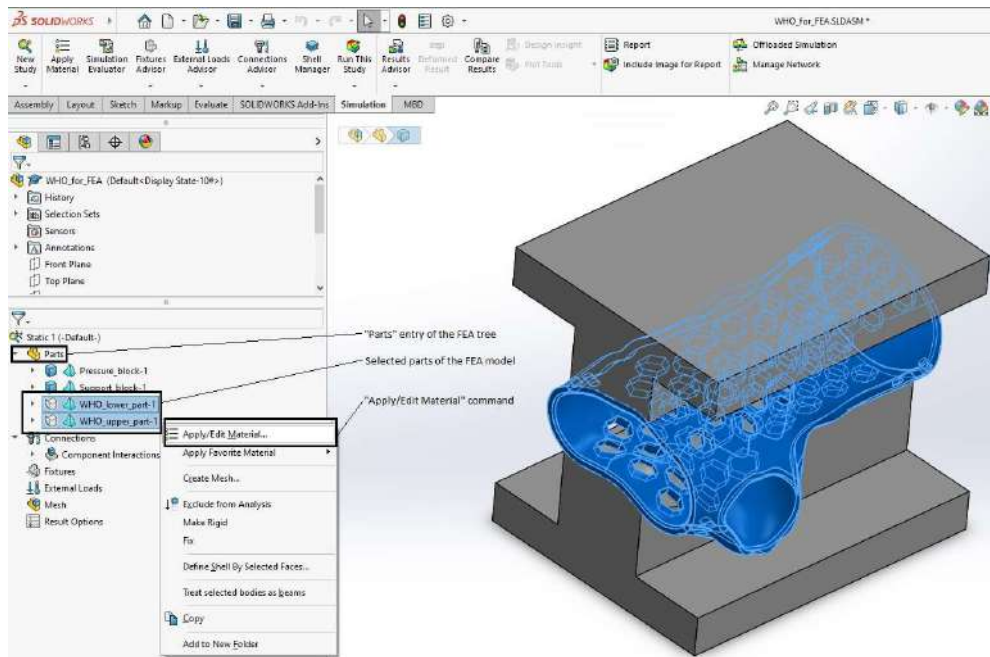


Figure 4.11: Defining the material properties of the lower and upper parts of the orthosis

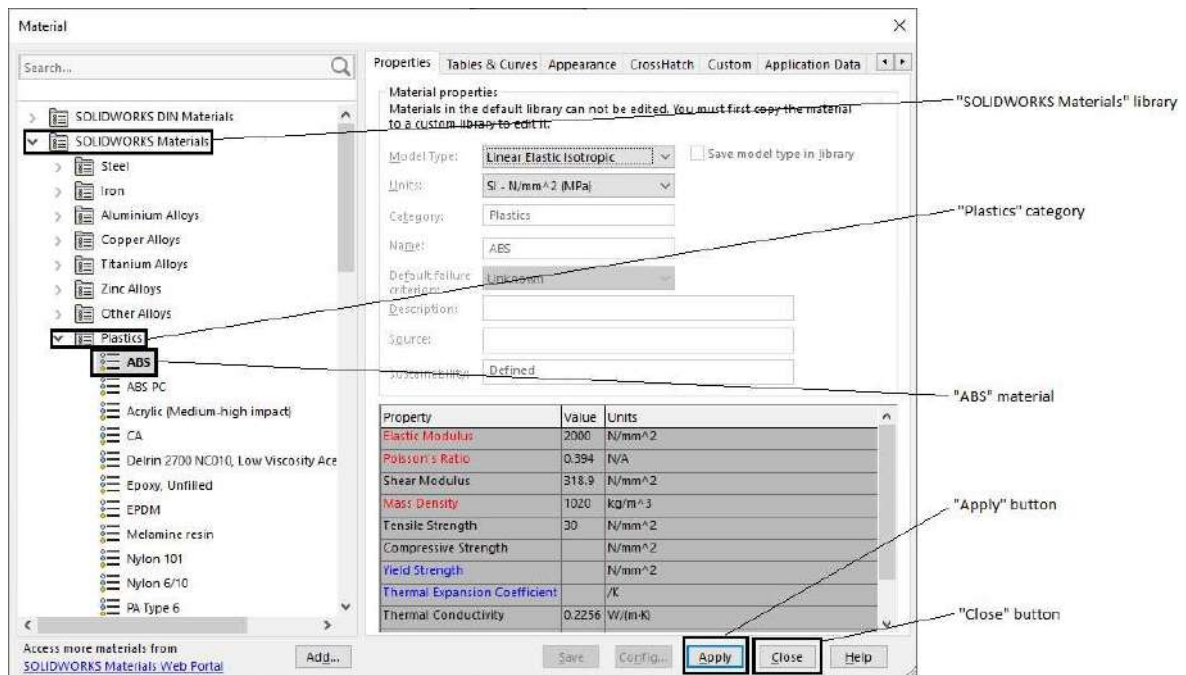


Figure 4.12: Associating the ABS material to the lower and upper parts of the orthosis

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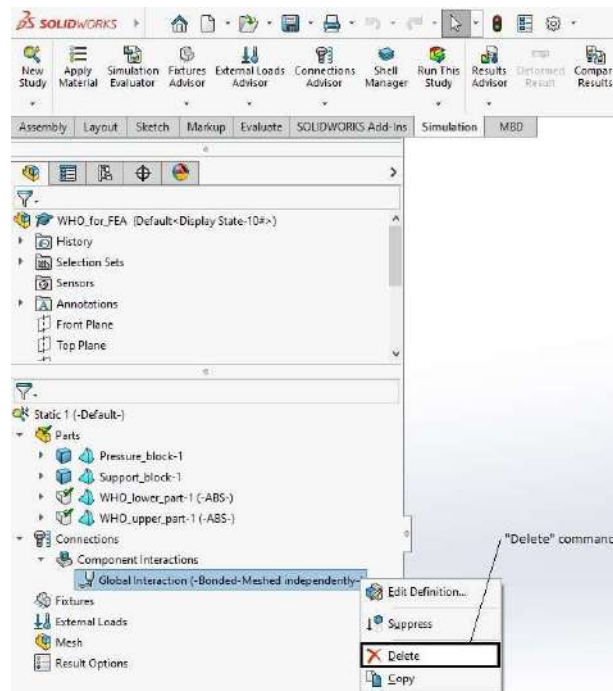


Figure 4.13: Removing the “Global Interaction” option from the FEA tree

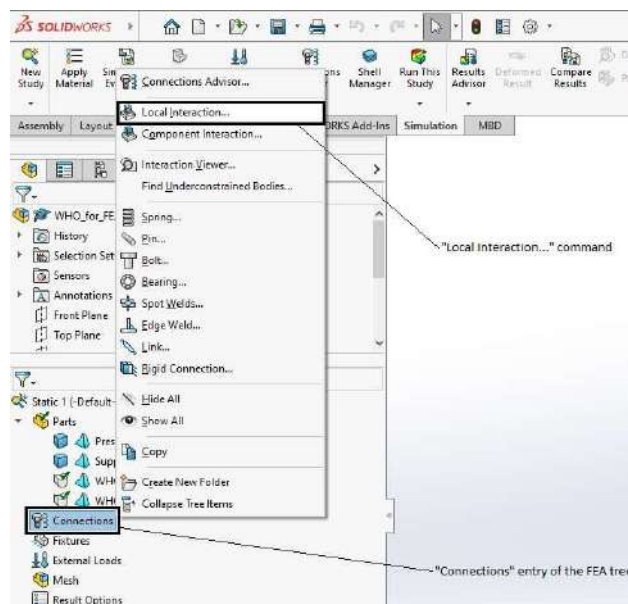


Figure 4.14: Defining a pair of contact surfaces by means of the “Local Interaction...” command

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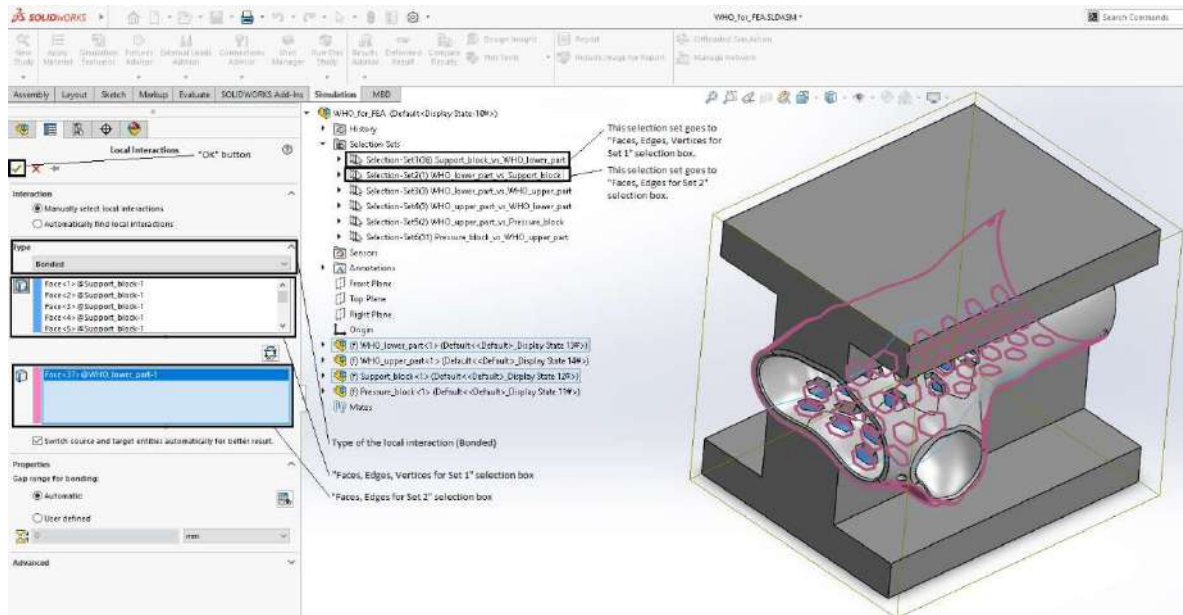


Figure 4.15: Defining the contact interaction between the support block and the lower part of the orthosis

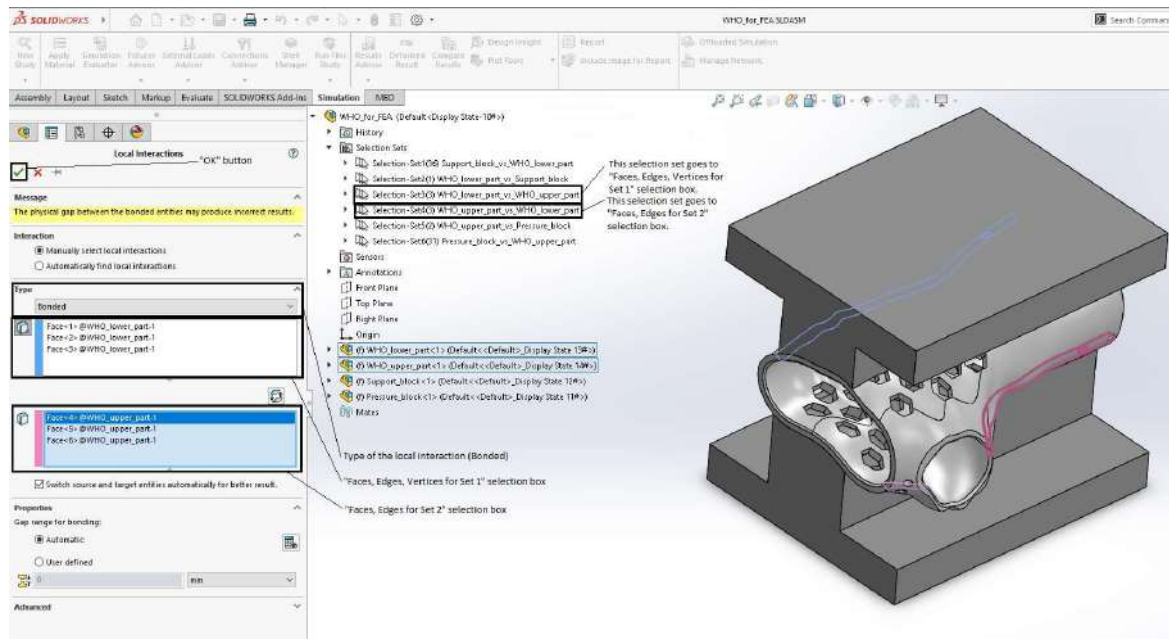


Figure 4.16: Defining the contact interaction between the lower and upper parts of the orthosis

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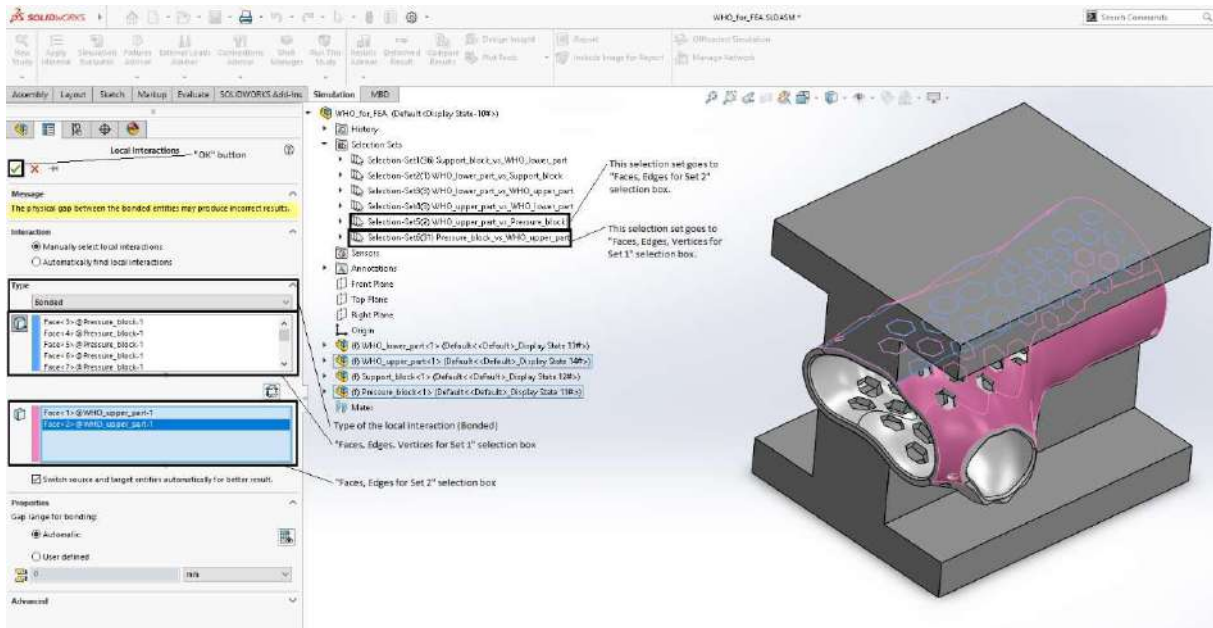


Figure 4.17: Defining the contact interaction between the pressure block and the upper part of the orthosis

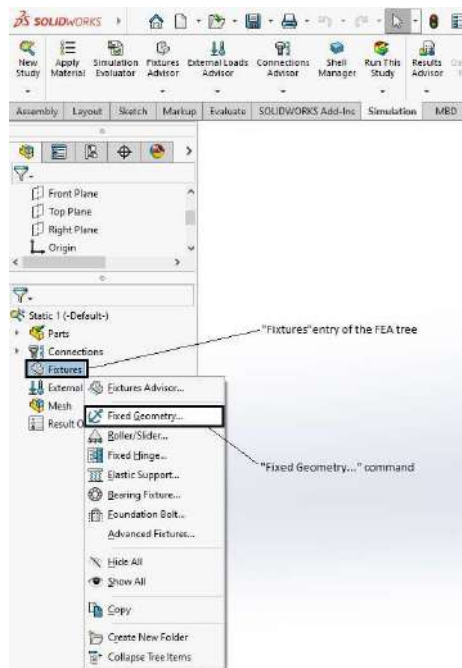


Figure 4.18: Defining a full locking boundary condition

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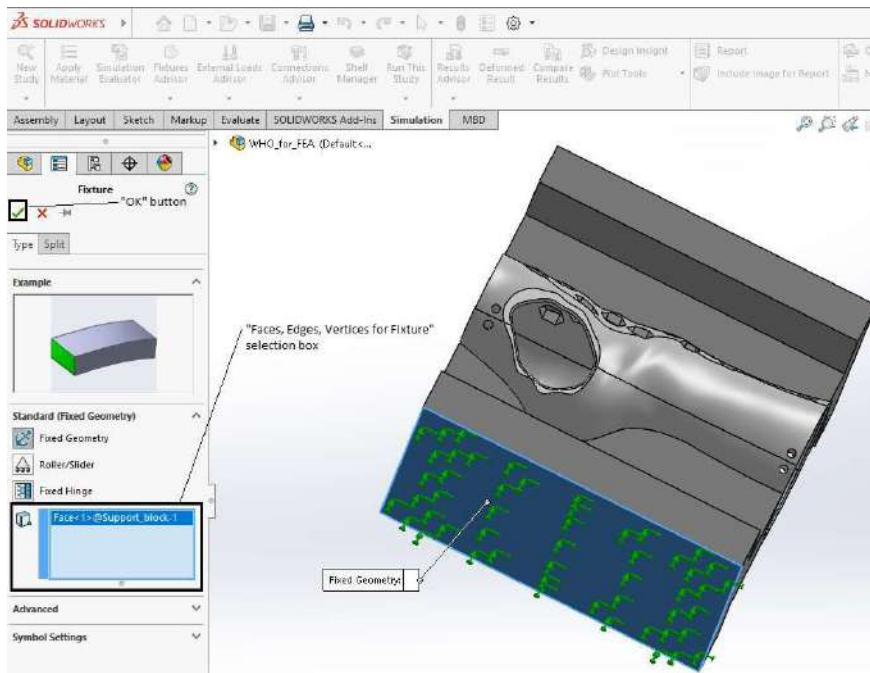


Figure 4.19: Full locking boundary condition enforced on the lower face of the support block

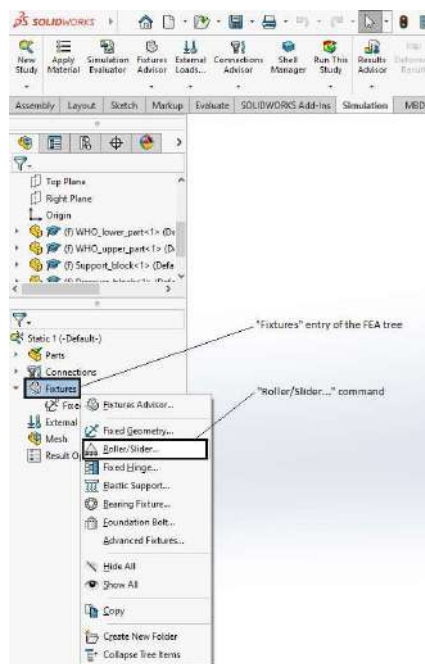


Figure 4.20: Defining a sliding boundary condition

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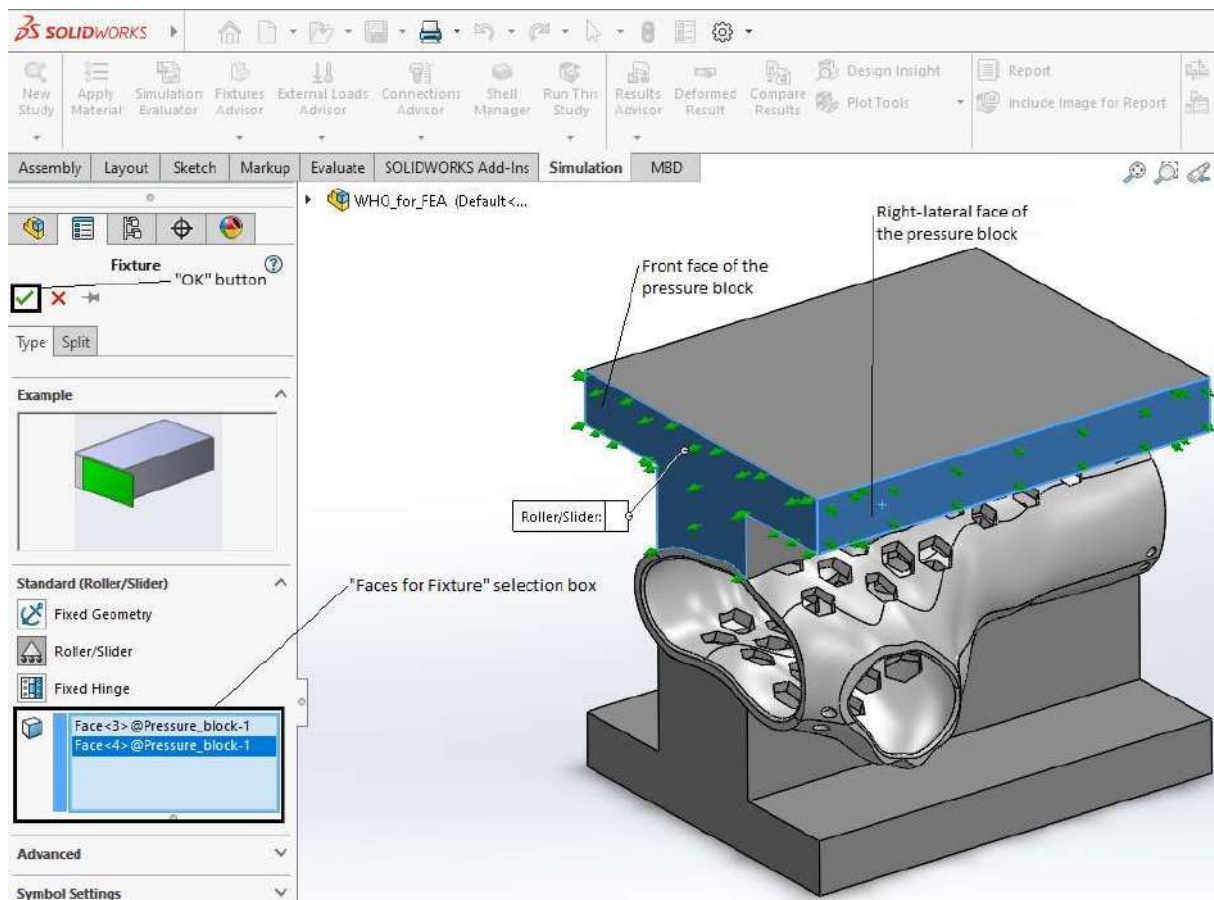


Figure 4.21: Enforcing the vertical sliding of the pressure block

- Press the left button of the mouse in the “Faces for Fixture” selection box of the “Fixture” dialogue box
- Select the front and right-lateral faces of the pressure block in the graphics area
- Press the “OK” button of the “Fixture” dialogue box.

Note: Since the pressure block is treated as a rigid body and its front and right-lateral faces are vertical and reciprocally perpendicular, the sliding boundary condition defined on these faces enforces the vertical displacement of this part. This motion is controlled by a normal force acting on the upper face of the pressure block (see the next step).

- k) Press the right button of the mouse on the “External Loads” entry of the FEA tree and select the “Force...” command in the drop-down menu (Fig. 4.22). Perform the following

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actions in the “Force/Torque” dialogue box to define the normal force that acts on the upper face of the pressure block (Fig. 4.23):

- Press the left button of the mouse in the “Faces and Shell Edges for Normal Force” selection box of the “Force/Torque” dialogue box
- Select the upper face of the pressure block in the graphics area
- Do not change the force specified by default (1 N) in the “Force Value” input box of the “Force/Torque” dialogue box
- Press the “OK” button of the “Force/Torque” dialogue box.

Note: The actual values of the normal force acting on the upper face of the pressure block are defined in step (m) as load cases.

- l) Press the right button of the mouse on the “Mesh” entry of the FEA tree and select the “Create Mesh...” command in the drop-down menu (Fig. 4.24). Perform the following actions in the “Mesh” dialogue box to generate the finite element mesh (Fig. 4.25):
- Activate the “Mesh Parameters” checkbox
 - Select the “Curvature-based mesh” radio button in the “Mesh Parameters” region
 - Specify the maximum element size in the “Maximum element size” input box: 20 (this quantity is expressed in millimeters by default)
 - Specify the minimum element size in the “Minimum element size” input box: 2 (this quantity is expressed in millimeters by default)
 - Press the “OK” button of the “Mesh” dialogue box.

Notes:

- SolidWorks Simulation uses by default the so-called standard meshing algorithm which works well in the case of bodies having regular shapes. This algorithm often fails to generate a consistent mesh for bodies having irregular boundaries. In such situations, the curvature-based meshing algorithm is the best alternative.
- The finite element mesh generated by SolidWorks Simulation is shown in Figure 4.26.

- m) Press the right button of the mouse on the root of the FEA tree and select the “Load Case Manager” command in the drop-down menu (Fig. 4.27). Consequently, the “Load Case View” tab is displayed at the bottom of the SolidWorks graphics area (Fig. 4.28). Perform the following actions in that tab to define the actual values of the normal force acting on the upper face of the pressure block:

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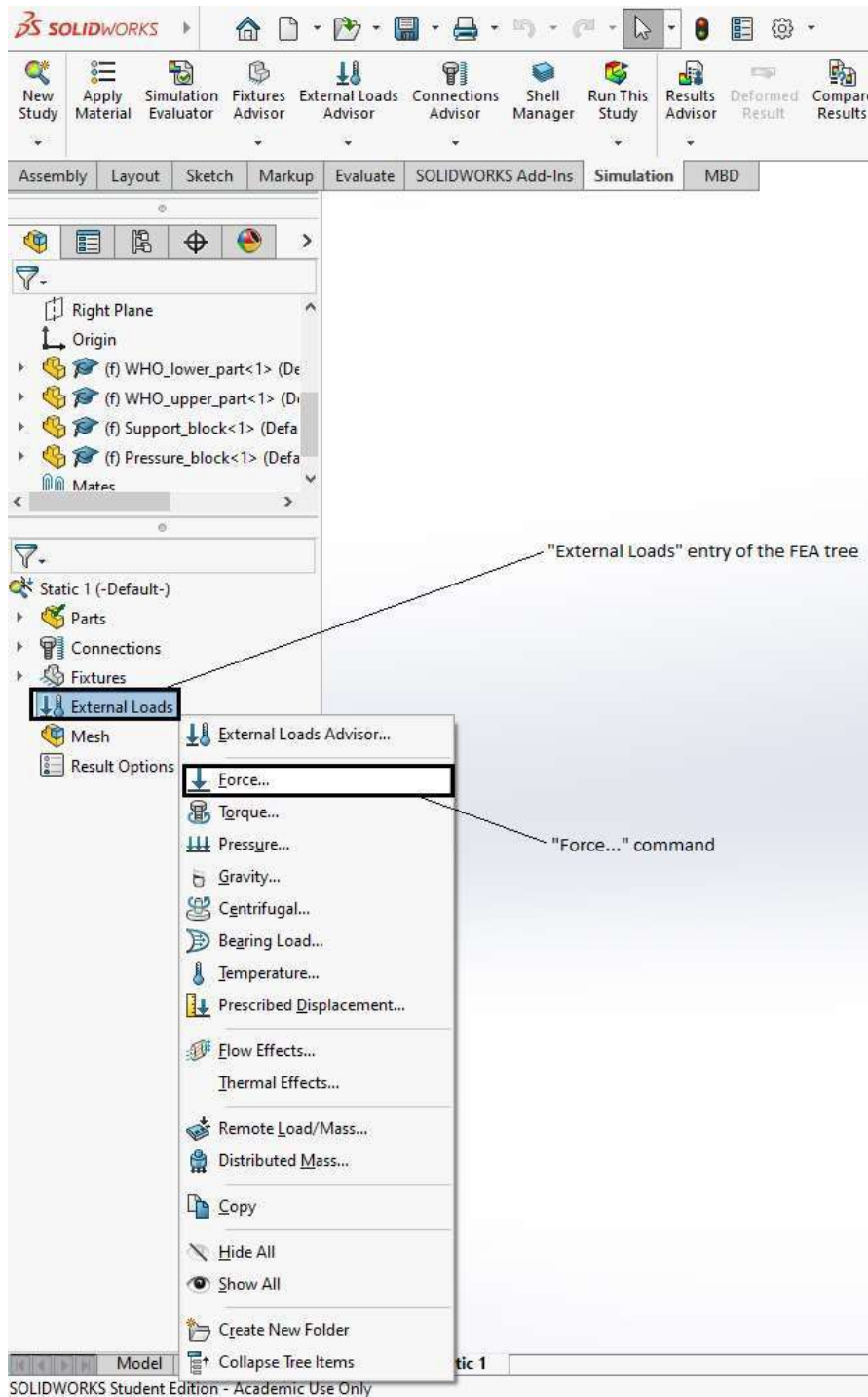


Figure 4.22: Defining a force-type boundary condition

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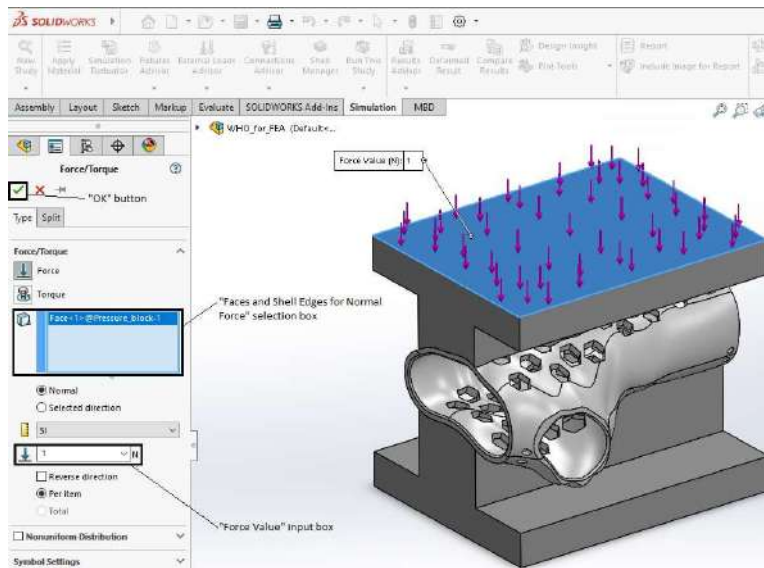


Figure 4.23: Defining the normal force that acts on the upper face of the pressure block

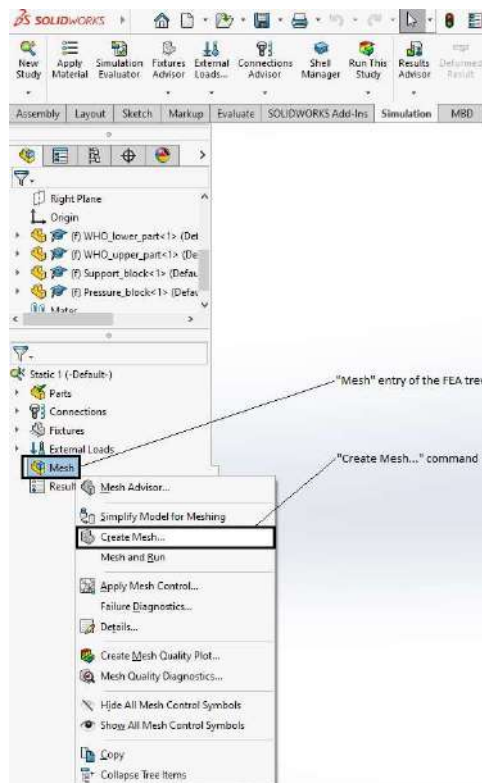


Figure 4.24: Initiating the generation of the finite element mesh

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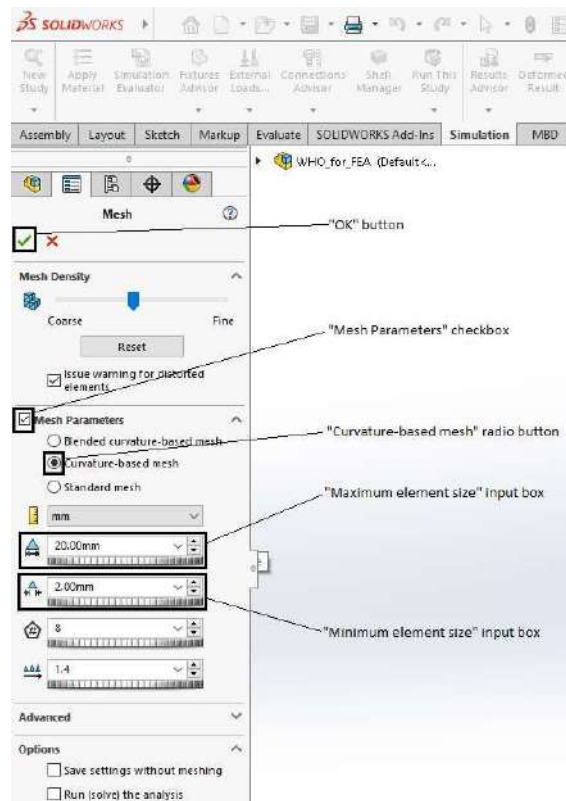


Figure 4.25: Defining the control parameters of the finite element mesh

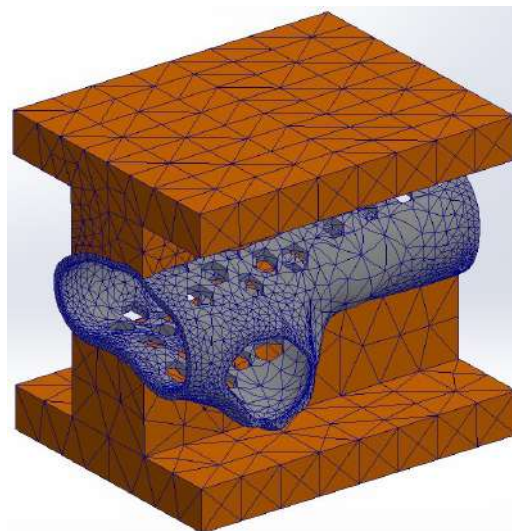


Figure 4.26: Finite element mesh generated by SolidWorks Simulation

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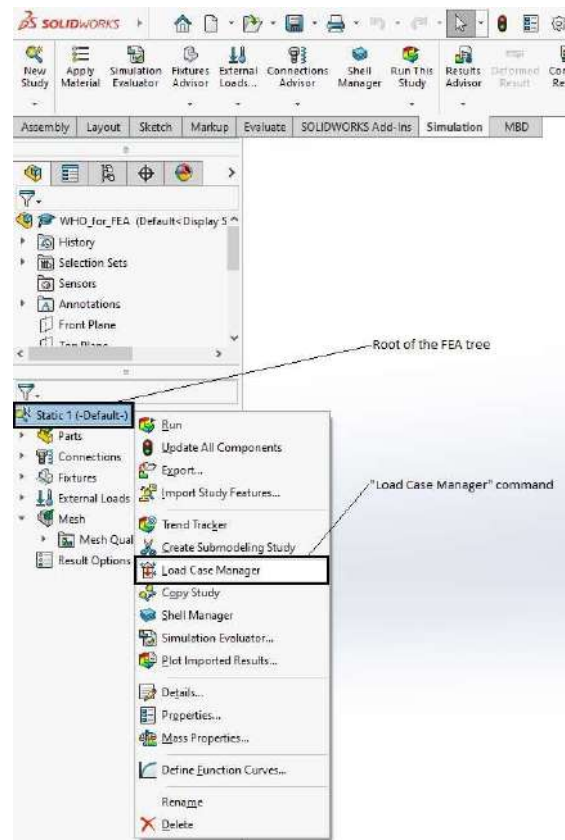


Figure 4.27: Accessing the Load Case Manager

- Press the left button of the mouse in the box labeled “+ Click here to add a primary load case” to define the first load case (Fig. 4.28)
- Replace the “Suppress” status of the “Force-1” cell with 0 (zero) i.e., the actual value of the normal force corresponding to “Load Case 1” (Fig. 4.29)
- Press the left button of the mouse in the box labeled “+ Click here to add a primary load case” to define the second load case (Fig. 4.29)
- Replace the “Suppress” status of the “Force-1” cell with 500 i.e., the actual value of the normal force corresponding to “Load Case 2” (Fig. 4.30)
- Proceed in the same manner to define “Load Case 3”: 1000 N, “Load Case 4”: 1500 N, “Load Case 5”: 2000 N, “Load Case 6”: 2500 N, “Load Case 7”: 3000 N, “Load Case 8”: 3500 N, and “Load Case 9”: 4000 N (Fig. 4.31)

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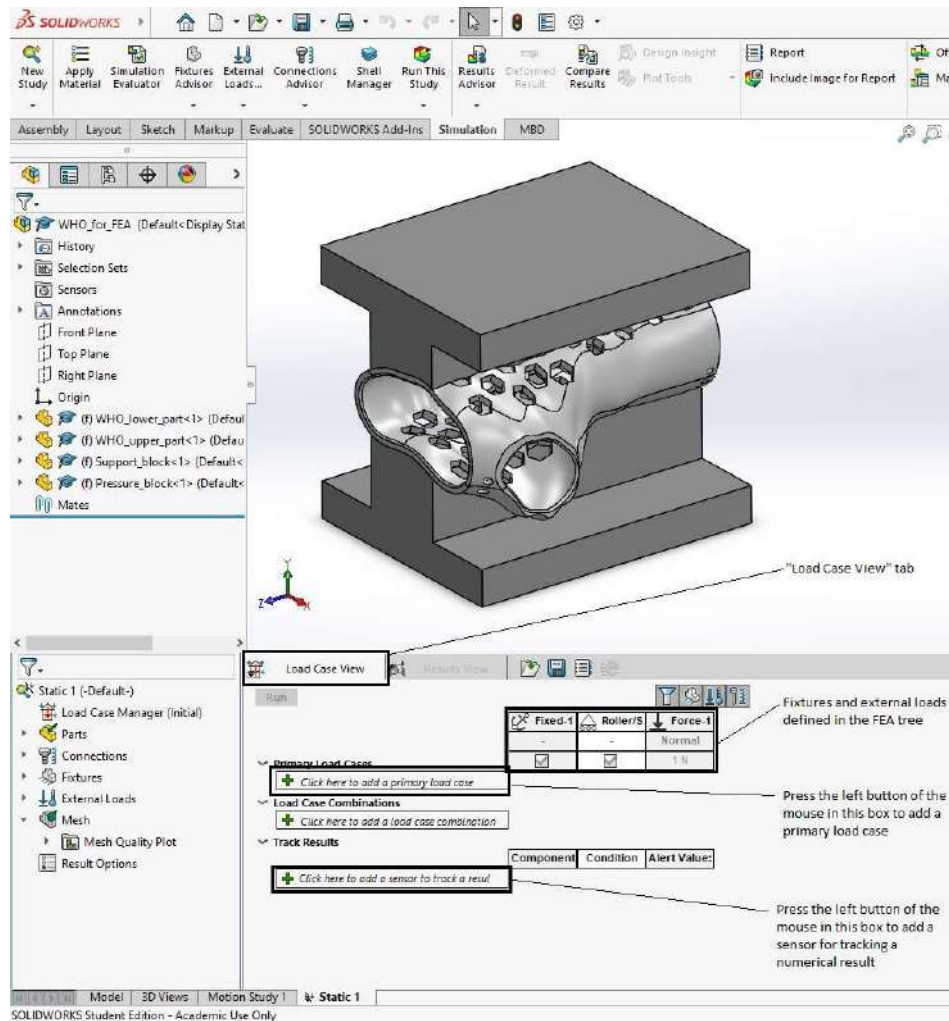


Figure 4.28: "Load Case View" tab displayed at the bottom of the SolidWorks graphics area

- Press the left button of the mouse in the box labeled "+ Click here to add a sensor to track a result" (Fig. 4.31)
- Select the "+ Add Sensor..." command in the drop-down list displayed at the bottom of the "Load Case View" tab (Fig. 4.32)
- Perform the following actions in the "Sensor" dialogue box to define a sensor for tracking the maximum value of the von Mises equivalent stress at the level of the lower and upper parts of the orthosis (Fig. 4.33):

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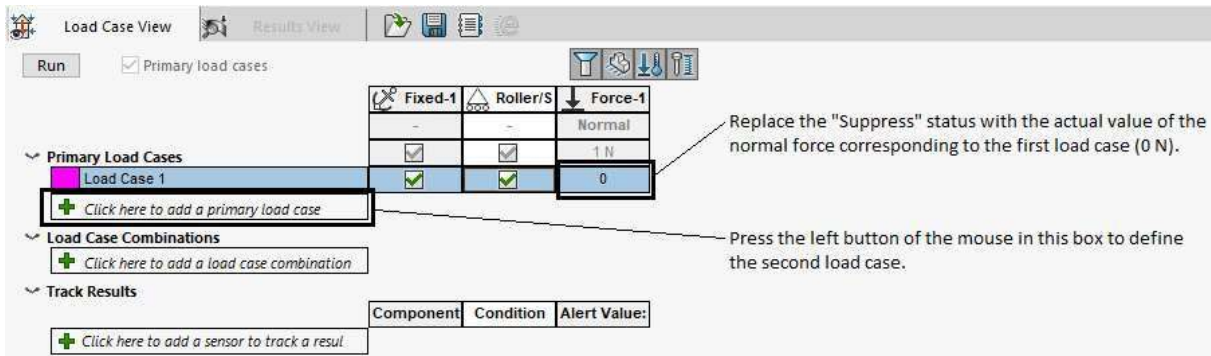


Figure 4.29: Defining the first load case (normal force of 0 N)

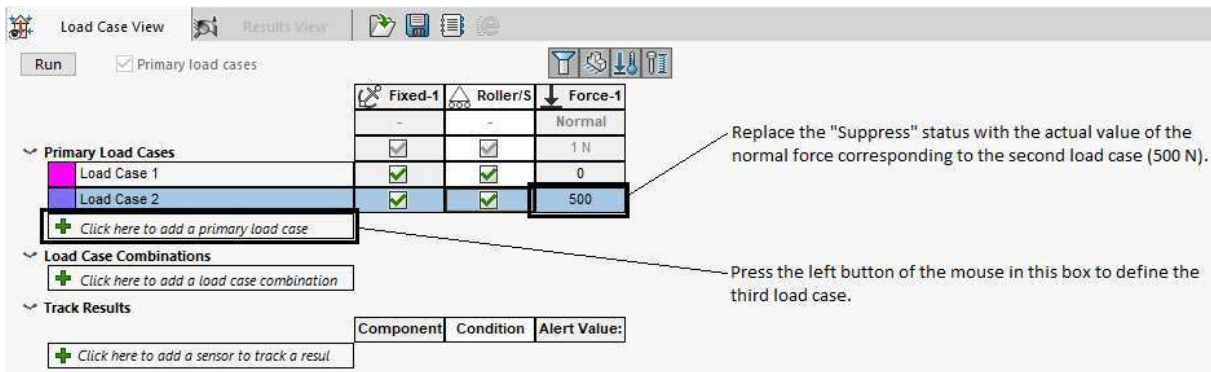


Figure 4.30: Defining the second load case (normal force of 500 N)

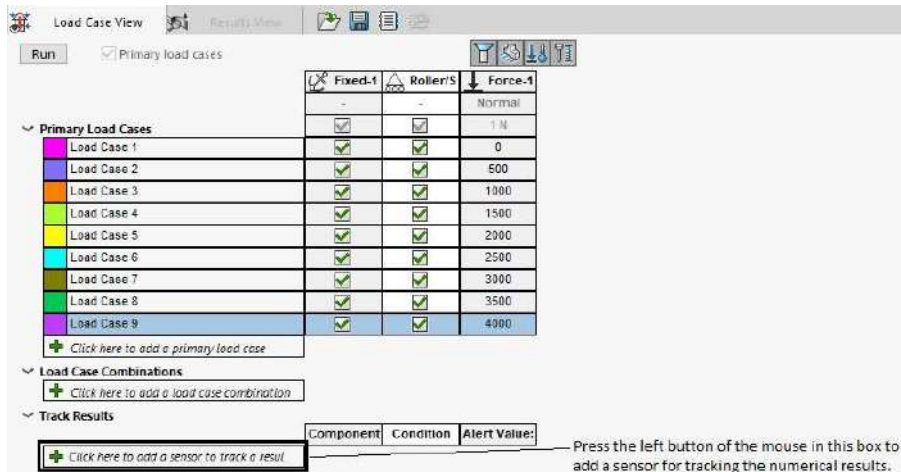


Figure 4.31: Actual values of the normal force acting on the upper face of the pressure block defined as load cases

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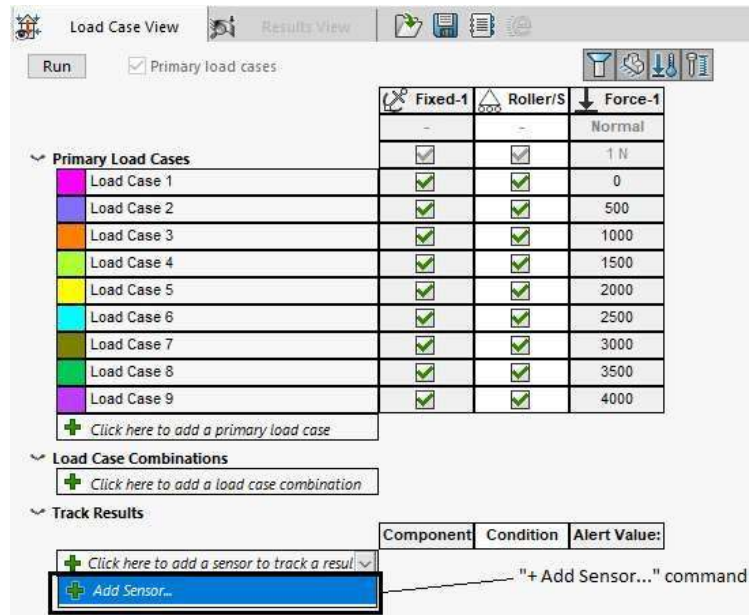


Figure 4.32: Initiating the definition of a sensor for tracking the numerical results

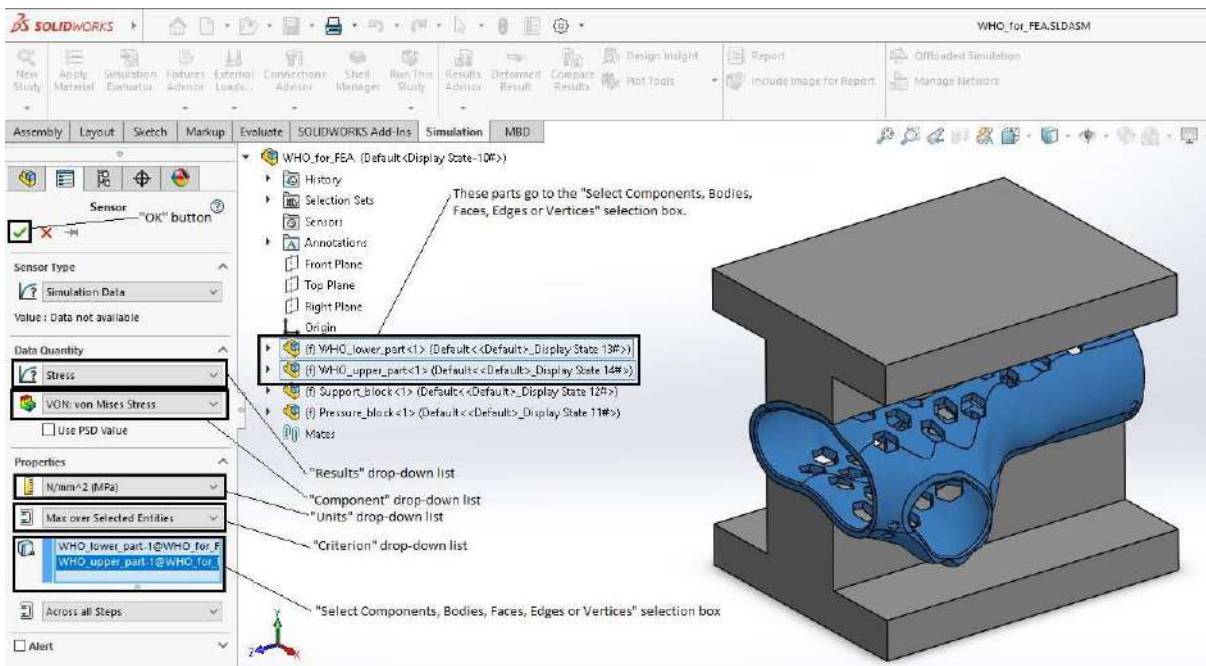


Figure 4.33: Definition of a sensor for tracking the maximum value of the von Mises equivalent stress at the level of the lower and upper parts of the orthosis

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- Select the option “Stress” in the “Results” drop-down list
- Select the option “VON: von Mises Stress” in the “Component” drop-down list
- Select the option “N/mm² (MPa)” in the “Units” drop-down list
- Select the option “Max over Selected Entities” in the “Criterion” drop-down list
- Press the left button of the mouse in the “Select Components, Bodies, Faces, Edges or Vertices” selection box
- Unroll the assembly tree placed at the upper-left corner of the SolidWorks graphics area
- Select the lower and upper parts of the orthosis in the assembly tree
- Press the “OK” button placed at the upper-left corner of the “Sensor” dialogue
- Come back to the “Load Case View” tab and press again the left button of the mouse in the box labeled “+ Click here to add a sensor to track a result” (Fig. 4.34)
- Select the “+ Add Sensor...” command in the drop-down list displayed at the bottom of the “Load Case View” tab (Fig. 4.34)
- Perform the following actions in the “Sensor” dialogue box to define a new sensor for tracking the maximum deflection at the level of the lower and upper parts of the orthosis (Fig. 4.35):
 - Select the option “Displacement” in the “Results” drop-down list
 - Select the option “URES: Resultant Displacement” in the “Component” drop-down list

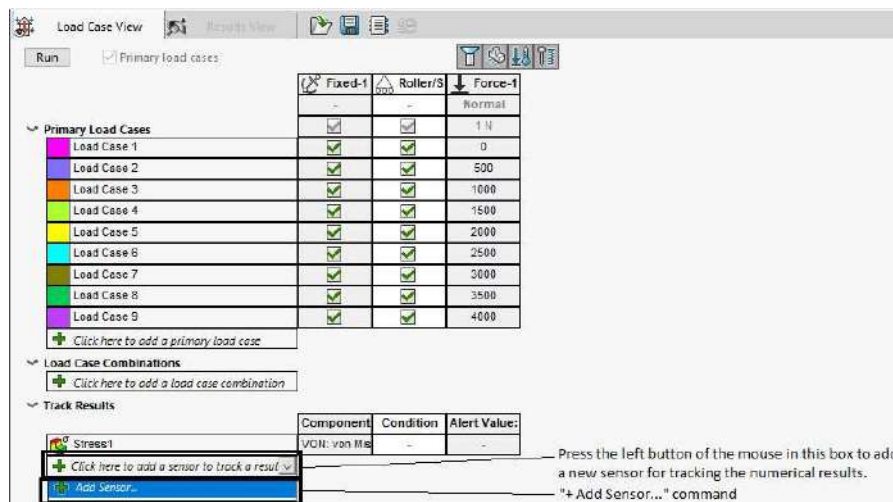


Figure 4.34: Initiating the definition of a new sensor for tracking the numerical results

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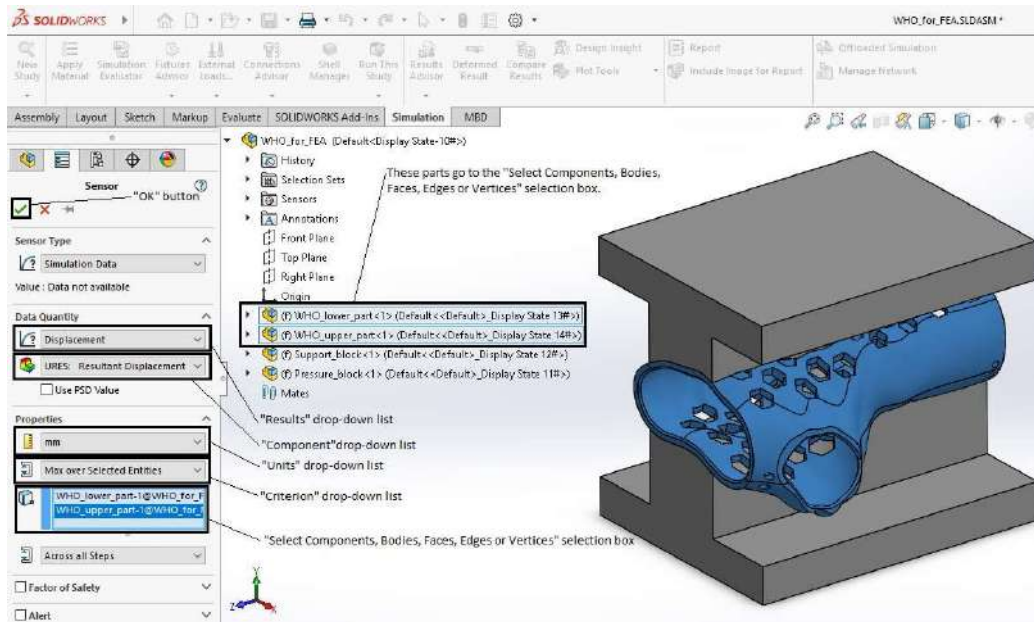


Figure 4.35: Definition of a sensor for tracking the maximum deflection at the level of the lower and upper parts of the orthosis

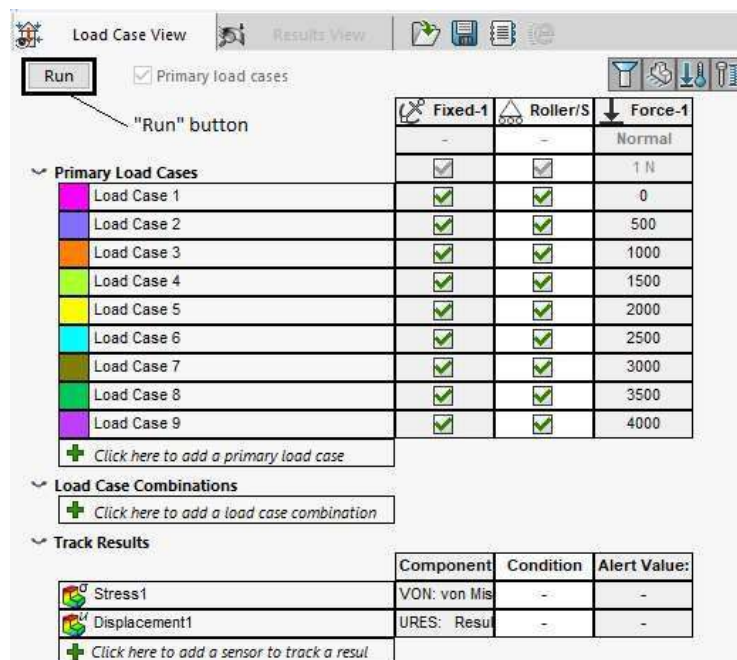


Figure 4.36: Transferring the finite element model to the SolidWorks Simulation solver

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- Select the option “mm” in the “Units” drop-down list
- Select the option “Max over Selected Entities” in the “Criterion” drop-down list
- Press the left button of the mouse in the “Select Components, Bodies, Faces, Edges or Vertices” selection box
- Unroll the assembly tree placed at the upper-left corner of the graphics area
- Select the lower and upper parts of the orthosis in the assembly tree
- Press the “OK” button placed at the upper-left corner of the “Sensor” dialogue.

At this stage, the finite element model of the compression test is prepared and transferred to the SolidWorks Simulation solver by pressing the “Run” button of the “Load Case View” tab (Fig. 4.36).

4.3. Interpretation of the numerical results

As soon as the solver finishes its job, the control is transferred to the “Results View” tab which is displayed at the bottom of the graphics area. At the same time, a color map showing the distribution of the von Mises equivalent stress at the level of the entire assembly appears on the screen (Fig. 4.37). This distribution corresponds to the first load case. The user can explore the other load cases by selecting them with the left button of the mouse in the first column of the “Primary Load Cases” table placed at the bottom of the “Results View” tab (Fig. 4.37).

Both the support block and pressure block are colored gray on the map showing the distribution of the von Mises equivalent stress (Fig. 4.37). This means that no stress information has been generated by the solver for them. Such a situation is normal because they are rigid bodies for which the stress concept is senseless. Due to the same reason, the support block and pressure block are uniformly colored in the deflection maps. In fact, it is preferable to prevent these bodies from being displayed in the graphics area since their volumes cover useful regions of the color maps associated to the lower and upper parts of the orthosis. Perform the following actions to hide the support block and pressure block:

- Press the right button of the mouse on the item “Stress1 (-von Mises-)” item under the “Load Case Results” entry of the FEA tree, and select the “Hide” command in the drop-down menu (Fig. 4.38)

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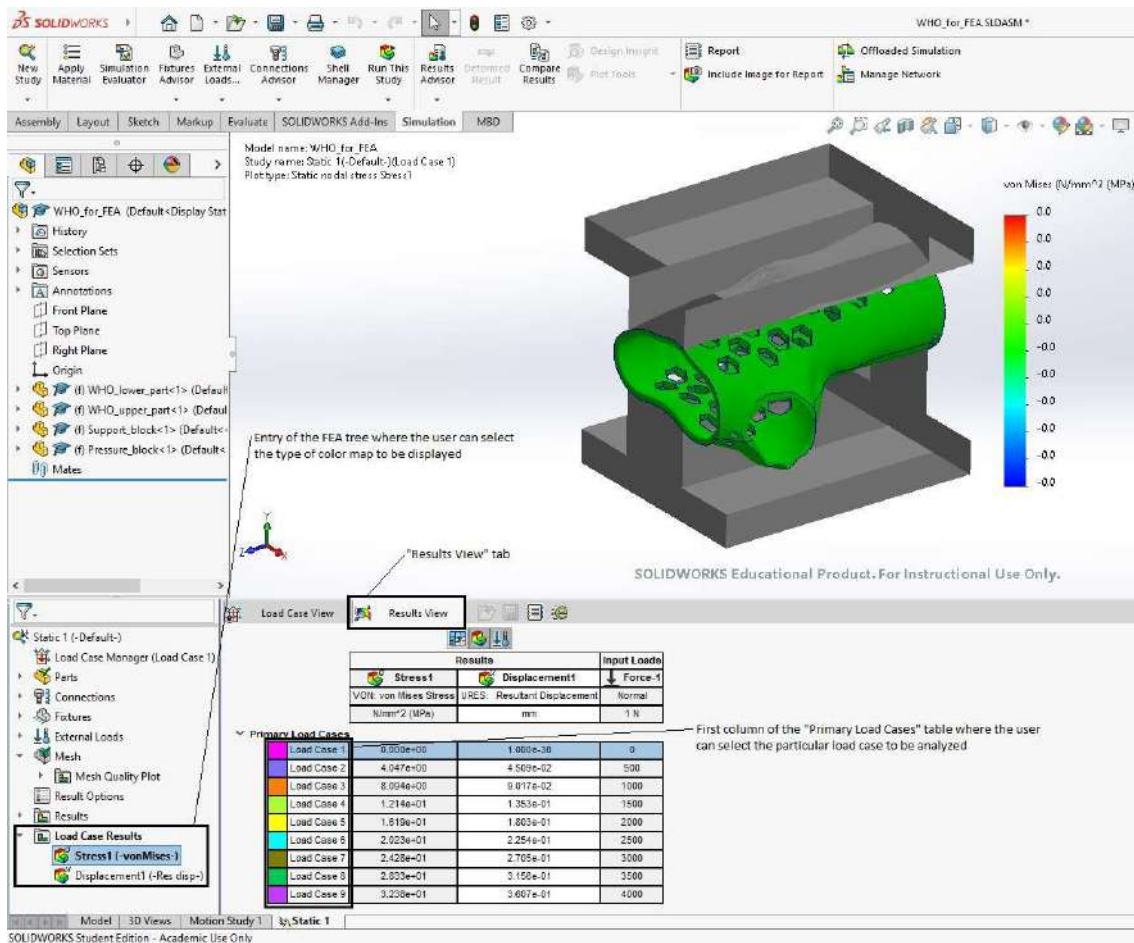


Figure 4.37: Analyzing the numerical results associated to different load cases with the help of the “Results View” tab and the “Load Case Results” entry of the FEA tree

- Select the support block and the pressure block in the assembly tree, press the right button of the mouse on any of them, and press the “Hide Components” button in the drop-down menu (Fig. 4.39)
- Press the right button of the mouse on the item “Stress1 (-von Mises-)” item under the “Load Case Results” entry of the FEA tree and select the “Show” command (Fig. 4.40).

After these actions, the color map of the von Mises equivalent stress distribution associated to the first load case should look as shown in Figure 4.41.

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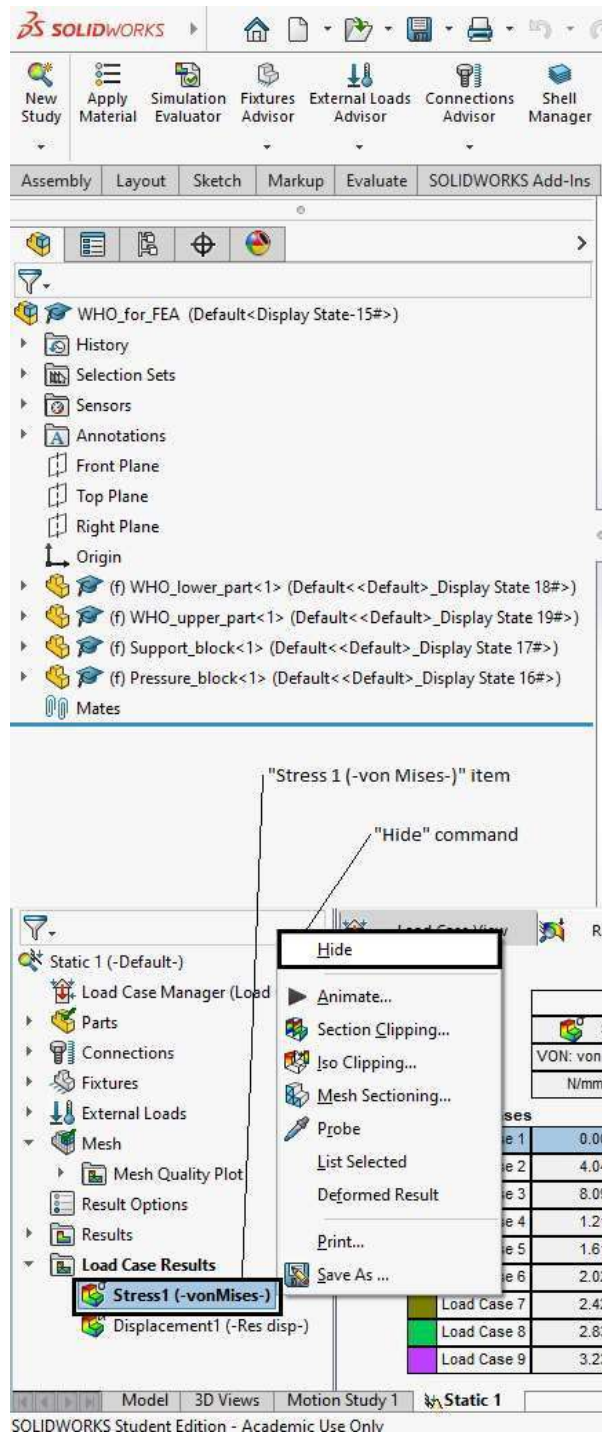


Figure 4.38: Hiding the color map “Stress1 (-von Mises-)”

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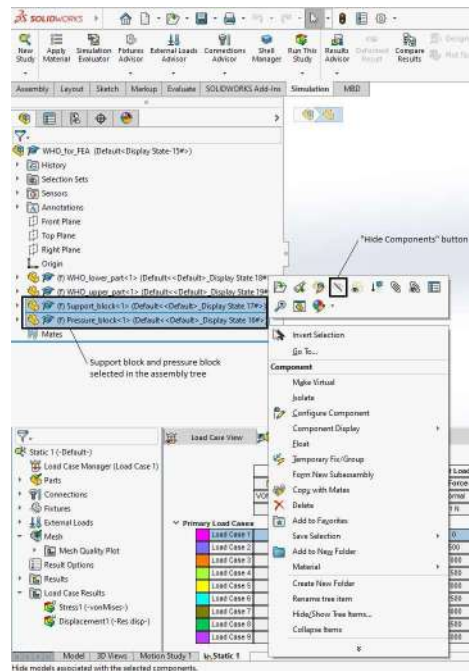


Figure 4.39: Preventing the support block and pressure block from being displayed in the graphics area

The numerical results associated to other values of the compression force applied to the orthosis can be examined by selecting the corresponding load cases in column 1 of the table “Primary Load Cases” (Fig. 4.37). For example, Figures 4.42 and 4.43 show the color maps of the von Mises equivalent stress distribution associated to the eighth and ninth load case, respectively.

The following actions should be performed to examine the deflections of the orthosis associated to different load cases:

- Press the right button of the mouse on the “Displacement1 (-Res disp-)” item under the “Load Case Results” entry of the FEA tree and select the “Show” command (Fig. 4.44).
- Select the load case to be examined in column 1 of the “Primary Load Cases” table.

For example, Figures 4.45 and 4.46 show the color maps of the deflections associated to the eighth and ninth load case, respectively.

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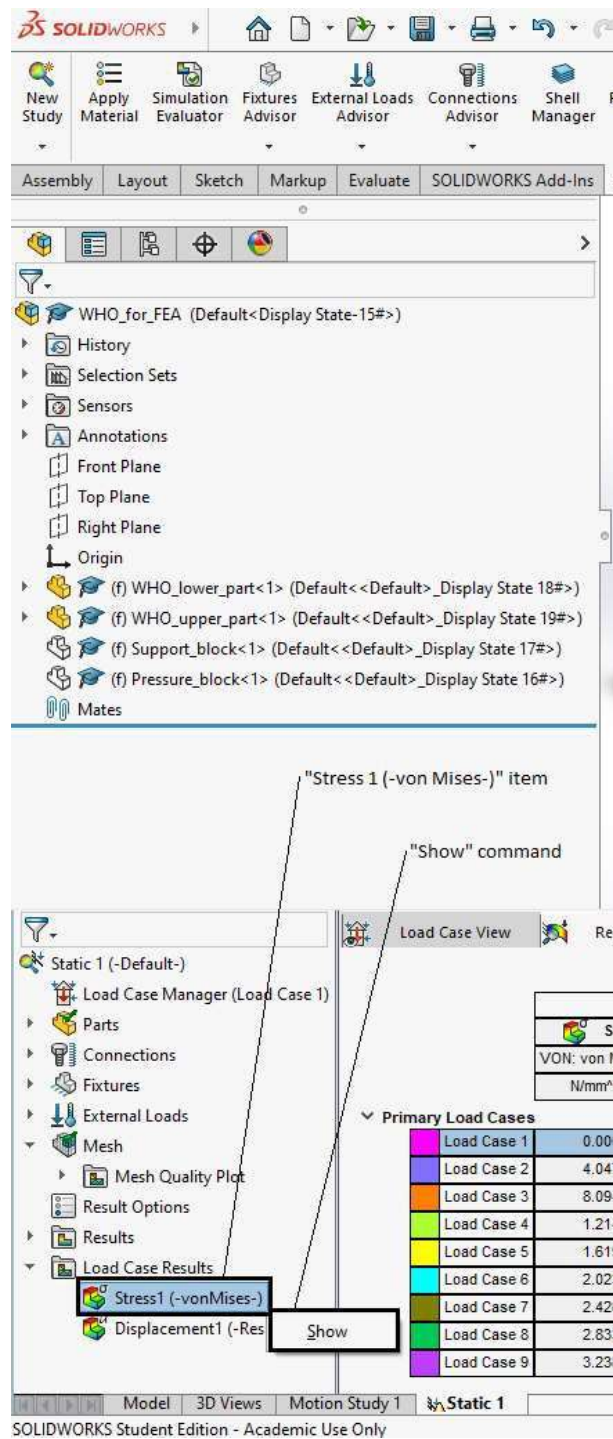


Figure 4.40: Displaying the color map “Stress1 (-von Mises-)”

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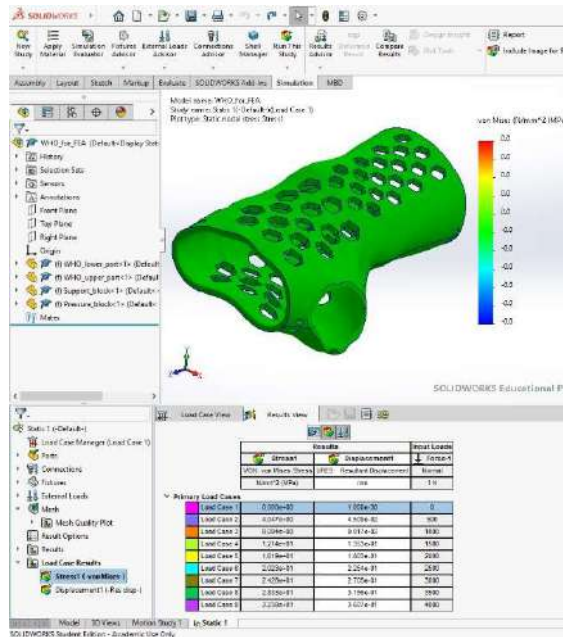


Figure 4.41: Color map showing the distribution of the von Mises equivalent stress at the level of the lower and upper parts of the orthosis (first load case)

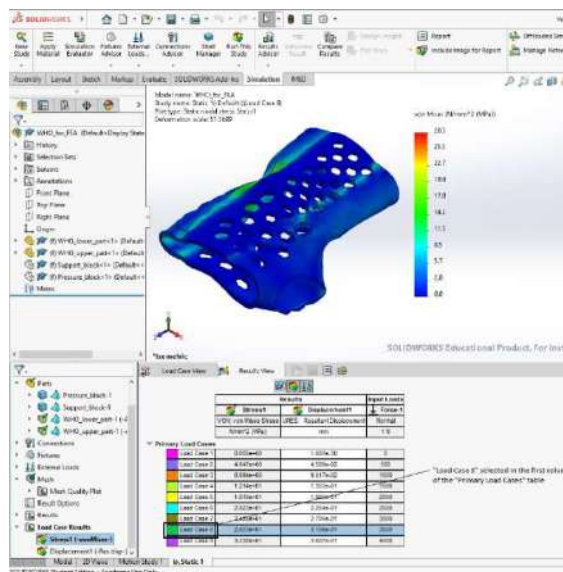


Figure 4.42: Color map showing the distribution of the von Mises equivalent stress at the level of the lower and upper parts of the orthosis (eighth load case: compression force of 3500 N)

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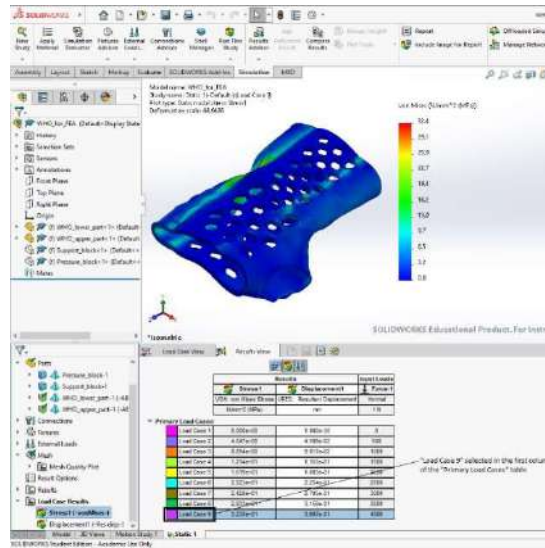


Figure 4.43: Color map showing the distribution of the von Mises equivalent stress at the level of the lower and upper parts of the orthosis (ninth load case: compression force of 4000 N)

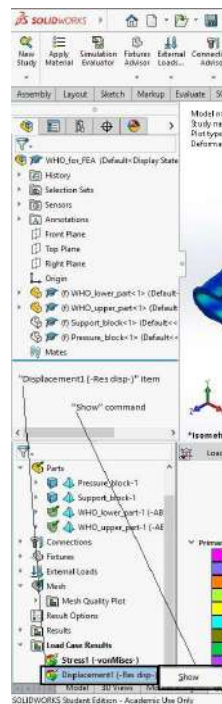


Figure 4.44: Displaying the color map “Displacement1 (-Res disp-)”

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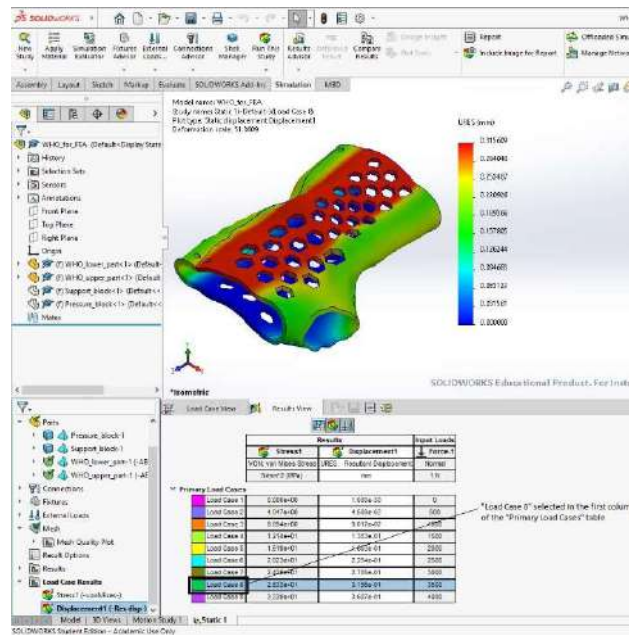


Figure 4.45: Color map showing the deflections at the level of the lower and upper parts of the orthosis (eighth load case: compression force of 3500 N)

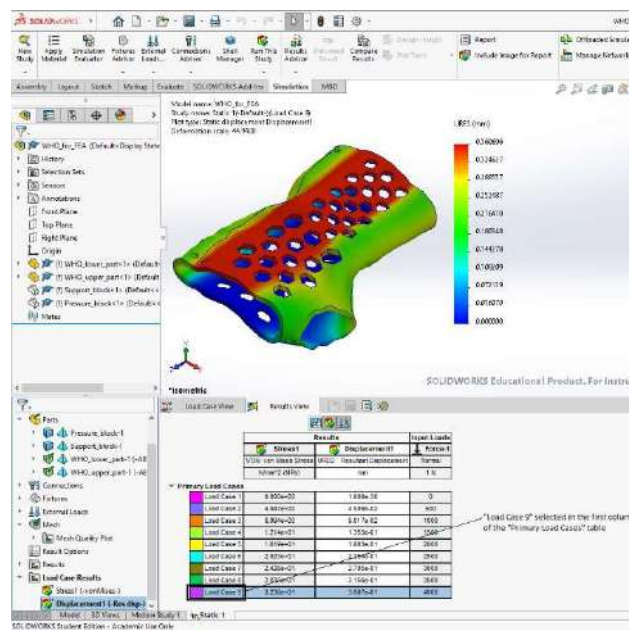


Figure 4.46: Color map showing the deflections at the level of the lower and upper parts of the orthosis (ninth load case: compression force of 4000 N)

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The maximum value of the von Mises equivalent stress, the maximum deflection, and the compression force corresponding to different load cases are listed in the second, third and fourth column of the “Primary Load Cases” table (Fig. 4.47). Table 4.1 presents this data in a more readable format.

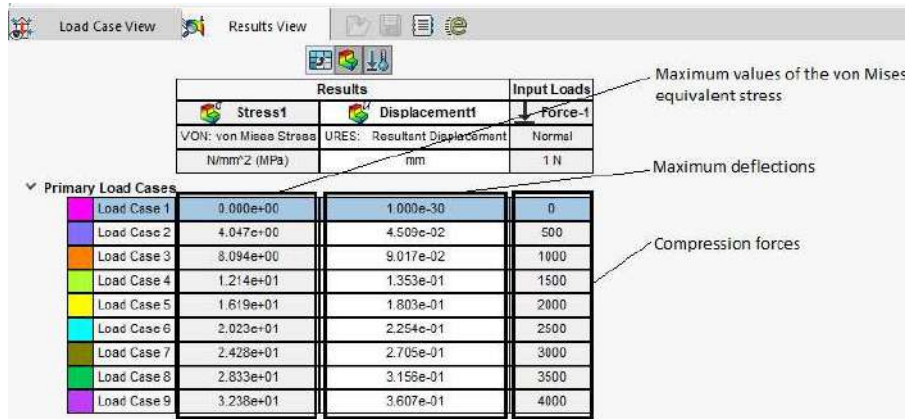


Figure 4.47: Maximum value of the von Mises equivalent stress, maximum deflection, and compression force corresponding to different load cases listed in the “Primary Load Cases” table

Table 4.1: Compression force, maximum value of the von Mises equivalent stress, and maximum deflection corresponding to different load cases (see also Figure 4.47)

Load case	Compression force F [N]	Maximum value of the von Mises equivalent stress $\sigma_{eq,max}$ [MPa]	Maximum deflection d_{max} [mm]
1	0	0.00	0.000
2	500	4.05	0.045
3	1000	8.09	0.090
4	1500	12.14	0.135
5	2000	16.19	0.180
6	2500	20.23	0.225
7	3000	24.28	0.271
8	3500	28.33	0.316
9	4000	32.38	0.361

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The plots in Figures 4.48 and 4.49 show the dependencies $\sigma_{eq,max}$ vs F and d_{max} vs F , respectively. Both diagrams allow noticing that the mechanical response of the orthosis is linear. In fact, the dependencies $\sigma_{eq,max}$ vs F and d_{max} vs F are well approximated by the regressions

$$\sigma_{eq,max} = 8.095 \cdot 10^{-3} \cdot F, \quad (4.1)$$

and

$$d_{max} = 9.025 \cdot 10^{-5} \cdot F, \quad (4.2)$$

respectively (see the black lines in Figures 4.48 and 4.49).

It can be easily seen in Table 4.1 and Figure 4.48 that $\sigma_{eq,max}$ equals the tensile strength of the ABS material $R_m = 30$ MPa (as defined in the “SOLIDWORKS Materials” library – see Figure 4.12) for a compression force $3500 \text{ N} < F_m < 4000 \text{ N}$. This critical load results from Eq (4.1) as soon as the replacement $\sigma_{eq,max} = R_m = 30$ MPa is made:

$$F_m = R_m \cdot 10^3 / 8.095 = 30 \cdot 10^3 / 8.095 \approx 3706 \text{ N}. \quad (4.3)$$

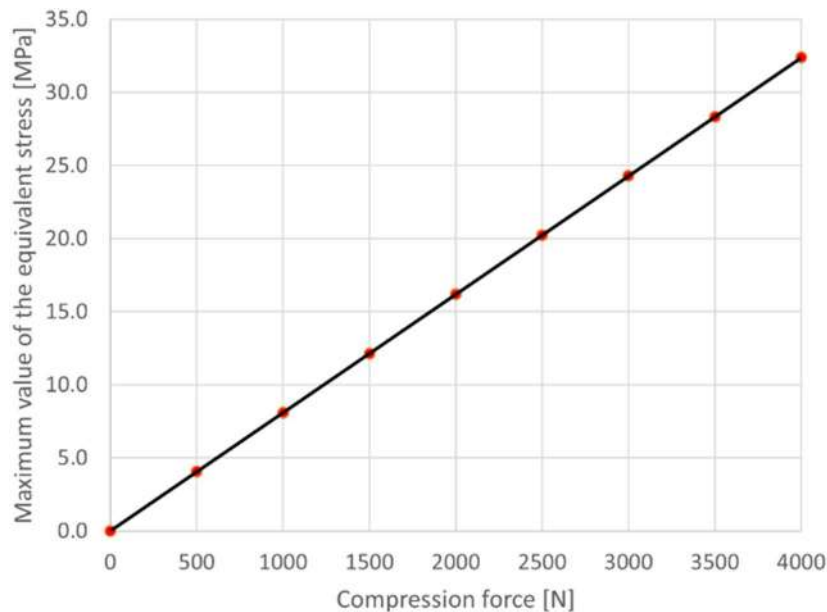


Figure 4.48: Dependence $\sigma_{eq,max}$ vs F : red dots – numerical results taken from Table 4.1; black line – linear regression defined by Eq (4.1)

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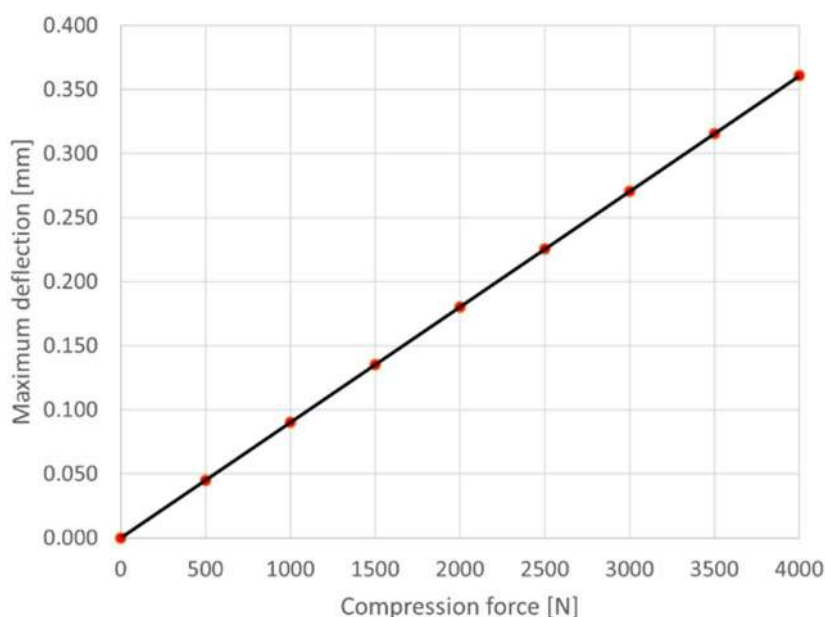


Figure 4.49: Dependence d_{\max} vs F : red dots – numerical results taken from Table 4.1; black line – linear regression defined by Eq (4.2)

The results of the finite element analysis show that the wrist hand orthosis exhibits a high compression strength. The critical value of the compression force $F_m \approx 3706$ N is much greater than the greatest load that normally occurs when patients wear such medical devices. Of course, the overall strength of the wrist hand orthosis is fully assessable only by analyzing its behavior in different loading conditions. As an example, the numerical simulation of a three-point bending test [Luk2020] could also be used for this purpose.

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1. Introduction

Welcome to Computer Programming Python Class -- this is a free class for people with a little bit of programming experience who want to learn Python. The class includes written materials and lots of code exercises to practice Python coding. These materials are used within to introduce Python to people who have just a little programming experience. The first exercises work on basic Python concepts like strings and lists, building up to the later exercises which are full programs dealing with text files, processes, and http connections. The class is geared for people who have a little bit of programming experience in some language, enough to know what a "variable" or "if statement" is. Beyond that, you do not need to be an expert programmer to use this material.

To get started, the Python sections are Python Set Up to get Python installed on your machine, Python Introduction for an introduction to the language, and then Python Strings starts the coding material, leading to the first exercise. The end of each written section includes a link to the code exercise for that section's material. The lecture videos parallel the written materials, introducing Python, then strings, then first exercises, and so on. All this material makes up an intensive class.

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2. Python Set Up

Basic definitions

This page explains how to set up Python on a machine so you can run and edit Python programs, and links to the exercise code to download. You can do this before starting the class, or you can leave it until you've gotten far enough in the class that you want to write some code. The Class uses a simple, standard Python installation, although more complex strategies are possible. Python is free and open source, available for all operating systems from python.org. In particular we want a Python install where you can do two things:

- Run an existing python program, such as hello.py
- Run the Python interpreter interactively, so you can type code right at it

Both of the above are done quite a lot in the lecture videos, and it's definitely something you need to be able to do to solve the exercises.

Download Google Python Exercises

As a first step, download the [google-python-exercises.zip](#) file and unzip it someplace where you can work on it. The resulting google-python-exercises directory contains many different python code exercises you can work on. In particular, google-python-exercises contains a simple hello.py file you can use in the next step to check that Python is working on your machine. Below are instructions for Windows and other operating systems.

Python on Linux, Mac OS X, and other OS

Most operating systems other than Windows already have Python installed by default. To check that Python is installed, open a command line (typically by running the "Terminal"

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program), and cd to the google-python-exercises directory. Try the following to run the hello.py program (what you type is shown in bold):

```
~/google-python-exercises$ python hello.py
Hello World
~/google-python-exercises$ python hello.py Alice
Hello Alice
```

If python is not installed, see the [Python.org download](#) page. To run the Python interpreter interactively, just type `python` in the terminal:

```
~/google-python-exercises$ python3
Python 3.X.X (XXX, XXX XX XXXX, 03:41:42) [XXX] on XXX
Type "help", "copyright", "credits" or "license" for more information.
>>> 1 + 1
2
>>> you can type expressions here .. use ctrl-d to exit
```

The two lines python prints after you type python and before the >>> prompt tells you about the version of python you're using and where it was built. As long as the first thing printed is "Python 3.", these examples should work for you. This course is designed for Python 3.X or later.

Python on Windows

To install Python on Windows, go to the [python.org download](#) page and download Python 3.X.X. Run the Python installer and accept all the defaults. This will install Python in the root directory and set up some file associations.

With Python installed, open a command prompt (Accessories > Command Prompt, or type cmd into the run dialog). Cd to the google-python-exercises directory (from unzipping google-

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python-exercises.zip). You should be able to run the hello.py python program by typing `python hello.py` (what you type is shown in bold):

```
C:\google-python-exercises> python hello.py
Hello World
C:\google-python-exercises> python hello.py Alice
Hello Alice
```

If this works, Python is installed. Otherwise, see [Python Windows FAQ](#) for help.

To run the Python interpreter interactively, select the Run... command from the Start menu, and type `Python --` this will launch Python interactively in its own window. On Windows, use **Ctrl-Z** to exit (on all other operating systems it's **Ctrl-D** to exit).

In the lecture videos, we generally run the Python programs with commands like `./hello.py`. On Windows, it's simplest to use the `python hello.py` form.

Editing Python (all operating systems)

A Python program is just a text file that you edit directly. As above, you should have a command line open, where you can type `python hello.py Alice` to run whatever exercise you are working on. At the command line prompt, just hit the up-arrow key to recall previously typed commands, so it's easy to run previous commands without retyping them.

You want a text editor with a little understanding of code and indentation. There are many good free ones:

Windows -- **do not use Notepad or Wordpad**. Try the free and open source [Notepad++](#) or the free and open source [JEdit](#)

Mac -- The built in TextEdit works, but not very well. Try the free [BBEdit](#) or the free and open source [JEdit](#)

Linux -- any unix text editor is fine, or try the above JEdit.

Editor Settings

Following are some recommended settings for your text editor:

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When you press **Tab**, it's best if your editor inserts spaces instead of a real tab character. All of the tutorial files use 2-spaces as the indent, and 4-spaces is another popular choice.

It's helpful if the editor will "auto indent" so when you press **Enter**, the new line starts with the same indentation as the previous line.

When you save your files, use the unix line-ending convention, since that's how the various starter files are set up. If running hello.py gives the error "Unknown option: -", the file may have the wrong line-ending.

Here are the preferences to set for common editors to treat tabs and line-endings correctly for Python:

Windows Notepad++ -- Tabs: Settings > Preferences > Edit Components > Tab settings, and Settings > Preferences > MISC for auto-indent. Line endings: Format > Convert, set to Unix.

JEdit (any OS) -- Line endings: Little 'U' 'W' 'M' on status bar, set it to 'U' (for Unix line-endings).

Windows Notepad or Wordpad -- do not use.

Mac BBEdit -- Tabs: At the top, BBEdit > Preferences (or Cmd + , shortcut). Go to Editor Defaults section and make sure Auto-indent and Auto-expand tabs are checked. Line endings: In Preferences go to Text Files section and make sure Unix (LF) is selected under Line breaks.

Mac TextEdit -- do not use.

Unix pico -- Tabs: Esc-q toggles tab mode, Esc-i to turns on auto-indent mode.

Unix emacs -- Tabs: manually set tabs-inserts-spaces mode: `M-x set-variable (return) indent-tabs-mode (return) nil.`

Editing Check

To try out your editor, edit the hello.py program. Change the word "Hello" in the code to the word "Howdy" (you don't need to understand all the other Python code in there - we'll explain it all in class). Save your edits and run the program to see its new output. Try adding a `print 'yay!'` just below the existing print and with the same indentation. Try running the

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program, to see that your edits work correctly. For class we want an edit/run workflow that allows you to switch between editing and running easily.

Quick Python Style

One of the advantages of Python is that it makes it easy to type a little code and quickly see what it does. In class, we want a work setup that matches that: a text editor working on the current file.py, and a separate command line window where you can just press the up-arrow key to run file.py and see what it does.

Teaching philosophy aside: the interpreter is great for little experiments, as shown throughout the lectures. However, the exercises are structured as Python files that students edit. Since being able to write Python programs is the ultimate goal, it's best to be in that mode the whole time and use the interpreter just for little experiments.

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3. Python Introduction

Language Introduction

Python is a dynamic, interpreted (bytecode-compiled) language. There are no type declarations of variables, parameters, functions, or methods in source code. This makes the code short and flexible, and you lose the compile-time type checking of the source code. Python tracks the types of all values at runtime and flags code that does not make sense as it runs.

An excellent way to see how Python code works is to run the Python interpreter and type code right into it. If you ever have a question like, "What happens if I add an `int` to a `list`?" Just typing it into the Python interpreter is a fast and likely the best way to see what happens. (See below to see what really happens!)

```
$ python          ## Run the Python interpreter
Python 3.X.X (XXX, XXX XX XXXX, 03:41:42) [XXX] on XXX
Type "help", "copyright", "credits" or "license" for more information.
>>> a = 6         ## set a variable in this interpreter session
>>> a             ## entering an expression prints its value
6
>>> a + 2
8
>>> a = 'hi'      ## 'a' can hold a string just as well
>>> a
'hi'
>>> len(a)        ## call the len() function on a string
2
>>> a + len(a)    ## try something that doesn't work
Traceback (most recent call last):
  File "", line 1, in
TypeError: can only concatenate str (not "int") to str
>>> a + str(len(a)) ## probably what you really wanted
'hi2'
>>> foo          ## try something else that doesn't work
Traceback (most recent call last):
  File "", line 1, in
```

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```
NameError: name 'foo' is not defined
>>> ^D          ## type CTRL-d to exit (CTRL-z in Windows/DOS terminal)
```

The two lines python prints after you type python and before the >>> prompt tells you about the version of python you're using and where it was built. As long as the first thing printed is "Python 3.", these examples should work for you.

As you can see above, it's easy to experiment with variables and operators. Also, the interpreter throws, or "raises" in Python parlance, a runtime error if the code tries to read a variable that has not been assigned a value. Like C++ and Java, Python is case sensitive so "a" and "A" are different variables. The end of a line marks the end of a statement, so unlike C++ and Java, Python does not require a semicolon at the end of each statement. Comments begin with a '#' and extend to the end of the line.

Python source code

Python source files use the ".py" extension and are called "modules." With a Python module `hello.py`, the easiest way to run it is with the shell command "python hello.py Alice" which calls the Python interpreter to execute the code in `hello.py`, passing it the command line argument "Alice". See the [official docs page](#) on all the different options you have when running Python from the command-line.

Here's a very simple `hello.py` program (notice that blocks of code are delimited strictly using indentation rather than curly braces — more on this later!):

```
#!/usr/bin/env python

# import modules used here -- sys is a very standard one
import sys

# Gather our code in a main() function
def main():
    print('Hello there', sys.argv[1])
    # Command line args are in sys.argv[1], sys.argv[2] ...
    # sys.argv[0] is the script name itself and can be ignored

# Standard boilerplate to call the main() function to begin
# the program.
```

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```
if __name__ == '__main__':  
    main()
```

Running this program from the command line looks like:

```
$ python hello.py Guido  
Hello there Guido  
  
$ ./hello.py Alice ## without needing 'python' first (Unix)  
Hello there Alice
```

Imports, Command-line arguments, and len()

The outermost statements in a Python file, or "module", do its one-time setup — those statements run from top to bottom the first time the module is imported somewhere, setting up its variables and functions. A Python module can be run directly — as above "python hello.py Bob" — or it can be imported and used by some other module. When a Python file is run directly, the special variable "__name__" is set to "__main__". Therefore, it's common to have the boilerplate `if __name__ == ...` shown above to call a `main()` function when the module is run directly, but not when the module is imported by some other module.

In a standard Python program, the list `sys.argv` contains the command-line arguments in the standard way with `sys.argv[0]` being the program itself, `sys.argv[1]` the first argument, and so on. If you know about `argc`, or the number of arguments, you can simply request this value from Python with `len(sys.argv)`, just like we did in the interactive interpreter code above when requesting the length of a string. In general, `len()` can tell you how long a string is, the number of elements in lists and tuples (another array-like data structure), and the number of key-value pairs in a dictionary.

User-defined Functions

Functions in Python are defined like this:

```
# Defines a "repeat" function that takes 2 arguments.  
def repeat(s, exclaim):  
    """  
    Returns the string 's' repeated 3 times.  
    If exclaim is true, add exclamation marks.  
    """
```

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```
result = s + s + s # can also use "s * 3" which is faster (Why?)
if exclaim:
    result = result + '!!!'
return result
```

Notice also how the lines that make up the function or if-statement are grouped by all having the same level of indentation. We also presented 2 different ways to repeat strings, using the + operator which is more user-friendly, but * also works because it's Python's "repeat" operator, meaning that '-' * 10 gives '-----', a neat way to create an onscreen "line." In the code comment, we hinted that * works faster than +, the reason being that * calculates the size of the resulting object once whereas with +, that calculation is made each time + is called. Both + and * are called "overloaded" operators because they mean different things for numbers vs. for strings (and other data types).

The def keyword defines the function with its parameters within parentheses and its code indented. The first line of a function can be a documentation string ("docstring") that describes what the function does. The docstring can be a single line, or a multi-line description as in the example above. (Yes, those are "triple quotes," a feature unique to Python!) Variables defined in the function are local to that function, so the "result" in the above function is separate from a "result" variable in another function. The return statement can take an argument, in which case that is the value returned to the caller.

Here is code that calls the above repeat() function, printing what it returns:

```
def main():
    print(repeat('Yay', False))      ## YayYayYay
    print(repeat('Woo Hoo', True))  ## Woo HooWoo HooWoo Hoo!!!
```

At run time, functions must be defined by the execution of a "def" before they are called. It's typical to def a main() function towards the bottom of the file with the functions it calls above it.

Indentation

One unusual Python feature is that the whitespace indentation of a piece of code affects its meaning. A logical block of statements such as the ones that make up a function should all have the same indentation, set in from the indentation of their parent function or "if" or

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whatever. If one of the lines in a group has a different indentation, it is flagged as a syntax error.

Python's use of whitespace feels a little strange at first, but it's logical and I found I got used to it very quickly. Avoid using TABs as they greatly complicate the indentation scheme (not to mention TABs may mean different things on different platforms). Set your editor to insert spaces instead of TABs for Python code.

A common question beginners ask is, "How many spaces should I indent?" According to [the official Python style guide \(PEP 8\)](#), you should indent with 4 spaces. (Fun fact: Google's internal style guideline dictates indenting by 2 spaces!)

Code Checked at Runtime

Python does very little checking at compile time, deferring almost all type, name, etc. checks on each line until that line runs. Suppose the above main() calls repeat() like this:

```
def main():
    if name == 'Guido':
        print(repeeeet(name) + '!!!!')
    else:
        print(repeat(name))
```

The if-statement contains an obvious error, where the repeat() function is accidentally typed in as repeeeet(). The funny thing in Python ... this code compiles and runs fine so long as the name at runtime is not 'Guido'. Only when a run actually tries to execute the repeeeet() will it notice that there is no such function and raise an error. There is also a second error in this snippet. name wasn't assigned a value before it is compared with 'Guido'. Python will raise a 'NameError' if you try to evaluate an unassigned variable. These are some examples demonstrating that when you first run a Python program, some of the first errors you see will be simple typos or uninitialized variables like these. This is one area where languages with a more verbose type system, like Java, have an advantage ... they can catch such errors at compile time (but of course you have to maintain all that type information ... it's a tradeoff).

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Variable Names

Since Python variables don't have any type spelled out in the source code, it's extra helpful to give meaningful names to your variables to remind yourself of what's going on. So use "name" if it's a single name, and "names" if it's a list of names, and "tuples" if it's a list of tuples. Many basic Python errors result from forgetting what type of value is in each variable, so use your variable names (all you have really) to help keep things straight.

As far as actual naming goes, some languages prefer underscore_parts for variable names made up of "more than one word," but other languages prefer camelCasing. In general, Python [prefers](#) the underscore method but guides developers to defer to camelCasing if integrating into existing Python code that already uses that style. Readability counts. Read more in [the section on naming conventions in PEP 8](#).

As you can guess, keywords like 'if' and 'while' cannot be used as variable names — you'll get a syntax error if you do. However, be careful not to use built-ins as variable names. For example, while 'str', 'list' and 'print' may seem like good names, you'd be overriding those system variables. Built-ins are not keywords and thus, are susceptible to inadvertent use by new Python developers.

More on Modules and their Namespaces

Suppose you've got a module "binky.py" which contains a "def foo()". The fully qualified name of that foo function is "binky.foo". In this way, various Python modules can name their functions and variables whatever they want, and the variable names won't conflict — module1.foo is different from module2.foo. In the Python vocabulary, we'd say that binky, module1, and module2 each have their own "namespaces," which as you can guess are variable name-to-object bindings.

For example, we have the standard "sys" module that contains some standard system facilities, like the argv list, and exit() function. With the statement "import sys" you can then access the definitions in the sys module and make them available by their fully-qualified name, e.g. sys.exit(). (Yes, 'sys' has a namespace too!)

```
import sys
```

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```
# Now can refer to sys.xxx facilities
sys.exit(0)
```

There is another import form that looks like this: "from sys import argv, exit". That makes argv and exit() available by their short names; however, we recommend the original form with the fully-qualified names because it's a lot easier to determine where a function or attribute came from.

There are many modules and packages which are bundled with a standard installation of the Python interpreter, so you don't have to do anything extra to use them. These are collectively known as the "Python Standard Library." Commonly used modules/packages include:

sys — access to exit(), argv, stdin, stdout, ...

re — regular expressions

os — operating system interface, file system

You can find the documentation of all the Standard Library modules and packages at <http://docs.python.org/library>.

Online help, `help()`, and `dir()`

There are a variety of ways to get help for Python.

Do a Google search, starting with the word "python", like "python list" or "python string lowercase". The first hit is often the answer. This technique seems to work better for Python than it does for other languages for some reason.

The official Python docs site — docs.python.org — has high quality docs. Nonetheless, I often find a Google search of a couple words to be quicker.

There is also an [official Tutor mailing list](#) specifically designed for those who are new to Python and/or programming!

Many questions (and answers) can be found on [StackOverflow](#) and [Quora](#).

Use the help() and dir() functions (see below).

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Inside the Python interpreter, the `help()` function pulls up documentation strings for various modules, functions, and methods. These doc strings are similar to Java's javadoc. The `dir()` function tells you what the attributes of an object are. Below are some ways to call `help()` and `dir()` from the interpreter:

`help(len)` — help string for the built-in `len()` function; note that it's "len" not "len()", which is a **call** to the function, which we don't want

`help(sys)` — help string for the `sys` module (must do an `import sys` first)

`dir(sys)` — `dir()` is like `help()` but just gives a quick list of its defined symbols, or "attributes"

`help(sys.exit)` — help string for the `exit()` function in the `sys` module

`help('xyz'.split)` — help string for the `split()` method for string objects. You can call `help()` with that object itself or an **example** of that object, plus its attribute. For example, calling `help('xyz'.split)` is the same as calling `help(str.split)`.

`help(list)` — help string for `list` objects

`dir(list)` — displays `list` object attributes, including its methods

`help(list.append)` — help string for the `append()` method for `list` objects

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4. Python Strings

Python has a built-in string class named "str" with many handy features (there is an older module named "string" which you should not use). String literals can be enclosed by either double or single quotes, although single quotes are more commonly used. Backslash escapes work the usual way within both single and double quoted literals -- e.g. `\n \'`. A double quoted string literal can contain single quotes without any fuss (e.g. "I didn't do it") and likewise single quoted string can contain double quotes. A string literal can span multiple lines, but there must be a backslash `\` at the end of each line to escape the newline. String literals inside triple quotes, `"""` or `'''`, can span multiple lines of text.

Python strings are "immutable" which means they cannot be changed after they are created (Java strings also use this immutable style). Since strings can't be changed, we construct **new** strings as we go to represent computed values. So for example the expression `('hello' + 'there')` takes in the 2 strings 'hello' and 'there' and builds a new string 'hellothere'.

Characters in a string can be accessed using the standard `[]` syntax, and like Java and C++, Python uses zero-based indexing, so if `s` is 'hello' `s[1]` is 'e'. If the index is out of bounds for the string, Python raises an error. The Python style (unlike Perl) is to halt if it can't tell what to do, rather than just make up a default value. The handy "slice" syntax (below) also works to extract any substring from a string. The `len(string)` function returns the length of a string. The `[]` syntax and the `len()` function actually work on any sequence type -- strings, lists, etc.. Python tries to make its operations work consistently across different types. Python newbie gotcha: don't use "len" as a variable name to avoid blocking out the `len()` function. The '+' operator can concatenate two strings. Notice in the code below that variables are not pre-declared -- just assign to them and go.

```
s = 'hi'
print s[1]          ## i
print len(s)       ## 2
print s + ' there' ## hi there
```

Unlike Java, the '+' does not automatically convert numbers or other types to string form. The `str()` function converts values to a string form so they can be combined with other strings.

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```
pi = 3.14
##text = 'The value of pi is ' + pi      ## NO, does not work
text = 'The value of pi is ' + str(pi)   ## yes
```

For numbers, the standard operators, +, /, * work in the usual way. There is no ++ operator, but +=, -=, etc. work. If you want integer division, use 2 slashes -- e.g. 6 // 5 is 1

The "print" function normally prints out one or more python items followed by a newline. A "raw" string literal is prefixed by an 'r' and passes all the chars through without special treatment of backslashes, so r'x\nx' evaluates to the length-4 string 'x\nx'. "print" can take several arguments to change how it prints things out (see [python.org print function definition](http://python.org/print-function-definition)) like setting "end" to "" to no longer print a newline after it finishes printing out all of the items.

```
raw = r'this\t\n and that'

# this\t\n and that
print(raw)

multi = """It was the best of times.
It was the worst of times."""

# It was the best of times.
# It was the worst of times.
print(multi)
```

String Methods

Here are some of the most common string methods. A method is like a function, but it runs "on" an object. If the variable s is a string, then the code s.lower() runs the lower() method on that string object and returns the result (this idea of a method running on an object is one of the basic ideas that make up Object Oriented Programming, OOP). Here are some of the most common string methods:

s.lower(), s.upper() -- returns the lowercase or uppercase version of the string

s.strip() -- returns a string with whitespace removed from the start and end

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`s.isalpha()/s.isdigit()/s.isspace()...` -- tests if all the string chars are in the various character classes

`s.startswith('other')`, `s.endswith('other')` -- tests if the string starts or ends with the given other string

`s.find('other')` -- searches for the given other string (not a regular expression) within `s`, and returns the first index where it begins or -1 if not found

`s.replace('old', 'new')` -- returns a string where all occurrences of 'old' have been replaced by 'new'

`s.split('delim')` -- returns a list of substrings separated by the given delimiter. The delimiter is not a regular expression, it's just text. `'aaa,bbb,ccc'.split(',')` -> `['aaa', 'bbb', 'ccc']`. As a convenient special case `s.split()` (with no arguments) splits on all whitespace chars.

`s.join(list)` -- opposite of `split()`, joins the elements in the given list together using the string as the delimiter. e.g. `'---'.join(['aaa', 'bbb', 'ccc'])` -> `aaa---bbb---ccc`

A google search for "python str" should lead you to the official [python.org string methods](https://docs.python.org/3/library/string.html) which lists all the str methods.

Python does not have a separate character type. Instead an expression like `s[8]` returns a string-length-1 containing the character. With that string-length-1, the operators `==`, `<=`, ... all work as you would expect, so mostly you don't need to know that Python does not have a separate scalar "char" type.

String Slices

The "slice" syntax is a handy way to refer to sub-parts of sequences -- typically strings and lists. The slice `s[start:end]` is the elements beginning at `start` and extending up to but not including `end`. Suppose we have `s = "Hello"`

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```
Hello
 0  1  2  3  4
-5 -4 -3 -2 -1
```

`s[1:4]` is 'ell' -- chars starting at index 1 and extending up to but not including index 4

`s[1:]` is 'ello' -- omitting either index defaults to the start or end of the string

`s[:]` is 'Hello' -- omitting both always gives us a copy of the whole thing (this is the pythonic way to copy a sequence like a string or list)

`s[1:100]` is 'ello' -- an index that is too big is truncated down to the string length

The standard zero-based index numbers give easy access to chars near the start of the string. As an alternative, Python uses negative numbers to give easy access to the chars at the end of the string: `s[-1]` is the last char 'o', `s[-2]` is 'l' the next-to-last char, and so on. Negative index numbers count back from the end of the string:

`s[-1]` is 'o' -- last char (1st from the end)

`s[-4]` is 'e' -- 4th from the end

`s[:-3]` is 'He' -- going up to but not including the last 3 chars.

`s[-3:]` is 'llo' -- starting with the 3rd char from the end and extending to the end of the string.

It is a neat truism of slices that for any index `n`, `s[:n] + s[n:] == s`. This works even for `n` negative or out of bounds. Or put another way `s[:n]` and `s[n:]` always partition the string into two string parts, conserving all the characters. As we'll see in the list section later, slices work with lists too.

String formatting

One neat thing python can do is automatically convert objects into a string suitable for printing. Two built-in ways to do this are formatted string literals, also called "f-strings", and invoking `str.format()`.

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Formatted string literals

You'll often see formatted string literals used in situations like:

```
value = 2.791514
print(f'approximate value = {value:.2f}') # approximate value = 2.79

car = {'tires':4, 'doors':2}
print(f'car = {car}') # car = {'tires': 4, 'doors': 2}
```

A formatted literal string is prefixed with 'f' (like the 'r' prefix used for raw strings). Any text outside of curly braces '{}' is printed out directly. Expressions contained in '{}' are printed out using the format specification described in [the format spec](#). There are lots of neat things you can do with the formatting including truncation and conversion to scientific notation and left/right/center alignment.

f-strings are very useful when you'd like to print out a table of objects and would like the columns representing different object attributes to be aligned like

```
address_book = [{'name':'N.X.', 'addr':'15 Jones St', 'bonus': 70},
                {'name':'J.P.', 'addr':'1005 5th St', 'bonus': 400},
                {'name':'A.A.', 'addr':'200001 Bdwy', 'bonus': 5},]
```

```
for person in address_book:
    print(f'{person["name"]:8} || {person["addr"]:20} ||
{person["bonus"]:>5}')
```

```
# N.X.      || 15 Jones St      ||      70
# J.P.      || 1005 5th St      ||     400
# A.A.      || 200001 Bdwy     ||         5
```

String %

Python also has an older printf()-like facility to put together a string. The % operator takes a printf-type format string on the left (%d int, %s string, %f/%g floating point), and the matching values in a tuple on the right (a tuple is made of values separated by commas, typically grouped inside parentheses):

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```
# % operator
text = "%d little pigs come out, or I'll %s, and I'll %s, and I'll blow
your %s down." % (3, 'huff', 'puff', 'house')
```

The above line is kind of long -- suppose you want to break it into separate lines. You cannot just split the line after the '%' as you might in other languages, since by default Python treats each line as a separate statement (on the plus side, this is why we don't need to type semi-colons on each line). To fix this, enclose the whole expression in an outer set of parenthesis -- then the expression is allowed to span multiple lines. This code-across-lines technique works with the various grouping constructs detailed below: (), [], { }.

```
# Add parentheses to make the long line work:
text = (
    "%d little pigs come out, or I'll %s, and I'll %s, and I'll blow your
%s down."
    % (3, 'huff', 'puff', 'house'))
```

That's better, but the line is still a little long. Python lets you cut a line up into chunks, which it will then automatically concatenate. So, to make this line even shorter, we can do this:

```
# Split the line into chunks, which are concatenated automatically by
Python
text = (
    "%d little pigs come out, "
    "or I'll %s, and I'll %s, "
    "and I'll blow your %s down."
    % (3, 'huff', 'puff', 'house'))
```

Strings (Unicode vs bytes)

Regular Python strings are unicode.

Python also supports strings composed of plain bytes (denoted by the prefix 'b' in front of a string literal) like:

```
> byte_string = b'A byte string'
> byte_string
b'A byte string'
```

A unicode string is a different type of object from a byte string but various libraries such as regular expressions work correctly if passed either type of string.

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To convert a regular Python string to bytes, call the `encode()` method on the string. Going the other direction, the byte string `decode()` method converts encoded plain bytes to a unicode string:

```
> ustring = 'A unicode \u018e string \xf1'
> b = ustring.encode('utf-8')
> b
b'A unicode \xc6\x8e string \xc3\xb1' ## bytes of utf-8 encoding. Note the
b-prefix.
> t = b.decode('utf-8')                ## Convert bytes back to a unicode
string
> t == ustring                          ## It's the same as the original,
yay!

True
```

In the file-reading section, there's an example that shows how to open a text file with some encoding and read out unicode strings.

If Statement

Python does not use `{ }` to enclose blocks of code for if/loops/function etc.. Instead, Python uses the colon (`:`) and indentation/whitespace to group statements. The boolean test for an if does not need to be in parenthesis (big difference from C++/Java), and it can have `*elif*` and `*else*` clauses (mnemonic: the word "elif" is the same length as the word "else").

Any value can be used as an if-test. The "zero" values all count as false: None, 0, empty string, empty list, empty dictionary. There is also a Boolean type with two values: True and False (converted to an int, these are 1 and 0). Python has the usual comparison operations: `==`, `!=`, `<`, `<=`, `>`, `>=`. Unlike Java and C, `==` is overloaded to work correctly with strings. The boolean operators are the spelled out words `*and*`, `*or*`, `*not*` (Python does not use the C-style `&& || !`). Here's what the code might look like for a health app providing drink recommendations throughout the day -- notice how each block of then/else statements starts with a `:` and the statements are grouped by their indentation:

```
if time_hour >= 0 and time_hour <= 24:
    print('Suggesting a drink option...')
if mood == 'sleepy' and time_hour < 10:
```

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```
print('coffee')
elif mood == 'thirsty' or time_hour < 2:
    print('lemonade')
else:
    print('water')
```

I find that omitting the ":" is my most common syntax mistake when typing in the above sort of code, probably since that's an additional thing to type vs. my C++/Java habits. Also, don't put the boolean test in parentheses -- that's a C/Java habit. If the code is short, you can put the code on the same line after ":", like this (this applies to functions, loops, etc. also), although some people feel it's more readable to space things out on separate lines.

```
if time_hour < 10: print('coffee')
else: print('water')
```

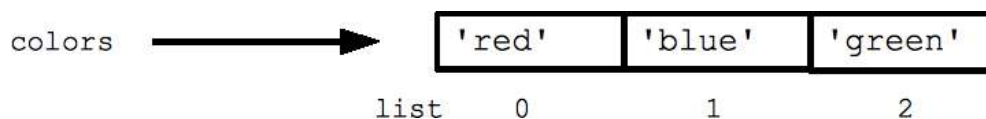
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5. Python Lists

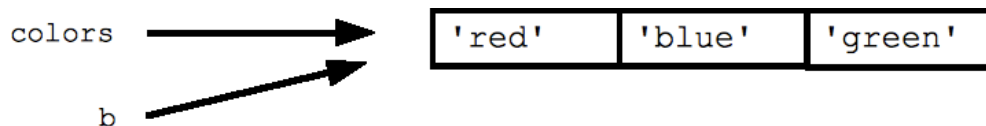
Python has a great built-in list type named "list". List literals are written within square brackets []. Lists work similarly to strings -- use the len() function and square brackets [] to access data, with the first element at index 0. (See the official [python.org list docs](https://docs.python.org/3/tutorial/listsandtuples.html).)

```
colors = ['red', 'blue', 'green']
print(colors[0])    ## red
print(colors[2])    ## green
print(len(colors)) ## 3
```



Assignment with an = on lists does not make a copy. Instead, assignment makes the two variables point to the one list in memory.

```
b = colors    ## Does not copy the list
```



The "empty list" is just an empty pair of brackets []. The '+' works to append two lists, so [1, 2] + [3, 4] yields [1, 2, 3, 4] (this is just like + with strings).

FOR and IN

Python's *for* and *in* constructs are extremely useful, and the first use of them we'll see is with lists. The *for* construct -- for var in list -- is an easy way to look at each element in a list (or other collection). Do not add or remove from the list during iteration.

```
squares = [1, 4, 9, 16]
sum = 0
for num in squares:
```

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```
sum += num
print(sum) ## 30
```

If you know what sort of thing is in the list, use a variable name in the loop that captures that information such as "num", or "name", or "url". Since Python code does not have other syntax to remind you of types, your variable names are a key way for you to keep straight what is going on. (This is a little misleading. As you gain more exposure to python, you'll see references to [type hints](#) which allow you to add typing information to your function definitions. Python doesn't use these type hints when it runs your programs. They are used by other programs such as IDEs (integrated development environments) and static analysis tools like linters/type checkers to validate if your functions are called with compatible arguments.)

The `*in*` construct on its own is an easy way to test if an element appears in a list (or other collection) -- `value in collection` -- tests if the value is in the collection, returning True/False.

```
list = ['larry', 'curly', 'moe']
if 'curly' in list:
    print('yay')
```

The `for/in` constructs are very commonly used in Python code and work on data types other than list, so you should just memorize their syntax. You may have habits from other languages where you start manually iterating over a collection, where in Python you should just use `for/in`.

You can also use `for/in` to work on a string. The string acts like a list of its chars, so `for ch in s: print(ch)` prints all the chars in a string.

Range

The `range(n)` function yields the numbers 0, 1, ... n-1, and `range(a, b)` returns a, a+1, ... b-1 -- up to but not including the last number. The combination of the `for`-loop and the `range()` function allow you to build a traditional numeric `for` loop:

```
## print the numbers from 0 through 99
for i in range(100):
    print(i)
```

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There is a variant `xrange()` which avoids the cost of building the whole list for performance sensitive cases (in Python 3, `range()` will have the good performance behavior and you can forget about `xrange()`).

While Loop

Python also has the standard while-loop, and the `*break*` and `*continue*` statements work as in C++ and Java, altering the course of the innermost loop. The above for/in loops solves the common case of iterating over every element in a list, but the while loop gives you total control over the index numbers. Here's a while loop which accesses every 3rd element in a list:

```
## Access every 3rd element in a list
i = 0
while i < len(a):
    print(a[i])
    i = i + 3
```

List Methods

Here are some other common list methods.

- `list.append(elem)` -- adds a single element to the end of the list. Common error: does not return the new list, just modifies the original.
- `list.insert(index, elem)` -- inserts the element at the given index, shifting elements to the right.
- `list.extend(list2)` adds the elements in `list2` to the end of the list. Using `+` or `+=` on a list is similar to using `extend()`.
- `list.index(elem)` -- searches for the given element from the start of the list and returns its index. Throws a `ValueError` if the element does not appear (use "in" to check without a `ValueError`).
- `list.remove(elem)` -- searches for the first instance of the given element and removes it (throws `ValueError` if not present)

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- `list.sort()` -- sorts the list in place (does not return it). (The `sorted()` function shown later is preferred.)
- `list.reverse()` -- reverses the list in place (does not return it)
- `list.pop(index)` -- removes and returns the element at the given index. Returns the rightmost element if index is omitted (roughly the opposite of `append()`).

Notice that these are *methods* on a list object, while `len()` is a function that takes the list (or string or whatever) as an argument.

```
list = ['larry', 'curly', 'moe']
list.append('shemp')          ## append elem at end
list.insert(0, 'xxx')        ## insert elem at index 0
list.extend(['yyy', 'zzz'])  ## add list of elems at end
print(list)                  ## ['xxx', 'larry', 'curly', 'moe', 'shemp', 'yyy', 'zzz']
print(list.index('curly'))   ## 2

list.remove('curly')         ## search and remove that element
list.pop(1)                  ## removes and returns 'larry'
print(list)                  ## ['xxx', 'moe', 'shemp', 'yyy', 'zzz']
```

Common error: note that the above methods do not *return* the modified list, they just modify the original list.

```
list = [1, 2, 3]
print(list.append(4))        ## NO, does not work, append() returns None
## Correct pattern:
list.append(4)
print(list)                  ## [1, 2, 3, 4]
```

List Build Up

One common pattern is to start a list as the empty list `[]`, then use `append()` or `extend()` to add elements to it:

```
list = []                    ## Start as the empty list
list.append('a')             ## Use append() to add elements
list.append('b')
```

List Slices

Slices work on lists just as with strings, and can also be used to change sub-parts of the list.

```
list = ['a', 'b', 'c', 'd']
print(list[1:-1])           ## ['b', 'c']
```

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```
list[0:2] = 'z'      ## replace ['a', 'b'] with ['z']  
print(list)        ## ['z', 'c', 'd']
```

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6. Summary

Python has become one of the most popular programming languages in the world in recent years. It's used in everything from machine learning to building websites and software testing. It can be used by developers and non-developers alike.



Python, one of the most popular programming languages in the world, has created everything from Netflix's recommendation algorithm to the software that controls self-driving cars. Python is a general-purpose language, which means it's designed to be used in a range of applications, including **data science**, **software and web development**, **automation**, and generally getting stuff done.

Let's take a closer look at what Python is, what it can do, and how you can start learning it.

Python is a computer programming language often used to build websites and software, automate tasks, and conduct data analysis. Python is a general-purpose language, meaning it can be used to create a variety of different programs and isn't specialized for any specific

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problems. This versatility, along with its beginner-friendliness, has made it one of the most-used programming languages today. A survey conducted by industry analyst firm RedMonk found that it was the second-most popular programming language among developers in 2021 [1].

What is Python used for?

Python is commonly used for developing websites and software, task automation, data analysis, and data visualization. Since it's relatively easy to learn, Python has been adopted by many non-programmers such as accountants and scientists, for a variety of everyday tasks, like organizing finances.

"Writing programs is a very creative and rewarding activity," says University of Michigan and Coursera instructor Charles R Severance in his book *Python for Everybody*. "You can write programs for many reasons, ranging from making your living to solving a difficult data analysis problem to having fun to helping someone else solve a problem."

What can you do with python? Some things include:

- Data analysis and machine learning
- Web development
- Automation or scripting
- Software testing and prototyping
- Everyday tasks

Why is Python so popular?

Python is popular for a number of reasons. Here's a deeper look at what makes it so versatile and easy to use for coders.

It has a **simple syntax** that mimics natural language, so it's easier to read and understand. This makes it quicker to build projects, and faster to improve on them.

It's **versatile**. Python can be used for many different tasks, from web development to machine learning.

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It's **beginner friendly**, making it popular for entry-level coders.

It's **open source**, which means it's free to use and distribute, even for commercial purposes.

Python's archive of **modules and libraries**—bundles of code that third-party users have created to expand Python's capabilities—is vast and growing.

Python has a **large and active community** that contributes to Python's pool of modules and libraries, and acts as a helpful resource for other programmers. The vast support community means that if coders run into a stumbling block, finding a solution is relatively easy; somebody is bound to have encountered the same problem before.

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MODULE VIRTUAL REALITY & AUGMENTED REALITY

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Authors	Filip GÓRSKI

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1. Introduction

Virtual reality is a technology that from the beginning of its inception (and symbolically this beginning can be placed in the 1960s) aroused great emotions and hopes related to the potential of simulating physical reality using computer systems. The VR paradigm – the creation of an artificial section of the real or potentially existing world and placing (immersing) the user in this world by means of multi-sensory stimulation – is not only another technology, but even a philosophy and a significant change in the approach to human life and activity. The idea of virtual reality is also well known in fiction and culture - the final incarnation of this technology, conceivable by the human mind, can be used as a tool that completely changes human existence. Ideas such as transhumanism, neural connections or even transferring the human mind and consciousness to a computer system come directly from the concept of VR and its implications.

The largest manufacturing concerns in the automotive and aeronautical industries set the direction of digital design and manufacturing a couple of decades ago. New products are created and tested in the digital space, starting from visual 3D modeling through virtual prototyping to design in CAx (computer aided technologies) systems [Gorski 2019]. A closely related area is virtual planning and optimization of production processes, especially taking into account the human factor, which is relatively difficult to control in physical, real-world conditions. Virtual design and prototyping is possible thanks to the use of virtual, augmented and mixed reality technologies. Virtual reality, i.e. computer simulation with the involvement of human senses (immersion), is a technology used successfully in the manufacturing industry for many years, and the first implementations can be noted as early as the late 1990s [Bell & Fogler 1995, Biocca & Delaney 1995]. Augmented and mixed reality, i.e. overlaying of 3D and 2D data on the image of the real world, has also been known and used since the late 1990s [Martin-Gutierrez et al. 2017; Azuma 1997].

Virtual reality is distinguished from other human-computer interaction methods by 3D graphics striving at realism, intuitive interaction and user immersion inside the digital scene [Gorski 2019]. Immersion is a feeling of being present inside an artificial environment, despite physical presence in the real world [Bowman 2007], and is achieved mostly by use of various stereoscopic projection devices, such as head-mounted displays (HMD) or CAVE systems [Cruz-Neira et al. 1993], joined with user tracking solutions for enhancement of

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feeling of presence inside the virtual world. Virtual Reality, along with Augmented Reality (AR) and Mixed Reality (MR) create the spectrum of XR (eXtended Reality) technologies, widely used in professional and recreational applications.

Although virtual reality has been known for decades, it has gained considerable recognition and has found a wide range of professional applications in the last decade. Several years ago - i.e. since the middle of the second decade of the 21st century - a certain revolution in the field of virtual reality happened. In the last few years, affordable virtual reality devices have debuted on the market, providing industry-acceptable quality in operation, and at the same time costing much less than previously available professional and expensive systems. This scale of potential savings made virtual reality (as well as mixed and augmented) techniques interesting for smaller and medium-sized enterprises, and large corporations began to use it to a wider extent. Development on the hardware side, however, would not be of much use if it were not for software development. Here, too, in recent years, significant, beneficial changes can be noted - the most popular tools for creating content in virtual reality have clearly become cheaper or are available completely free for individual users and small businesses. The ways of building applications are also rapidly evolving – writing very complex code is no longer required, visual programming methods are readily available, and online libraries of existing scripts and code are growing thanks to the growing community of VR developers [Gorski 2019].

A VR environment can heavily influence behavior and feelings of a user and can be used for teaching knowledge and skills. The positive educational effect of VR has been observed and reported in literature as early as the 90's [Bell & Fogler 1995] and proven in further studies [Velev & Zlateva 2017, Abdul Hadi et al. 2011], both in industrial applications [Gorecky et al. 2017], general education [Symonenko et al. 2020, Southgate et al. 2019] and medical education [Kyaw et al. 2019]. The same applies to AR and MR [Martin-Gutierrez et al. 2017; Martin-Gutierrez & Meneses Fernandez 2014]. There are many different possibilities of use of VR in medical education, from simple applications that can replace a book, such as virtual anatomical atlases [Falah et al. 2015, Hamrol et al. 2013], to more complex presentations, such as applications for full, realistic simulation of surgical procedures [Zhang et al. 2012]. For realistic simulation, haptic devices with force simulation are frequently used, as it allows trainees to develop required abilities before first contact

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with a real patient [Escobar-Castillejos et al. 2016]. There is also a considerable amount of therapeutic applications, both in the field of psychotherapy [Bun et al. 2017; Boeldt et al. 2019], physiotherapy [Brepohl & Leite 2022] and pain management [Perry et al. 2018].

This e-book focuses on basics of XR technology – definitions, concepts, types of hardware and basic processes in software development.

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2. XR technology – basic concepts

2.1 Basic definitions

2.1.1. Virtual Reality

The classic definitions of VR are given below:

Grigore C. Burdea: A high-end user interface that involves real-time simulation and interaction through multiple sensorial channels (vision, sound, touch, smell, taste) [Burdea & Coiffet 2003]. In Polish, this definition can be presented as: An extensive user interface that allows real-time simulation and interaction through multiple sensory channels (image, sound, touch, smell and taste).

Steve Bryson: Virtual reality is the use of computer technology to create the effect of an interactive three-dimensional world in which the objects have a sense of spatial presence [Bryson 1999]. In Polish, the definition is: Virtual reality is the use of information technology to create the effect of an interactive three-dimensional world in which each object has a sense (property) of being present in this space.

Reducing the above definitions to simple concepts, it can be said that virtual reality is the use of a computer (digital technology) in order to achieve the effect of "transferring" the user (or rather his consciousness) to a different place than the one where he is in reality. The VR user must therefore somehow be placed in the so-called virtual environment (VE), created using three-dimensional computer graphics, and be able to interact with elements of this environment [Gorski 2019].

VR specialists often use the so-called I3 triangle to refine the basic definition. This triangle is shown in Fig. 2.1 - it contains three key features without which VR currently does not exist. These are:

- immersion (ang. immersion),
- interaction,
- imagination.

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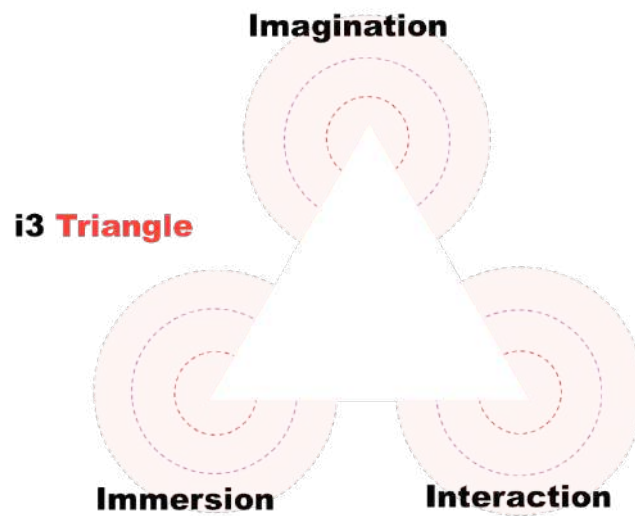


Figure 2.1 i3 Triangle, on the basis of [Burdea & Langrana 1993]

Interaction is the influence made by user on the digital world around them and vice versa - the behavior of objects of the digital world that forces action on the part of the user. Interaction is a necessary condition for VR technology, but not a sufficient one. Its basic assumption in VR is intuitiveness, i.e. the minimum need to learn how to use artificial interfaces - the use of gesture recognition techniques, voice recognition, natural movements and human behavior.

Immersion in VR systems is a concept that can be most easily described as the feeling of being physically present in a non-physical world, created digitally. It has been assumed that this is a feature assessed only subjectively by the user using a given VR system - there is no uniform standard for evaluating immersion (i.e. the ability to evoke a feeling of immersion) other than a subjective survey assessment. Immersion is related to cutting off sensory stimuli coming to the user from the real world and replacing them with compatible stimuli from the digital world (Fig. 2.2). Immersion can be defined as a sufficient condition for the existence of virtual reality.

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Figure 2.2 Immersive interactive VR system users

Imagination – as an element of VR – is a concept that assumes imperfection of hardware and software methods of inducing immersion in the user. Simply put, an ideal VR system does not require the use of imagination from the user. However, at the same time it is assumed – at the current level of technology development – that a perfect system does not exist now nor will it be built in the near, foreseeable future. Hence, the deficiencies of multi-sensory stimulation must be supplemented by the user to varying degrees by using their own imagination. It can be defined in a different way as the “good will” of a user – in a situation where the use of VR is enforced, its effectiveness will be much lower.

2.1.2. Augmented and Mixed Reality

Augmented reality was defined and described by Ronald Azuma in the late 1990s. It is characterized by the following features:

- real and virtual images are combined,
- the virtual image is interactive, the user influences its behavior,
- virtual images are fixed in the real image permanently [Azuma 1997].

Unlike virtual reality, AR user does not experience immersion. The real world is always in user's field of view, and interactive virtual images refer to the elements of this world, becoming its integral part. VR is designed to replace physical reality, and AR - to expand its

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perception. To perceive augmented reality, solutions such as helmets are not always needed - often displays held in the user's hand are enough.

The concept of immersion in AR is replaced by the broadly understood concept of realism of the presented digital objects – they should be integrated with real objects as smoothly as possible, constituting a single whole in the eyes of the user. Then the effect of using AR in training or designing will be the greatest.

Mixed reality (MR) is an idea similar to augmented reality, with the exception of the third assumption of AR, which is the constant connection of digital models with elements of the real world. In MR technology, there is no such connection – the displayed digital objects can be freely moved by the user and are not contextually related to the real environment in which they are displayed. Visualizations in MR are often referred to as holograms. A hologram is a 3D/2D object freely placed in real space by the user and remaining in the place chosen by him while using the application. The concept does not function in AR.

The distinction between MR and AR is shown in Fig. 2.3. The lack of spatial context gives freedom in choosing the environment in which digital content is displayed.



Figure 2.3 Difference between AR (left, [Meredith 2017]) and MR (right, [wired.co.uk])

Mixed Reality can also be divided into two conceptually different classes:

- "virtual" mixed reality – closer to VR by concept, with the user's focus mainly on digital content, without any connection to real-world objects; the view of the real world is needed only so that the user does not lose contact with it; examples are various interactive educational visualizations or games,

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- "real" mixed reality – closer to AR by concept, with a focus on integrating holograms with the real world - an example can be applications for virtual arrangement of a real space (e.g. surgery room or factory).

2.1.3. XR technologies – similarities and differences

All virtual technologies create the so-called XR spectrum – a continuum in which the real world and the completely digital world are at the extreme positions. The continuum by Milgram et al. [1994] is shown in Figure 2.4.

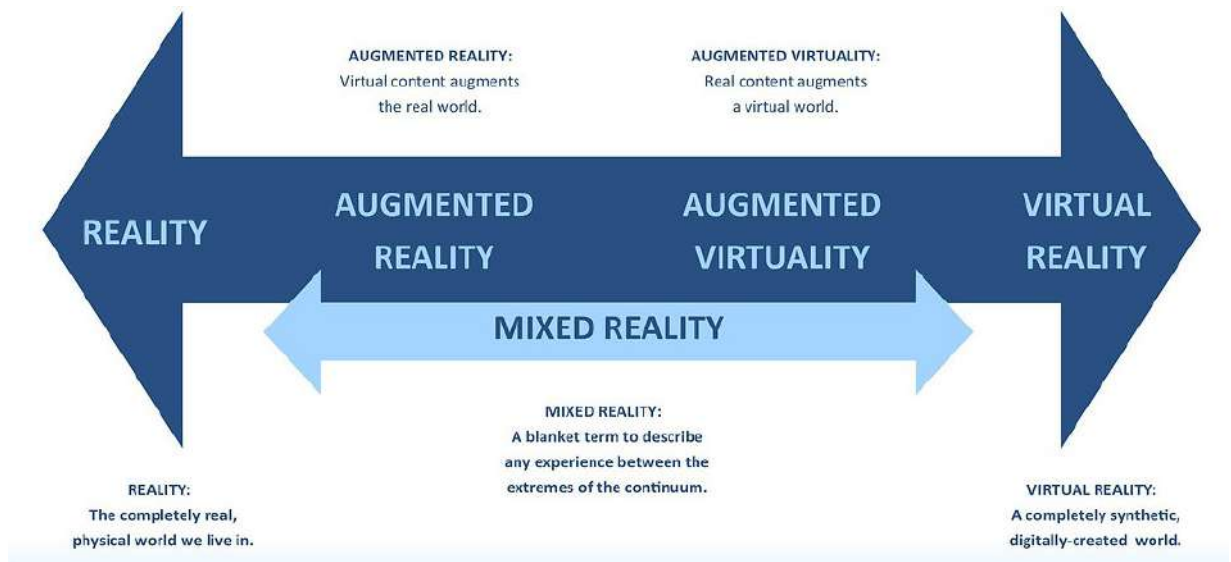


Figure 2.4 Milgram's XR continuum [Milgram et al. 1994]

Nowadays, of original Milgram's continuum, VR, AR and MR are the three prominent technologies, with augmented virtuality not considered as a separate class of XR technology. The most important distinguishing features of each XR technology are presented below:

- Virtual Reality - only the digital world is perceived, user cut off from the real world,
- Augmented Reality – the real world is enriched with digital elements in specific places,
- Mixed Reality – the connection and mixing of the virtual and real world, the real world in the background to the virtual simulation.

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The diagram in Figure 2.5 shows the common and distinctive features of all main XR spectrum technologies.

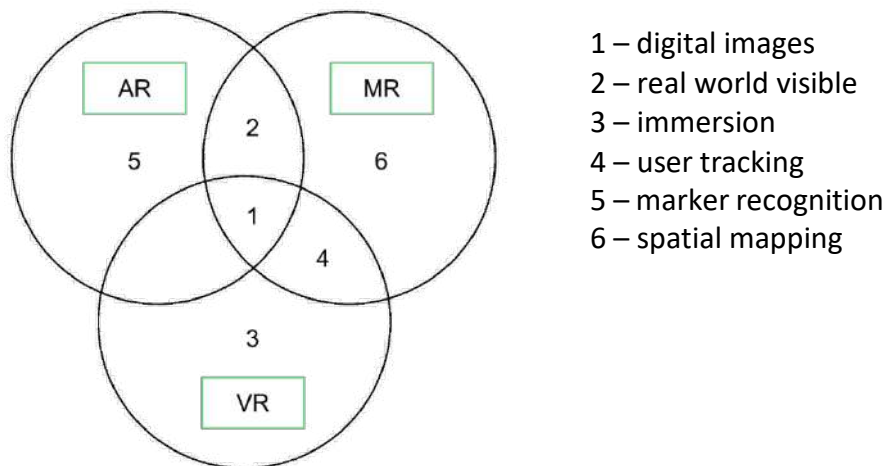


Figure 2.5 Common and distinctive features of main XR technologies

2.2 XR systems

2.2.1. Definition, structure, classification

Taking into account the requirements and the most important features of extended reality technologies, a virtual reality system can be defined as a properly configured and interconnected hardware and software (application) enabling the performance of a digitally generated (computer) simulation with the involvement of the senses (immersion) of the user-human, with the fulfillment of the assumptions of interactive interaction and immersion. Even very early scientific publications in the field of VR [Biocca & Delaney 1995] define a VR system as a technical device, where in the center there is a computing unit (computer or a set of connected computers) generating a simulation (software), combined with hardware enabling both input and output of the user. The basic input/output channels are shown in Fig. 2.6. The division into hardware and software components in groups proposed by the author is presented in Fig. 2.7.

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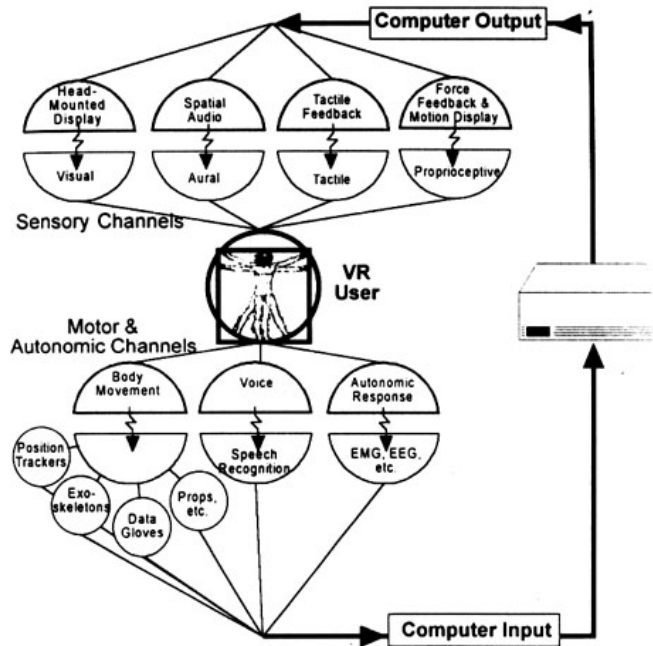


Figure 2.6 Basic input/output channels of VR system [Biocca & Delaney 1995]

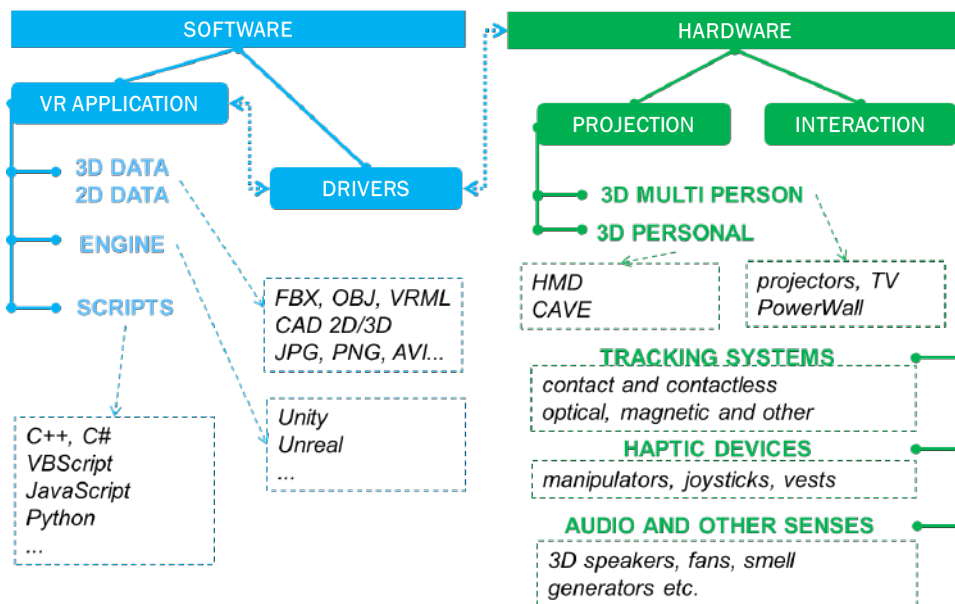


Figure 2.7 Basic hardware/software components of VR system [Górski et al. 2017]

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Virtual reality systems can be divided into the following classes:

- standing position, with the ability to dynamically change it and move on their own feet within a defined position tracking area; here, helmets or CAVE class devices coupled with gesture tracking and recognition systems are most often used, without haptic devices – due to their stationary nature,
- desktop VR, where a single user uses the VR system in a seated position, using projection devices located on a regular desk – these can be 3D monitors or goggles without the full range of position tracking, often the system is supplemented by haptic devices with a small or medium working space,
- projective VR, where the XR system is used by one or many users at the same time, using large-screen projection devices, most often in a standing position, although often without tracking the location of users; interaction can be based on tracking systems, gesture recognition and haptic devices with a larger working space.

Augmented and mixed reality systems, can be classified as follows:

- immersive AR/MR - where the user uses the system freely wearing goggles or glasses (optical see-through or video see-through), as in the case of immersive VR, with the possibility of free movement (wireless) and interaction, most often with free hands (gesture and voice recognition),
- handheld AR/MR – where the user uses a tablet or mobile phone device, holding it in his hand, observing the surroundings through the camera in the device, and visualizations superimposed on the image from the camera,
- stationary AR/MR - where the user, as a rule, works in a limited space, having a stationary display (TV, projector) at his disposal, or goggles connected with a cable; motion tracking can be done by stationary systems, and the interaction is tactile or via gesture recognition / voice control.

2.2.2. Hardware

A typical consumer VR system consists of a helmet and two motion controllers. In addition, the operation of such a system can be extended by using additional motion sensors

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placed, for example, on the feet, on the trunk or on auxiliary objects. Controllers can also be replaced with immersion gloves, i.e. devices that faithfully transfer users' finger and hand movements to the VR system.

The VR helmet is the basic device used to perceive virtual reality. The term *Head-Mounted Display* (HMD) is most often used, meaning a projection device placed on the head. The term *VR goggles* is also used, i.e. VR goggles, or simply *VR headset*. Due to their construction, VR helmets can provide the user with the strongest immersion experience among the available projection solutions [Górski 2019]. An example of a helmet is shown in Fig. 2.8.



Figure 2.8 Example of a VR headset – HTC Vive Pro – with controllers and base stations [vive.com]

Helmets are certainly the most classic VR hardware solution, identified with this technology. However, it should be remembered that there are also other projection solutions in VR systems, e.g. large-screen multi-person projection systems or CAVE class systems [Cruz-Neira et al. 1993].

VR headsets were originally purely projection devices – meaning that from a communication point of view, only the image is sent to them and no data is received. The current generation of helmets most often includes built-in markers of the tracking system, enabling real-time tracking of the position of the wearer who uses the helmet. Currently, VR headsets do not function completely independently – they are usually sold in a set with motion controllers, also equipped with a tracking system markers (in-built). This means that after purchasing such an integrated set (headset and controllers), the user is ready to go – the appropriate software is all it is needed to start working in VR.

Controllers are wireless devices that combine motion tracking functionality with the functions of traditional input devices such as a joystick, keyboard or trackpad (touchpad).

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Controllers are usually held in hands and therefore disturb the natural interaction principle in VR, because it is required to learn, for example, the arrangement and functionality of buttons in a given application. However, learning time is usually short and they significantly facilitate the preparation of the application and its use by different people. The position of the controllers is usually reflected in the application by their virtual counterpart or simply by dynamic image of the user's hand (Fig. 2.9).



Figure 2.9 VR controller example, with its virtual representation [oculus.com]

An alternative to using universal methods of interaction (i.e. controllers) are dedicated solutions, i.e. physical objects with a shape dedicated to a given application (e.g. assembly tool, surgical tool, etc.), equipped with markers of tracking systems. This means that a physical object has its representation in VR, and the user can put these objects away and pick them up according to the needs and scenario of a given application (Fig. 4.22). This approach is often referred to as *Tangible User Interfaces*, or TUI for short [Harley et al. 2017]

Solutions that enable more intuitive interaction (gloves, armbands, etc.) require calibration for each user to maintain tracking accuracy and repeatability. Immersion gloves or bands can work on the principle of resistive bending sensors, optical fibers or muscle conduction testing. They are not standard devices and nowadays are gradually replaced by optical systems for hand tracking for most applications – excluding applications where high precision of finger maneuvers is needed (such as precise surgical simulators).

In the case of AR/MR devices, the following types of equipment used to receive AR/MR content should be distinguished (according to the previously mentioned system categories):

- 2D and 3D smart glasses,
- optical see-through helmets / goggles (Figure 2.10),

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- video see-through helmets,
- tablets and smartphones,
- holographic displays (Figure 2.10),
- projectors and TVs.



Figure 2.10 Examples of mixed reality devices – holographic goggles [microsoft.com] and a holographic display [3dholodisplay.com]

2.2.3. Software

VR applications are usually built using 3D engines for creating interactive applications and games. The 3D engine is a programming tool that includes a graphics engine (renderer), a programming language implementation and a user-friendly interface that allows you to manage the structure and functions of the created application. The main features that distinguish work with 3D engines from work in e.g. CAD systems, graphic modeling systems or pure programming environments are [Górski 2019]:

- representation of 3D geometry in the form of a polygon mesh, without parameterization,
- no geometric constraints between 3D objects, only hierarchy and grouping constraint exist (parent-child),
- 3D objects represented by three connected components: mesh, material and a frame that gives position, orientation and scale (transform),
- positioning objects in 3D space using three vectors: position, orientation, i.e. the so-called Euler angles and scale,

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- no possibility to create and edit parametric 3D models and 2D graphics in the engine, except for geometric primitives (cube, cylinder, sphere, etc.) and exceptional situations (e.g. terrain editor, special plug-in solutions),
- programming consisting mainly in creating mutual references between individual objects and their groups in a given “scene” (i.e. level),
- available library of predefined (built-in) components and the ability to create users’ own components, most often by writing scripts in the selected object-oriented programming language,
- objects (components) of a given scene with specific properties that can be changed from the editor level or dynamically from the simulation level,
- work in two modes: developer (scene editing: adding and arranging components, editing properties and programming connections) and test (simulation reflecting the user's point of view, most changes are not saved permanently),
- saving the finished application in the form of an executable file that can be run as a standalone application on a computer or other device that meets specific hardware requirements,
- the presence of an online community (portal, e-shop) for free or paid exchange of created components, scripts, 3D objects, ready-made scenes and plugins that change the operation of the engine.

The following common interface features of most 3D engines can be distinguished [Górski 2019]:

- tree of the structure (hierarchy) of a 3D scene being built – it is an interface element containing a hierarchical structure of all objects in a given scene,
- object properties panel – a place where the properties of individual objects can be changed, or their internal structure (sub-components) modified,
- component toolbox, library – a place from which individual predefined or custom components or their whole sets can be added to a given scene,
- 3D scene preview,
- switch between development and test (play, game) mode,

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- console (log) - a place where errors and messages are displayed when compiling the solution,
- script and/or logical connection editor, if visual programming methods are available.

Examples of engines include Unity or Unreal Engine. User interface of the most popular engine – Unity – is shown in Fig. 2.11

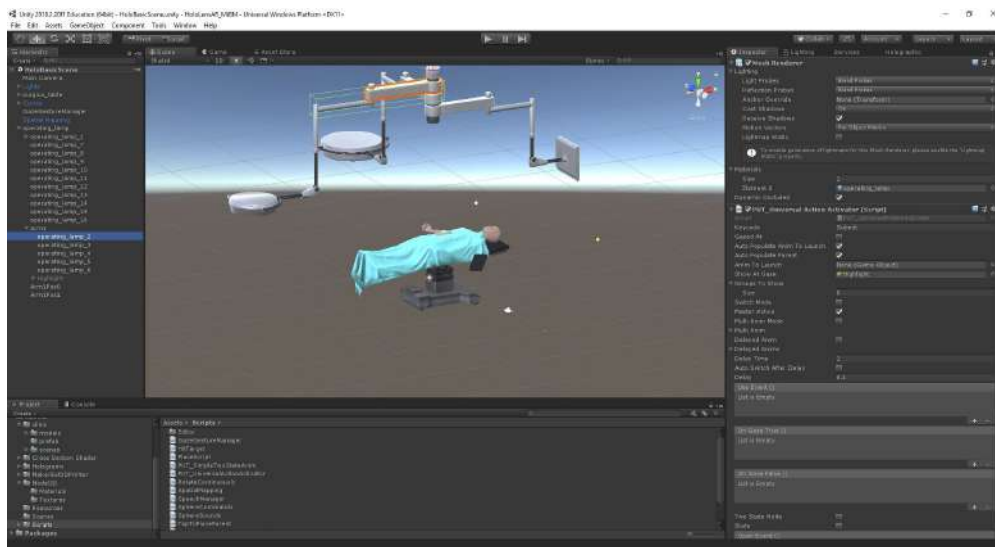


Figure 2.11 Unity game engine

2.3 Applications of XR technologies

The task of VR systems (partly also AR and MR) is to realistically simulate a specific section of existing or theoretically possible reality, with the effect of immersing a person in the simulation - assuming this assumption, VR can be used in virtually every aspect of professional activity and everyday human life. There are certain groups of virtual reality applications where its advantages allow for a particularly significant increase in the efficiency of certain processes. These are:

- general engineering: mechanical (machine building), production, construction, electrical, etc.,

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- education and training - both in terms of school (children and youth) and professional (e.g. in combination with engineering, training for company employees),
- medicine and medical education – for doctors and patients (rehabilitation, therapy),
- military - military engineering, training and training, military medicine,
- entertainment - computer games, interactive animations and experiences that are not games.

The successful use of VR in education is related to the positive impact of immersion on the assimilation of new content by users, found as early as in the 1990s [Bell & Fogler 1995]. VR in education and training is one of the main areas of application of this technology, which receives a lot of attention in the world [Martin-Gutierrez et al. 2017]. Applications may concern both school education – primary, secondary – and higher education (e.g. in relation to engineering or medicine) and professional training (e.g. technical training or even soft skills). Effective industrial training using VR is one of the methods of increasing production efficiency in industrial enterprises implementing the Industry 4.0 concept [Romero et al. 2016; Schroeder et al. 2017]. More information on VR in education and training and validation of knowledge is presented later in this study.

The application of VR in classical engineering (Fig. 2.12) often boils down to the so-called virtual product, mainly to support the design and virtual prototyping of a new product and its subsequent efficient introduction into production and on the market. Typically, a division can be made into product-centric and process-centric applications.

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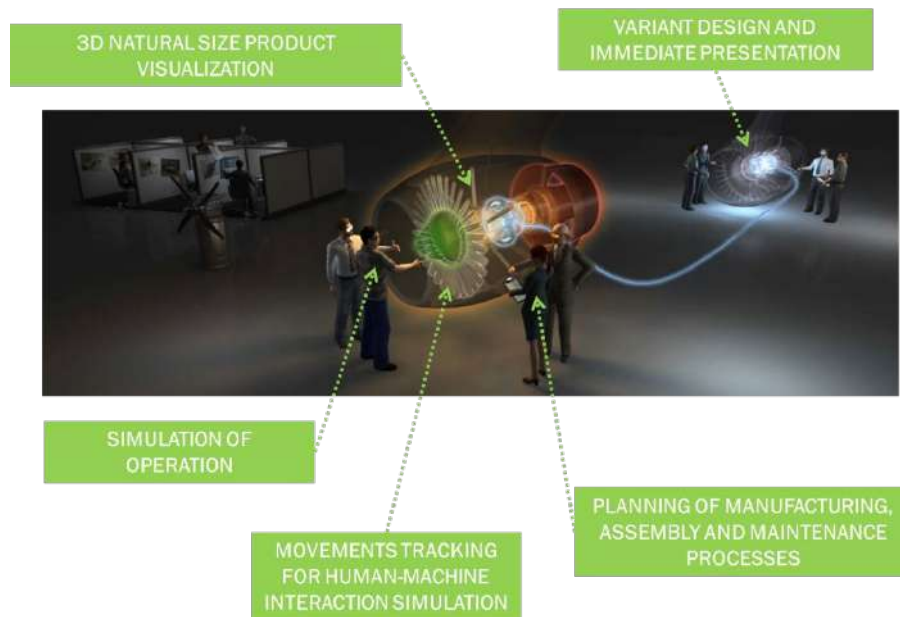


Figure 2.12 Applications of VR in engineering, based on [Górski 2019]

Medicine, medical engineering and related issues are also one of the most important directions of application of VR techniques [Riener & Harders 2012]. Medical VR applications can be divided depending on the target groups - for doctors and students, educational and training applications will be primarily intended (mainly allowing for learning issues related to human anatomy, physiology and pathophysiology, as well as methods of conducting procedures and operations). For patients, however, there are special applications supporting the rehabilitation process or acting in a therapeutic way (a term such as Virtual Reality Exposure Therapy - VRET [Buń et al. 2017] can be distinguished).

In the military, VR is used in several versions - to support the design of new military equipment, for training and tactical training [James 2015] or for therapy of soldiers, e.g. as a result of post-traumatic stress disorder (PTSD) [Rizzo et al. 2017]. Military VR systems differ from civilian ones in terms of technical requirements, especially in terms of tracking and display accuracy, resistance to loads and changing conditions of use, and ergonomics of use.

The VR industry is developing dynamically mainly thanks to the most common application - entertainment. Various computer games can be distinguished here, where the effect of the player's involvement in the game is enhanced by appropriate interaction and immersion devices. There are also shorter and longer forms of interaction in VR that are not

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games - they are referred to as *experiences* . They can be used, for example, to get to know new places (virtual tourism), history (virtual museums and historical stagings) or works of art (virtual art installations).

Examples of VR applications in medicine and military are shown in Fig. 2.13.



Figure 2.13 Examples of VR use in medicine [medscape.com] and military [James 2015]

When it comes to related technologies, i.e. AR or MR, their applications often complement VR applications. For example, in terms of training, employees (e.g. machine operators, but also doctors or pilots) can be trained with the use of VR before starting work, while training with the use of AR can be undertaken already in the physical workplace (production line, operating room, cockpit, etc.). Both types of training can be used separately or sequentially, depending on the needs. The use of AR in designing can also be treated as a supplement to the original VR support - in VR it will be the visualization of a physical object that does not yet exist, and in AR - the visualization of new, proposed features of an already created object or prototype. There is also a whole range of AR applications that use the specific advantages of this technology [Górski 2019; Downey 2016]. Examples of AR and MR applications are shown in Fig. 2.14.

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Figure 2.14 AR and MR applications [skanska.pl] [Downey 2016] [Kaminsky 2019] [fashionbi.com]

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3. XR technologies in biomedical applications

3.1 XR simulation and application - definitions

Simulation can be defined as an artificial reproduction of the properties of a given object or phenomenon using its model. There are two main types: “hard” simulations, i.e. based on analytical solutions of equations describing given physical phenomena, and “soft” simulations, built on the basis of empirical formulas being the results of laboratory experiments.

Virtual, or mixed reality (or, in general, XR) simulation can usually be described in basic terms as hard simulation - it contains visual representation of a certain fragment of reality, described by basic equations of the laws of physics (equations of kinematics, Newton's laws of dynamics, gravity, etc.). However, it may contain elements of soft simulation, e.g. particle effects, liquid material flow effects, etc.

A computer program containing a XR simulation is referred to as a "XR application". The concept of application can be understood as a closed entity in the grammatical, logical and functional sense; an application is a program containing an executable file that requires a selected operating system and specific hardware.

An application (simulation) of virtual reality, to be named in this way, must have certain features and functions resulting directly from the definition of virtual reality. In particular, these are:

- immersion and realism,
- three-dimensional, dynamic 3D graphics,
- free navigation and interaction.

The realism of a VR application can manifest itself in various ways, almost never in its entirety (at the current moment of development of computer systems, it is practically impossible even for not very complex systems of objects). It is generally assumed that the virtual environment reflects a selected section of the real or theoretically possible world. Even in entertainment applications presenting unreal, often abstract situations, realism is sought at least in the sphere of basic physical phenomena affecting the user's character, e.g. the aforementioned gravity, Newton's laws of motion, etc. If a given VR application is

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described as "realistic", it always needs to be specified in which sphere this realism is manifested. These may include aspects such as [Górski 2019]:

- realism of graphics (in the case of achieving a near-perfect state, indistinguishable from physical reality, the term "photorealism" is used),
- realism of the situation (representation of physically existing or possible objects and related processes, activities, etc.),
- realism of physics (representation of physical laws and phenomena - Newton's laws of motion, laws of universal gravitation, friction, magnetism).

Three-dimensional graphics means that the virtual environment (what a XR application user sees and feels) has been digitally generated, based on three-dimensional vector graphics. The term "3D model" is used here, which means a three-dimensional geometric representation of a given object saved in a digital way, most often as a set of points (vertices) located in space and connected by lines forming polygons, curved surfaces, etc. The term "dynamic" means that individual, selected elements of the virtual environment may independently change their position and shape (as well as other features, e.g. color) in real time when using the application - this is necessary to meet the second of the distinguishable features, i.e. free interaction.

Free interaction combined with navigation means that the user can explore a virtual environment and take actions of their choice using the objects in this environment. For production systems, for example, a virtual assembly station is where the user must be able to move around the station, pick up and drop parts, and use tools to make connections. These activities should correspond to reality to the maximum extent, taking into account the purpose of using a given VR application – if it is, for example, a training application, it is reasonable to introduce some simplifications that will make it easier for novice trainees to carry out the process.

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3.2 *Designing VR/AR applications for medicine and biomedical engineering*

3.2.1. Requirements and types of applications

Concepts in this and subsequent chapters are mostly based on earlier works by the author and his scientific team, mostly [Górski 2019, Górski et al. 2017, Buń et al. 2017, Hamrol et al. 2013] and others.

Each professional virtual reality application contains a specific amount of knowledge available to its user. The amount of this knowledge and its types determine the level of complexity of building the system that is to provide it, and therefore are crucial when formulating technical requirements and carrying out works related to building the system.

It is proposed to divide educational VR applications into three basic levels according to the type of knowledge they contain (Fig. 3.1) [Górski et al. 2017]:

1. Level 1 – general knowledge. At this level, general information about a given object or process is presented: appearance (visualization, animation), construction (structure), basic variability. Their equivalent among traditionally used sources of knowledge may be a book or a catalogue. Applications from this level are, for example, simple interactive visualizations of processes or three-dimensional illustrations of facts or information to assimilate.
2. Level 2 – procedural knowledge. At this level, the user can gain knowledge about the sequence, i.e. the algorithm that must be used in a given case. With regard to traditionally used sources of knowledge, this level corresponds to a manual or manual. Applications from this level are very popular, they include virtual instruction manuals or presentations of various processes.
3. Level 3 – practical skills. At the highest level, the user can acquire specific practical skills, even reaching the so-called muscle memory. Here, mainly activities performed manually are considered, e.g. controlling machines, performing operations and medical procedures, etc. The physical equivalent of using such an application is practical exercises - working with a real object or process. Applications at this level include virtual trainers (e.g. of surgical procedures) or ergonomic workstation simulators. They are mainly used for training, but they are also used in the virtual design of machines, devices and whole systems.

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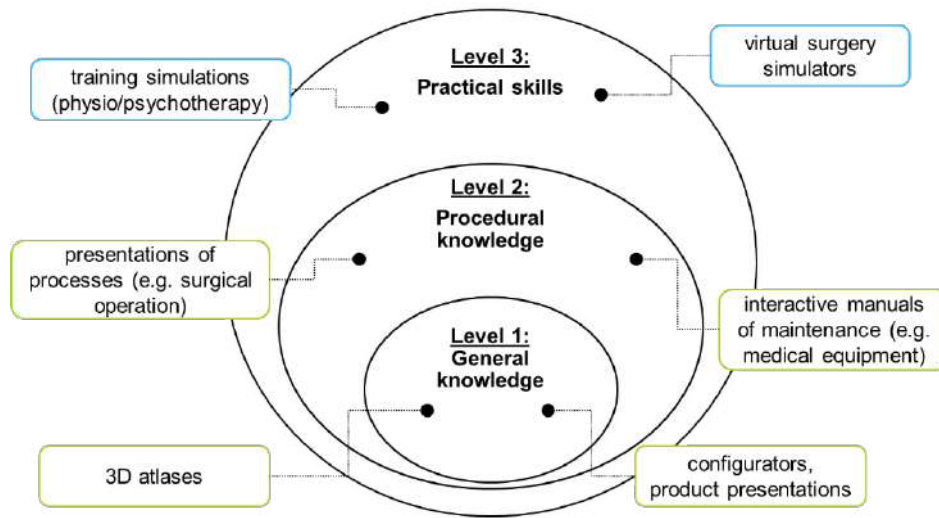


Figure 3.1 Levels of XR applications by knowledge [Górski et al. 2017]

The levels of knowledge can be also referred to expertise of expected user group of a given application. An attempt of mapping the three distinguished levels to classes of potential users of medical XR applications is presented in Fig. 3.2.

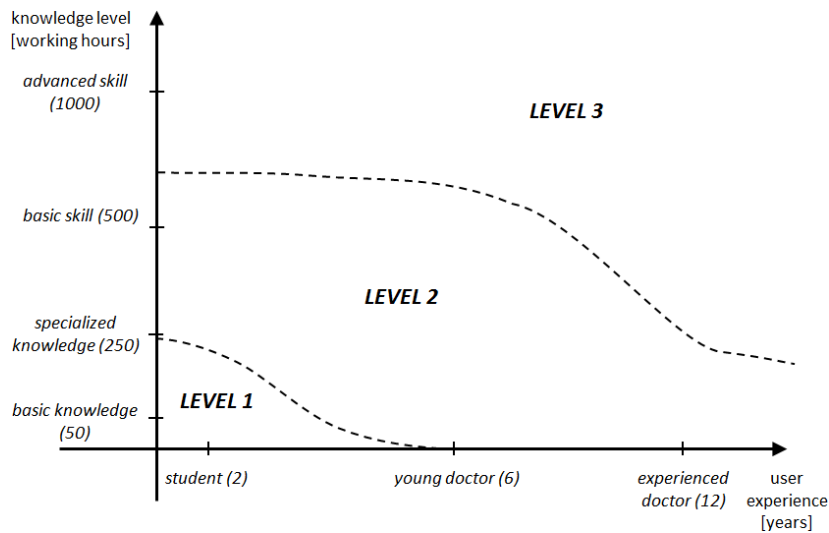


Figure 3.2 Levels of XR applications and mapping to specific user classes [Górski et al. 2017]

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Each application level has different technical and organizational requirements. These requirements are presented in Table 3.1. The levels of knowledge in the application therefore determine the use of appropriate technical means and the need to reach for the so-called “hidden knowledge”, i.e. possessed by specialists in a given field and not registered in a formal way.

Table 3.1. Requirements of applications of different knowledge levels [Górski et al. 2017]

Features/requirements	Level 1	Level 2	Level 3
Visualization	Static – pre-rendering (possible static images and pre-rendered sequences)	Kinematic – real-time rendering (3D engine, live animation)	Dynamic – real-time rendering with object deformations
Human tissue data form	Illustrative (3D modeled by graphic designer with no medical imaging)	Selected cases (modeled on the basis of pre-selected patient data from medical imaging)	Real data (data from CT scans or other medical imaging, processed for better visualization)
Animations	Simple, pre-rendered	Rigid bodies – real-time, deformations – pre-rendered	Both rigid and deformable bodies in real time
Object manipulation and interaction methods	Mouse, keyboard, graphical user interface, gestures	Graphical user interface, gestures, tracking	Graphical user interface, gestures, tracking, haptic manipulation with force feedback
Collisions and force feedback	Unnecessary	Beneficial	Mandatory if no physical props
Full immersion (HMD)	Beneficial	Needed but not mandatory	Mandatory if no physical props
Required tracking and force accuracy	Low or N/A	medium/low	high
Required computing power	low/medium	medium/high	high
Participation of specialists - medical doctors	Planning stage - definition of requirements	Planning and building stage – sharing procedural knowledge	Planning, building and verification – recording of procedure

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3.2.2. Process of VR/AR/MR application design

In the effective building and implementation of professional (industrial and medical alike) XR applications, the human factor is very important, which should be taken into account especially at the first stages of system development. It is reasonable to use the tools and methods of development and introduction of innovations available in the literature. The XR application development cycle, taking into account this assumption (based on earlier works), is shown in the diagram in Fig. 3.3. The cycle is based on available knowledge management methodologies, such as MOKA [Gorski 2017].

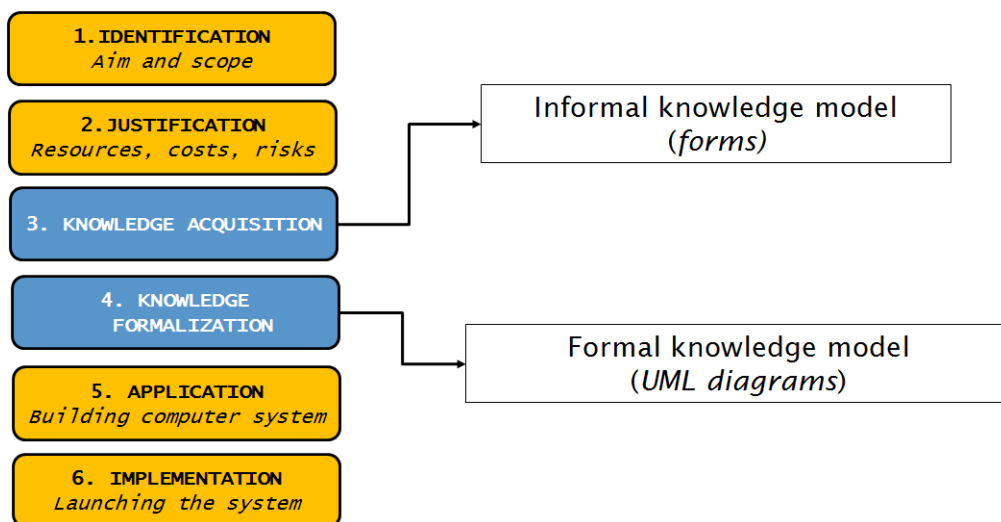


Figure 3.3 Stages of XR application design and preparation process [Górski 2019]

The first stage of designing a XR application can be described as the identification. It involves providing detailed answers to three key questions:

1. Who will be the recipient of the application?
2. What problem does the recipient face?
3. What value should the application provide to the recipient?

At the identification stage, it is therefore most important to define the so-called target group, i.e. the group of direct recipients of the XR application. Then, the technique of empathizing should be used, i.e. analyzing the situation from the point of view of a given person or group of people. It is a technique taken from the Design Thinking methodology, used in the development of innovations. The author, based on previous experience,

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recommends the use of Design Thinking elements in the development of XR educational simulations. This stage of work should end with the development of the application concept. The second stage of application design is called justification. On the basis of the concept formulated in the first stage, it is necessary to proceed to detailed planning of its implementation, justifying the business model of the application. The actions taken at the justification stage are therefore mainly aimed at specifying the concept and defining the risk.

In particular, the following works should be undertaken [Górski 2019]:

1. Determination of potential sources of knowledge and its possible forms.
2. Assigning human resources to build the application (working team on the side of the VR developer and in the institution implementing the simulation).
3. Determining the hardware and software components of the system necessary for its construction in accordance with the concepts of MVP (Minimum Viable Product [Ries 2009]) and MAYA (Most Advanced Yet Acceptable) [Thompson 2017] concepts.
4. Determining the time frame for the building and implementation of the application.
5. Risk calculation, final decision (starting or discontinuing the development process).

The third stage of application design consists in collecting and formalizing the knowledge that will be used to implement the solution. Knowledge acquisition is a process in which the following stages should be implemented:

1. Identification of the subject of interest.
2. Identification of sources of knowledge, determination of the type of knowledge (explicit/hidden).
3. Determining the method of knowledge representation.
4. Acquisition of knowledge and its recording.
5. Verification of the obtained knowledge base.
6. Supplements - expansion of the knowledge base.
7. Validation of the knowledge base [Zawadzki 2016].

Recording knowledge at the stage of its acquisition does not yet mean giving it a formal form - this step takes place only in the next stage of work, usually already during programming in the 3D engine. Nevertheless, the structure of the informal knowledge base should be as simple as possible, and the record of knowledge should be complete, understandable and unambiguous. The acquired entities of knowledge should be ordered

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and properly described, so that the context of their acquisition and purpose are known. The methods of knowledge acquisition, its sources and the accuracy of the recording should be adapted each time first to the level of the application (1, 2 or 3), and secondly - to the most important target group of application recipients and the problem in which it is to help. Gathering knowledge is a process that can be supported by Knowledge Engineering techniques, widely described in the literature [Schreiber 2012].

After the planning of the application is completed and the necessary knowledge has been gathered, the design stage can be considered completed. The next stage is associated with programming work and can be described as knowledge implementation, i.e. building a specific application (simulation) containing specific content.

3.3 Building medical VR/AR applications

3.3.1. XR application development process

The application development process can be conventionally divided into 3 main phases, often realized in parallel [Górski 2019]:

1. Visualization.

In this phase, the main goal is to obtain a three-dimensional visualization of objects that will be the main subject of action in the prepared interactive application. This phase includes activities from the preparation and optimization of 3D data, their import, through giving the appropriate visual features, to providing a method of navigation in a virtual environment so that the perception of 3D models from any perspective is possible. This phase should be finished when the highest available and desired level of graphic quality of all 3D objects that will be the subject of the application is obtained. The visualization phase includes also manipulations related to the hierarchy of objects in the scene tree (parent-child relationships) and assigning a navigation system, i.e. the way the user moves around the scene. The milestone of the visualization phase is obtaining a non-interactive, three-dimensional visualization, i.e. the so-called virtual walk - objects composed and displayed in the assumed quality, already on the appropriate projection equipment, with the possibility of free movement of the user, but without any behavior of these objects and without a visible user interface.

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2. Behavior programming.

In this phase, 3D objects should be enriched with features that enable interaction with them - i.e. animation or change of appearance after meeting certain logical conditions. Testing the programmed behavior of objects should be done with the use of temporary user interfaces, based on easily accessible devices (keyboard, mouse, joystick). In order to speed up the work, it is recommended that behavior programming should not be carried out continuously in the immersive mode (with the use of a helmet and interaction devices), but only on the screen of a regular PC (i.e. offline), emulating the behavior of selected devices, such as tracking systems and controllers based on them, as well as gesture recognition devices. It is definitely more difficult when the application assumes the use of haptic devices, and the behavior of objects depends on the forces generated by the user - then programming offline interactions may turn out to be impossible.

3. Interface programming.

In this phase, all interaction mechanisms available to the end user are created, and temporary interfaces are replaced with final ones. This applies to both the graphical interface and the ways of interaction, e.g. with the use of gesture recognition systems or haptic devices. It is recommended that the target projection and interaction devices should be put into practice only in the final stage of phase 3, of course after ensuring their correct operation in phases 2 and 1.

The layout and examples of activities performed in each phase are shown in the graph in Fig. 3.4.

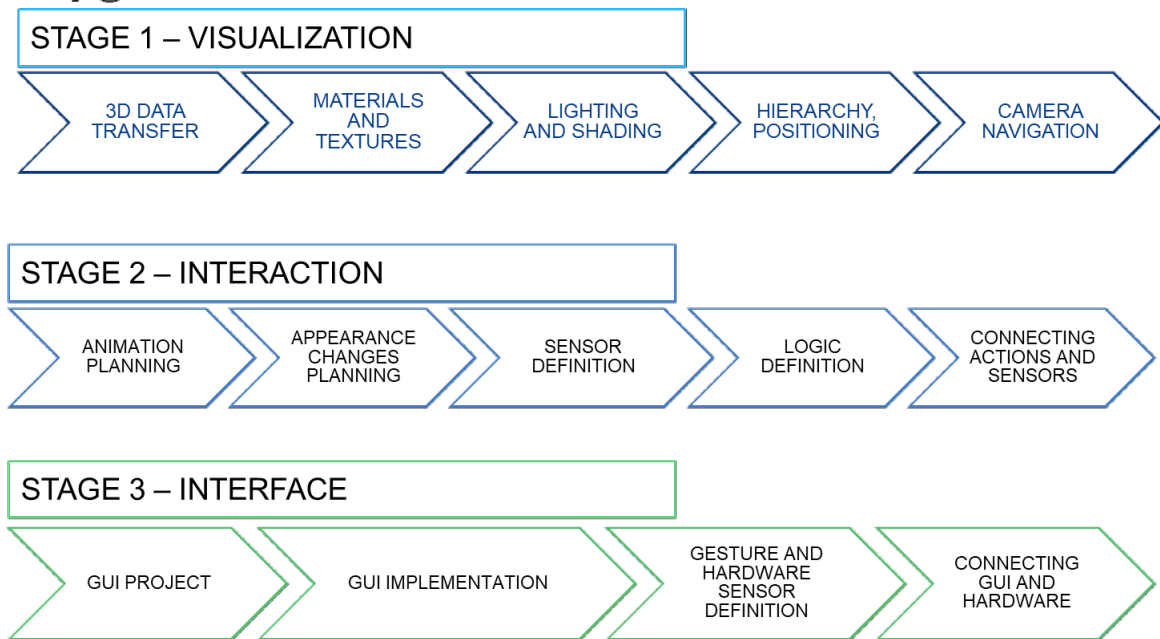


Figure 3.4 Phases of XR application development process

Visualization in XR systems and the techniques used to improve the appearance of objects do not differ significantly from the techniques used in 3D graphics programs. Detailed information on visualization techniques can be found in materials provided by 3D engine manufacturers, such as Unity 3D or Unreal Engine, as well as in countless tutorials, instructions and textbooks. Due to space constraints, details will not be discussed here.

Planning and implementing the proper behavior of objects in VR, AR or MR scenes is the basic activity performed by the programmer (application creator), aimed at obtaining full interactivity. It usually takes relatively the most time spent on application development. At the same time, it is a set of activities for which it is difficult to make significant generalizations, because it can be different for each type of application.

The basic scheme of interaction with objects in XR systems is shown in Fig. 3.5. The whole concept revolves around 4 notions: components with actions and sensors with inhibitors. Components are objects that are populating a virtual scene. Actions are sets of specific behaviors, assigned to components. Sensors are input sources used to trigger the actions and inhibitors are logical means to prevent the triggering when it is not desirable.

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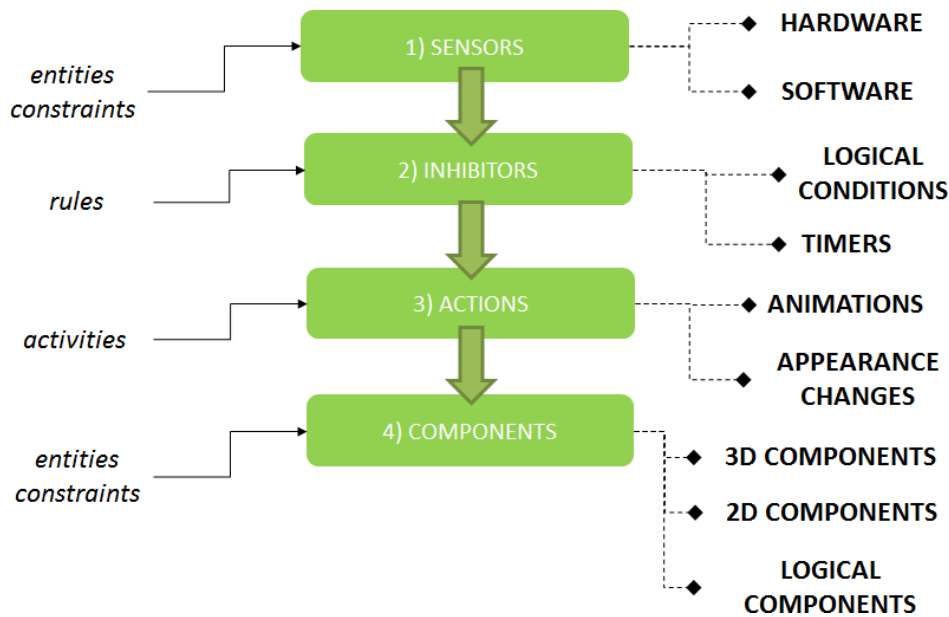


Figure 3.5 Main concepts in creating interactions in XR applications

Creating and assigning actions to individual objects and making logical connections, i.e. mainly transmitting appropriate sensors and inhibitors and creating complete logical and time sequences, is the most time-consuming part of building a level 2 and 3 XR application. The process is repetitive and iterative – its details, however, depend on the type of application being built, the hardware and software used, and the adopted methodology.

There is a very rich literature on the techniques of building interactive VR visualizations and programming the behavior of objects contained in them. It includes classic textbooks such as [Sherman & Craig 2003], [Burdea & Coiffet 2003] or [Riener & Harders 2012]. Interaction building is also part of the numerous video and text instructions provided by the manufacturers of 3D engines, such as Unreal Engine or Unity 3D. Due to the existence of a very wide base of literature and Internet sources, it was decided not to include specific instructions and examples of creating object behaviors in this part of the module.

The last stage of work during the construction of a virtual reality application should be the preparation of the proper (final) user interface. The user interface should be understood here primarily in two terms:

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- graphical interface, GUI,
- specific hardware virtual/augmented/mixed reality interface, most often based on dedicated equipment.

The graphical interface, used to call basic functions and operate the application, rarely has a classic single-screen form in accordance with the well-known WIMP approach (windows, icons, menu, pointer). In fully immersive VR/MR applications, the interface can be displayed on a selected flat surface in 3D space available to the user, the interaction is done using a controller or looking and clicking. In this case, the graphical interface does not have to be limited to a single screen – different sections can be displayed in different parts of the scene.

The process of creating an interface usually consists of the following stages:

1. Graphic design. This stage is usually performed by a 2D/3D artist who is familiar with the interaction methods and scenarios of using the interface in the application. The tool is usually raster graphics software, and the result is a set of flat graphics.
2. Extracting graphics. At this stage, the graphic design is divided into individual graphic files representing individual elements of the entire interface.
3. Positioning. At this stage, the interface elements are positioned (geometric transformation) - on a plane and/or in three dimensions, depending on the type of interface and the scenario of its use.
4. Programming. At this stage, interface elements are marked as sensors and specific actions are assigned to them.

The development and implementation of the user interface completes the technical phase of application development. Further stages are related to its refinement, testing and design of the station and preparation for implementation and transfer to the group of target users.

3.3.2. Implementing and maintaining professional XR applications

The implementation stage of the VR application consists mainly of two types of activities – related to the construction of the hardware layer and integration with the software layer, and related to iterative testing and improvement of the application until a fully functioning solution is obtained. The moment of completion of the tests and obtaining confirmed full

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operational efficiency is the beginning of the VR system operation phase in a given place (institution, company etc.). At this stage, it is also necessary to allocate appropriate material and human resources within the entity to maintain the solution.

In order to undertake the implementation of the VR application, assuming the readiness of the software solution (i.e. the application) and the development of requirements for the hardware layer (type and specification of devices - helmets, controllers, additional devices and computer stations), the following actions should be taken.

1. Design and prototyping of XR stations. Here, the issues of ergonomics and aesthetics are important, but also the freedom of action and observation of the user.
2. Purchase and installation of target hardware components. “XR equipment” is mainly understood as projection and interaction devices – for VR it is usually helmets with controllers (ready sets), as well as optional supplementary equipment (sensors, cameras, gloves, etc.) and computer equipment (computer stations with software, peripherals and monitors/projectors for viewing XR content).
3. Allocating appropriate human resources. In addition to system users, the three main roles that need to be assigned are:
 - instructors / power users - this is the staff responsible for organizing activities at a given VR stand; in the case of self-work and free access to workstations, instructors shall supervise the schedule of use of the system; their task is also to monitor users (not necessarily continuous), track their progress, provide substantive advice, etc.
 - IT administrators - these are the personnel responsible for maintaining the readiness of hardware and software, administrators supervise the necessary inspections of the equipment, react in the event of failures or faults, supervise software and driver updates, etc.,
 - content creators – an optional role, existing only in open systems (i.e. those to which new content can be freely added without programming) – their task is to develop new models, objects, interactions and levels (scenes) and place them in the given application.

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4. Conducting a pilot on a group of target users. The task of the pilot is to check whether the system brings the effects as assumed, and to train and implement the staff whose task is to maintain the system.

3.4 Examples of VR/AR applications for medicine and biomedical engineering

3.4.1. Wheelchair designer

The wheelchair configurator was created as part of diploma thesis [Myślewska 2017]. The application enables virtual design of a wheelchair in a very wide range of configurations (Fig. 3.6). Its basic capabilities include:

- visualization of the product in natural size, in different surroundings,
- orbital or first-person navigation, switched in the application - both projective VR and immersive VR systems can be use , in this case the Oculus Rift goggles,
- product configuration - 14 different options, each containing several values (a total of about 150 million possible to generate product variants),
- save and load configuration, export to a report in the form of a PDF file.



Figure 3.6 Application - wheelchair configurator [Myślewska 2017]

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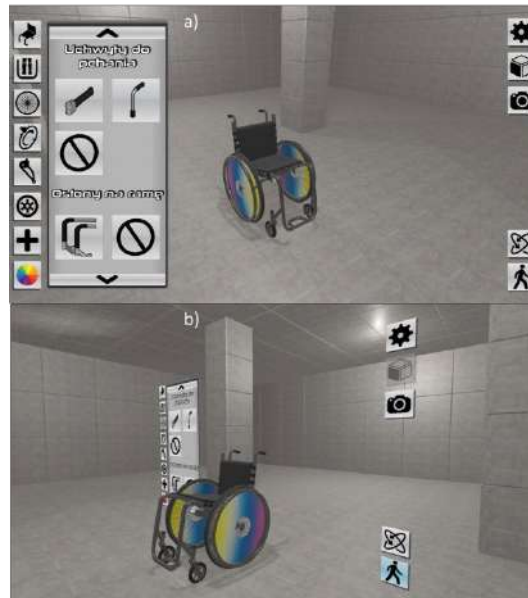


Figure 3.7 Wheelchair configurator – standard and immersive mode

The configuration application was developed primarily as a tool supporting the work of consultants of wheelchair manufacturers who cooperate with customers in the selection of equipment. However, it can be used in two ways. The first is based on the use of an HMD device and a joystick. In this case, the configuration of the wheelchair using the configurator would be carried out with the participation of a company's representative (in the company's office or at potential customer's home) equipped with the appropriate hardware. A helmet-free method is more universal. In this solution, the application can be left at the disposal of the customer, who can configure the wheelchair at home using standard peripheral devices (mouse and keyboard) or a joystick. In this situation, the application can be placed on a website and work as a part of an online store [Myślewska 2017].

3.4.2. Fear of heights therapy

The application was created as part of the diploma thesis [Połczyńska 2020]. The application was created as a means to support psychotherapy aimed at overcoming acrophobia in the patient. It is intended to complement the traditional treatment of anxiety by exposing the patient to the trigger, a method known as Virtual Reality Exposure Therapy

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(VRET) [Buń et al. 2017]. The target place of using the application may be doctor's offices equipped with equipment enabling the use of a virtual environment. The main advantage of the application is the safety of the person using it. The patient is exposed to the factor that triggers fear in them, i.e. the open space. They will be obliged to perform a number of tasks that will allow to get used to the feeling of being at a considerable height. The treating physician is able to monitor the patient's behavior and reactions during the examination on an ongoing basis.

The basic assumptions of the application include the possibility of using it in the limited space of the doctor's office, ensuring the gradation of the degree of difficulty and ensuring the appropriate degree of immersion to achieve a therapeutic effect, without simultaneously deepening the trauma through excess and intensification of sensations.

Unity software and a set of HTC Vive Pro goggles were used in the creation of the application. In an area of approx. 3x3 m, which corresponds to the average size of the recommended room for full-scale interaction in VR, a virtual tower was planned in the form of an open four-level scaffolding (Fig. 3.8), placed in a gentle green environment.



Figure 3.8 Fear of heights therapy – ground view [Połczyńska 2020]

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The user controls the character's avatar using Valve Index controllers and Vive Pro goggles connected to a wireless headset (any other VR headset compatible with the SteamVR platform can be also used, e.g. Oculus Quest). Vertical climbing of individual scaffolding floors is done by climbing a ladder with the use of controllers. At the level, the scaffoldings are connected with narrow beams, which have to be walked through naturally ("on your own feet") - this is the moment of proper exposure to height (Fig. 3.8), in real life causing strong fear and anxiety in patients suffering with acrophobia.



Figure 3.9 Fear of heights therapy – top view [Polczyńska 2020]

The assumption of the application is natural movement - teleportation is possible, but not recommended. The entire scaffolding can be walked without using it, which enhances the impression of reality. The scenario of using the application by people undergoing therapy is as follows:

1. Patients are instructed on how the app and the VR headset work. Their general psychophysical condition is determined.
2. The stage of getting acquainted with the application and the virtual environment follows - until patients are fully comfortable - without interacting with the proper subject of therapy, i.e. scaffolding.
3. Subjects are asked to go to a specific corner of the room (physically) which will allow them to climb all four levels, and then teleport to the base of the ladder so that it is in front of the subject and within reach.

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4. The first step is to climb a ladder to a platform 5 meters above the ground. Then it is necessary to go over the footbridge to the next platform with a ladder.
5. The task of climbing and walking over the plank is repeated until all four levels are passed, the user falls to the ground level, or the user resigns from continuing to explore the scaffolding.
6. After reaching the last level and crossing the last footbridge, the subjects - if they are in the appropriate psychophysical condition - are asked to perform the last task consisting in returning to the footbridge and performing the so-called "swallow", i.e. bending over, spreading both arms and stretching one leg back (Fig. 3.10).



Figure 3.10 Test user making the “swallow” posture [Połczyńska 2020]

The created application is a prototype of a therapeutic application supporting the treatment of fear of heights. It has been tested by over 100 users and the necessary data has been collected to improve it. The overall operation of the application was positively assessed as an application that has a lot of potential and, after refining certain aspects, has a chance to become a truly effective therapeutic tool. In the literature, one can find cases of using VR in the clinical treatment of fear of heights – it is one of the most frequently used therapeutic methods based on XR techniques [Zobal 2021].

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4. Summary

In this course module, basic information about virtual, augmented and mixed reality techniques were presented. The reader was familiarized with basic concepts and definitions, XR system structure and possible components, as well as applications. Also, a methodology of building XR applications was presented, in form of a development process proposal and description of its particular stages, illustrated with examples of specific applications. Below, effects that should be achieved after familiarizing with the chapter are specified.

1. Reader is able to define, distinguish and classify concepts of Virtual Reality, Augmented and Mixed Reality.
2. Reader has knowledge about Virtual, Augmented and Mixed Reality systems: projection, tracking, gesture recognition and haptics, as well as available software classes for XR application creation.
3. Reader should know about possibilities and examples of application of Virtual Reality systems in product lifecycle for medicine and biomedical engineering.
4. Reader should know how to design an interactive VR application for presentation of properties of a specific product, activity or workplace.

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1 Introduction

1.1 Measurement systems

A **measurement system** is a set of devices, apparatus, equipments etc, used for extracting information from a process and to pass that information further (figure 1).

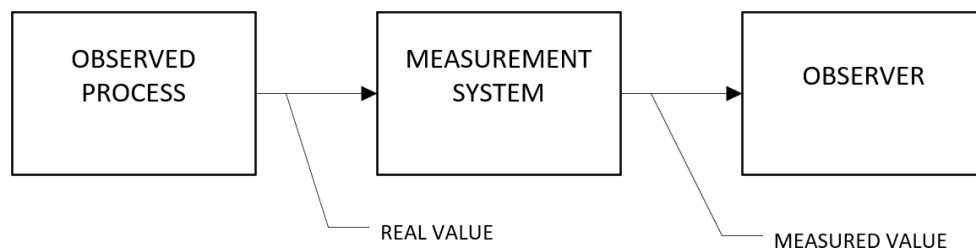


Figure 1. Measurement system's place, between the observed process and the observer. In

most cases, information refers to the values of one or more physical quantities: mechanical, thermal, electrical, chemical, optical etc. As information can not be transmitted without a transfer of matter and without an energy transfer, some material connection has to be established between the observed process and the measurement system. This material connection does not necessarily has to be thought as a mechanical one. Matter means also electrons or photons, so this connection could also be in the form of an electro-magnetical wave, either radio, infrared or visible light.

For a connection to exist, some part of the measurement system has to be in contact with the observed process. In figure 2, this component is described as the **sensor**.

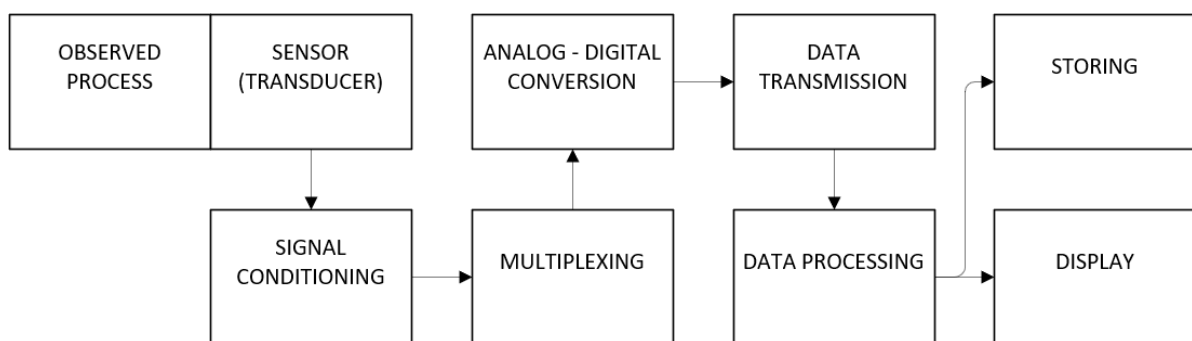


Figure 2. General structure of a measurement system.

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One or more sensor's parameters are changing their values according to the value of the measured physical quantity. For example: a piece of wire, which is changing its length when a pulling force is applied to the wire, the mercury in a thermometer, changing its volume when the temperature is changing, or a specific substance, changing its chemical properties when in contact with a certain gas. This leads to the conclusion that, when designing the measurement system, the sensor has to be chosen according to the physical quantity to be measured. Also, a separate sensor is needed for each physical quantity to be measured in the process.

For the sensor to be influenced, a certain amount of energy has to be extracted from the observed process. Because the measurement has to influence the observed process as less as possible, the sensor is designed so that the amount of energy passed to it is usually very small, so the changes in sensor's parameters, which may be not directly observable, are also very small. These changes represents the signal which the sensor is generating.

This is one of the roles of the **signal conditioning** module in figure 2. Being powered from an external source, the module amplifies the sensor's signal, making it compatible and able to be processed in the next components of the measurement system. If the sensor's signal it's not an electrical one, the signal conditioning consists also in transforming the energy generated by the sensor in electrical energy, a voltage signal being generated.

When the component containing the sensor contains also a signal conditioning module, that component is called a **transducer**. A measurement system can contain more signal conditioning components, some of which may be in the transducers.

When a measurement system contains more than one sensor, a **multiplexer** is needed to receive the various signals from the sensors, on separate transmission paths, and send them to the next components using a single transmission path. A good example of using a multiplexer is the way in which cable TV works: the cable company is receiving the signals from different TV channels, each on its own transmission path, the signals are multiplexed and all arrive in one user's TV using a single cable. There is a demultiplexer in the TV, the channel selector, which is extracting the desired signal from the multiplexed one and is sending it to the displaying components.

Till the multiplexer, the electric signals are transmitted in analogue ones, the information contained in them is represented by the voltage or electric current levels. If this information is to be processed by a computer system, the signals have to be transformed into the digital format, where the voltage level can reperesent one of the two binary digits, 0 or 1. The

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conversion from one signal format to the other is performed by the **analog to digital converter**.

Modern transducers contain not only a signal conditioning component but also their own analog to digital converter, and even a microprocessor which allows sending the digital signal following a specific data transmission protocol. In these cases, if a multiplexer is needed, this is a digital one, in fact a microprocessor subsystem, and is placed after the digital transducers.

The next components of the measurement system are those specific to a microprocessor based system, or a computer: digital data can be send at a certain distance, using for example the Internet, serial communication or radio transmission, data is processed according to a algorithm, results are displayed in various formats and data is also stored.

1.2 Types of sensors and transducers

There are many criteria to clasify the sensors and the transducers, but one of them is taking into account where the energy containing the information is generated.

When interacting with the observed process, some sensors are changing some of their parameters without generating any amount of energy. These are called **parametric (passive) sensors**.

Another category of sensors are those which are generating a certain amount of energy when interacting with the observed process. These are called **generative (active) sensors**.

1.2.1 Parametric sensors

Discussing only about electrical parameters based sensors, parametric sensors can be further classified, according to the variable parameter, in **resistive**, **capacitive** and **inductive** sensors.

One of the most used category of **resistive** sensors are the **strain gages** (figure 3).

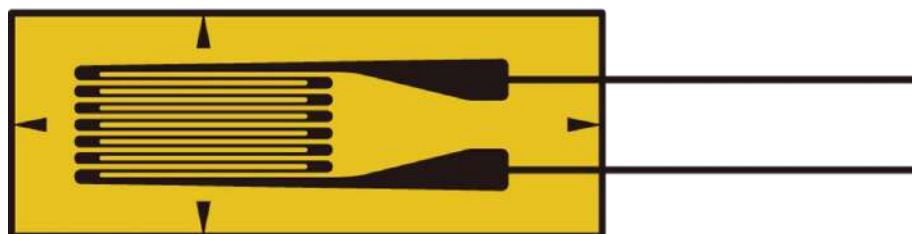


Figure 3. Strain gage example.

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These consist in a metallic pattern on an insulating flexible support. To allow the metallic pattern to be connected in an electrical circuit, wires are attached to the gage's solder pads.

The strain gage is attached to the object whose strain is to be measured using an adhesive, so is deforming in the same way the object does. Deforming the strain gage causes the length of its metallic pattern to change, thus causing a change in its electrical resistance according to equation (1).

$$RR = \rho \rho \frac{LL}{S} [\Omega] \quad (1)$$

where ρ is the resistivity of the material, in $\Omega \cdot m$, L is the length of the wire and S is the area of a transversal section in the wire.

If the strain gage is part of an electrical circuit, powered with a certain voltage, changing its resistance will cause the voltage across that portion of the circuit to change, so an electrical signal is obtained, which is proportional with the object's strain.

Apart from measuring the strain of the object to which the strain gage is attached, if a relation is known between the strain and the force applied to the object, then force can be measured, this being one of the main applications where strain gages are used.

An other type of resistive sensors is represented by the **Resistance Temperature Detectors** (RTD). These are built from materials which are changing their electrical resistance when temperature changes. Made from platinum, nickel or sometimes copper, RTDs are capable of measuring temperatures up to 300 – 600 C, with a tolerance of up to ± 0.15 C [1]. A thin film miniature RTD, 3 mm long, is presented in figure 4.



Figure 4. Miniature thin film RTD

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A **capacitor** is an electronic component which can store energy in the form of an electrical charge, producing a potential difference across its plates. It consists of two or more parallel conductive plates which are not connected or touching each other, but are electrically separated either by air or by some form of an insulating material (figure 5).

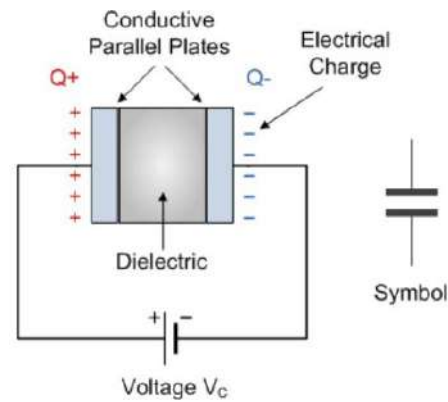


Figure 5. Capacitor's structure.

Its capacitance, measured in microfarad, the ratio of the amount of stored electric charge to the difference in electric potential, can be computed as in equation (2),

$$C = \epsilon\epsilon_0 \cdot \epsilon\epsilon_r \cdot \frac{S}{d} [\mu F] \quad (2)$$

where C is the capacitance, ϵ_0 is an electric constant, in F/m, ϵ_r is the relative permittivity of the insulating material, S is the overlapping area of the two conductive plates and d is the distance between the two plates.

If one of the variables ϵ_r , S or d from equation (2) is changing, due to the relative motion between the plates and insulating material (ϵ_r is changing) or between the two plates (S or d are changing), then the capacitance will change its value and the displacement can be measured.

A special type of capacitive sensor is that called proximity sensor, which can measure the distance to an object, either metallic or non-metallic. In this case, the insulating material is composed both from the air in front of the sensor's measuring face and from the object to be measured. When the object moves, the value of the relative permittivity is changing, so the displacement can be measured (figure 6).

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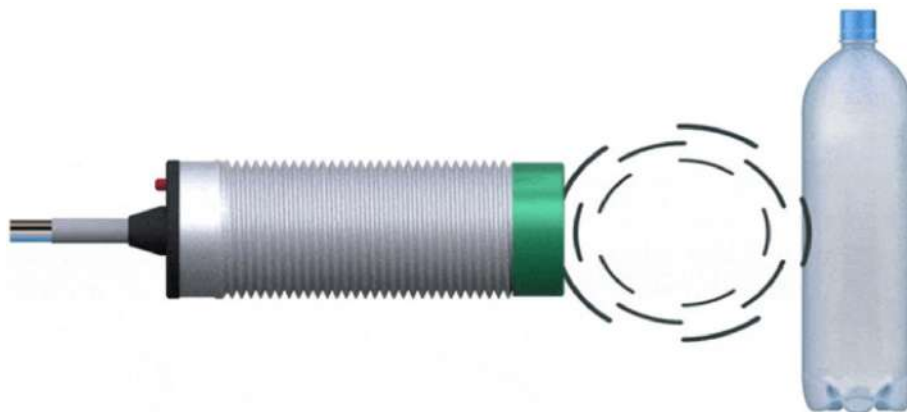


Figure 6. Proximity capacitive sensor.

Another type of capacitive sensors are measuring the capacity of an seismic mass under acceleration (figure 7). They are called **MEMS** (Micro-Electro-Mechanical System) **accelerometers** and one of their main advantage is that they have extremely small dimensions and their manufacturing is very cheap.

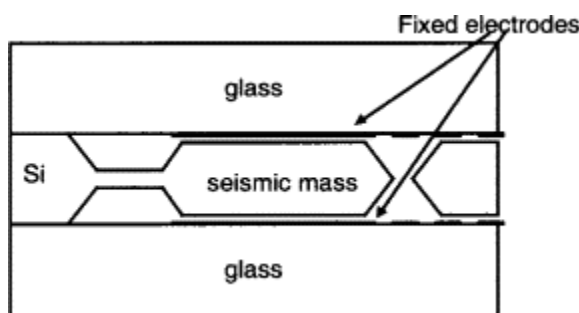


Figure 7. The structure of a MEMS accelerometer

MEMS sensors have an extremely large number of applications, one of them being inside the mobile phones, allowing for example to determine the phone's rotation angle and thus to rotate the screen image accordingly.

An **inductive sensor** uses the principle of electromagnetic induction, discovered by Michael Faraday: an electromotive force is produced across an electrical conductor in a changing magnetic field. The value of the electromotive force can be described by equation (3), where ε is the electromotive force, Φ_B is the magnetic flux, in weber (Wb) or volts-seconds, and t is the time.

$$\varepsilon = - \frac{d\Phi_B}{dt} [N] \quad (3)$$

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A metallic object moving in the sensor's magnetic field will create an electrical current which will flow in the sensor's circuits (figure 8), so the principle can be used in the inductive proximity sensors to detect metallic objects or to measure the distance between the object and the sensor's face.



Figure 8. Inductive proximity sensor detecting a metallic object.

A different type of inductive sensors, called **Linear Variable Differential Transformers** (LVDT), are used for measuring displacement by having a shaft attached to the moving object. Inside the sensor, the shaft is attached to a magnetically conductive core which moves inside the sensor's coil (figure 9).



Figure 9. LVDT Inductive displacement sensor.

1.2.2 Generative sensors

Generative (active) sensors are usually classified according to the physical quantity they are measuring. One of the most used types are those for measuring temperature, called thermocouples. A **thermocouple** is made from two electrical conductors, from different materials, connected at one end called hot junction (figure 10). The other end, where the measurement device is placed, is called the cold junction.

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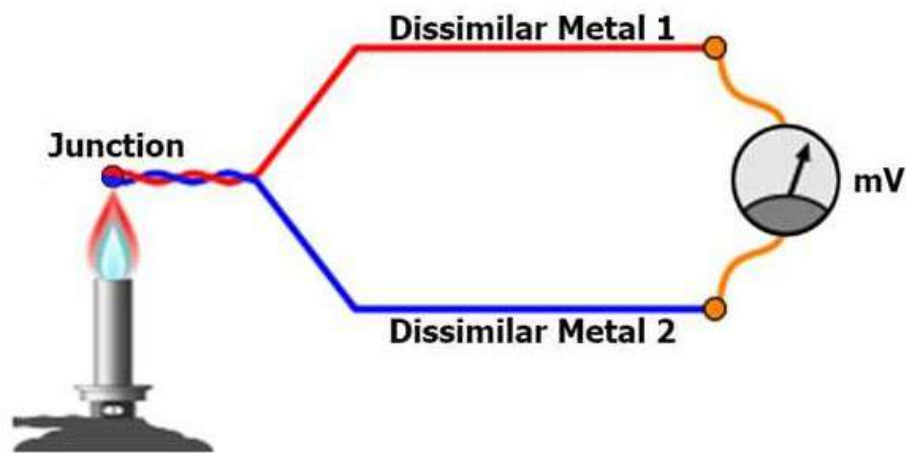


Figure 10. A thermocouple's structure.

According to Seebeck (thermoelectric) effect, when the two ends of a thermocouple are placed at different temperatures, electricity is flowing from the hot junction to the cold junction, so a difference in potential (a voltage), can be measured at the cold junction.

There are several materials couples from which thermocouples can be made: nickel-alloy (type E: chromel–constantan, type J: iron–constantan, type K: chromel–alumel, type N: Nicrosil–Nisil, type T: copper–constantan), platinum / rhodium-alloy (types B, R and S), tungsten / rhenium-alloy (types C, D and G), Chromel–gold / iron-alloy, platinum / molybdenum-alloy and iridium / rhodium alloy being the most well known.

Using thermocouples, temperatures up to 1700 C can be measured, but their accuracy can go down to several degrees and their response time can be as long as several seconds. Miniature thermocouples can have their diameters as small as 0.25 mm.

A distinct and important category of generative sensors are build based on the **direct piezoelectric effect**, which is the property of some materials to generate electric charges when a mechanical stress is applied. **Converse (reverse) piezoelectric effect** also exists, which consists in generating a stress when an electrical field is applied, this effect being used for building actuators and piezoelectric motors. Examples of piezoelectric materials are: the quartz, lead zirconate titanate (PZT), barium titanate and lithium niobate.

The **piezoresistive pressure sensors**, one of the most used type of pressure sensors, are using strain gages attached to a thin membrane which is bending when pressure is applied. The strain gages are made from semiconducting materials, usually doped silicon [2]. A change

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in the strain gage's resistance appears due to the piezoresistive effect. A change in length also appears, accompanied by a change in resistance, but this is much smaller than the change due to the piezoresistive effect, this being the reason for each these sensors are considered as belonging to the generative category and not to the parametric one.

Pressure sensors may be classified according to the type of pressure they are measuring: absolute pressure, when the pressure is compared with the one of a vacuum volume inside the sensor, relative pressure, when the pressure is compared with the atmospheric air pressure, and relative pressure, when the sensor has two inputs and is measuring the pressure difference between them.

Piezoelectric sensors can be used for measuring not only pressure, but also acceleration, temperature, strain and force.

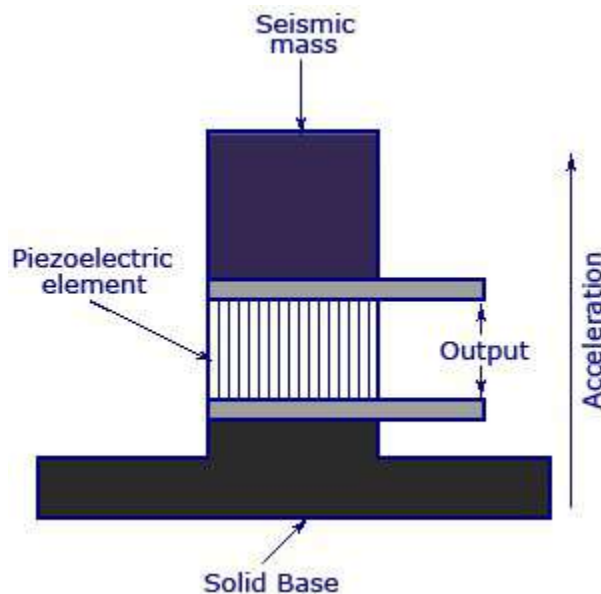


Figure 11. An accelerometer's structure.

A piezoelectric acceleration sensor, called an **accelerometer** (like also the capacitive ones), is using a piezoelectric element, made from natural quartz or from lead zirconate titanate (PZT), which is in contact with a so called seismic mass, a body with a weight much higher than that of the piezoelectric element (figure 11).

When acceleration is applied, the seismic mass is creating a stress in the piezoelectric element, so electrical charges appear on its faces. Piezoelectric accelerometers are mainly used in measuring high frequency vibrations, but they work also well at lower frequencies.

Piezoelectric temperature sensors consist in a multilayer cantilever containing, between them, a layer of doped silicon and an aluminium layer (figure 12). Due to the different thermal expansion coefficients of the multilayer materials, a thermal stress is generated in the silicon layer, thus being generated an electrical signal which is proportional to the temperature.

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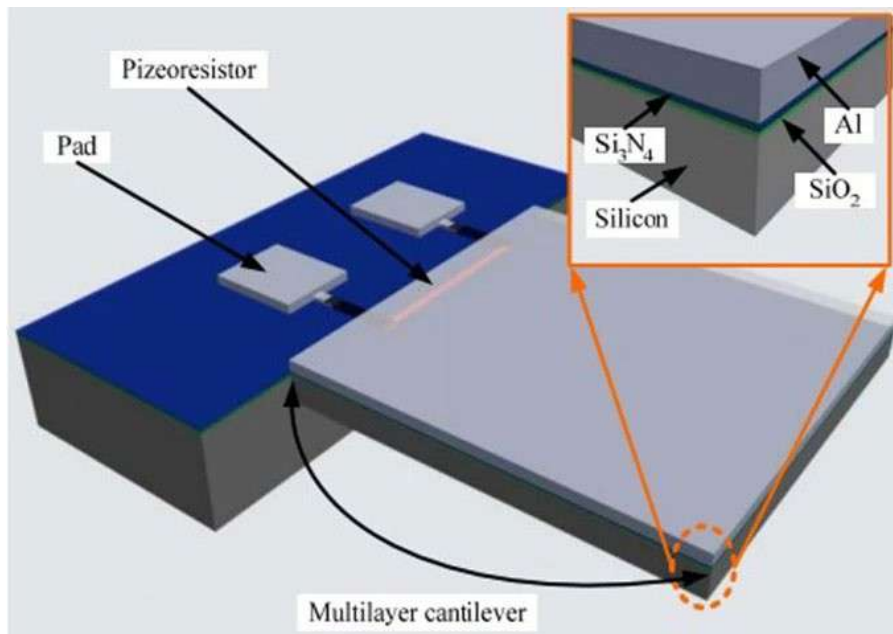


Figure 12. The structure of a piezoresistive temperature sensor.

Piezoelectric components can be also attached to different types of membranes, cantilevers or other elastic components, so a force applied to the elastic component will induce a stress in the piezoelectric material, allowing to measure the applied force or the strain of the elastic component.

Photoelectric generative sensors are based on the **photoelectric effect**, when electrons are emitted by a material which is hit by light. The best materials for obtaining an usable photoelectric effect are semiconductors like silicon, cadmium telluride, gallium arsenide and copper indium diselenide [3]. One main category of photoelectric generative sensors are the **photodiodes**. One immediate use of this type of sensors is the measurement of illuminance, the amount of light falling on a certain area.

If it's not the amplitude of the signal which is measured, but the signal's presence or absence, then a whole family of sensors can be built for detecting the presence of an object or for measuring one object's displacement.

For the first category, **photodetectors**, one possible configuration is that in which the object to be detected is situated between the light emitter (transmitter) and the photoelectric sensor (figure 13), the so called thru-beam model. Other configurations are possible, with the

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emitter and the sensor on the same side of the object: when the emitted light is reflected by the detected object (reflective model) or when the light from a reflector (on the other side of the object) is interrupted by the object (retroreflective model). The last case is often used in automatic parking or garage barriers, to avoid closing the barrier when the presence of a car or person is detected (figure 14).

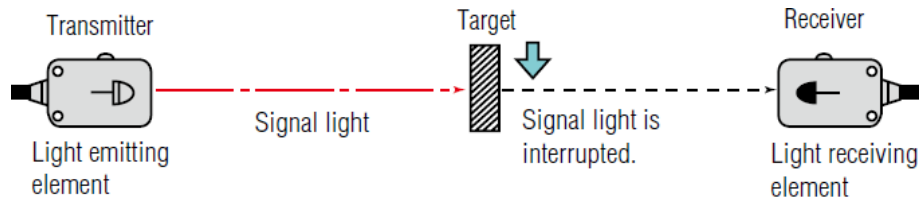


Figure 13. Thru-beam photodetector model.

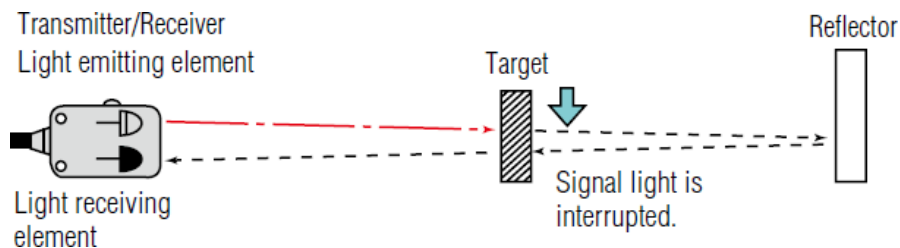


Figure 14. Retroreflective photodetector model.

When the light from the emitter is reaching the receiver, a pulse type signal appears in the measurement system's circuits. If each pulse is corresponding to the displacement of an object over a certain distance and if the measurement system is able to count the signals, then a displacement sensor can be built using the photoelectric effect.

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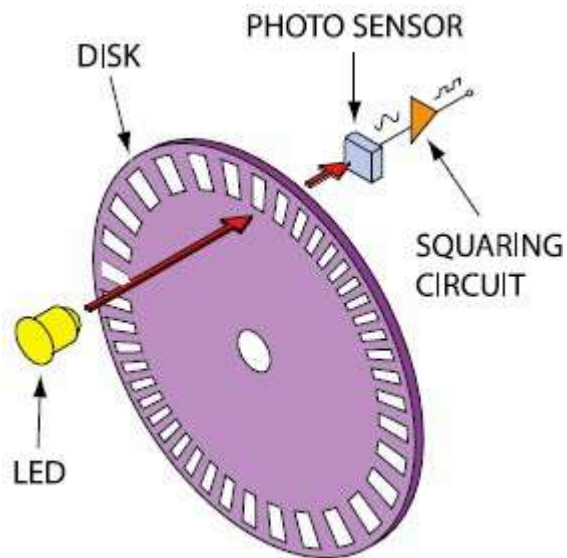


Figure 15. A rotary encoder.

A **rotary encoder** is a sensor in which a disk, having alternating opaque and transparent sections, is rotating between a light source and a photodetector (figure 15). Each time the light passes through a transparent section, a pulse is registered, so it is known that the disc rotated with a certain angle.

The same principle can be applied for building linear encoders, where the disk is replaced by a linear scale.

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2 Signal conditioning

Signal conditioning represents the transformation of an analog signal in such a way that this becomes compatible with the next components of the measurement system. Extracting only the useful part of one signal also represents a category of signal conditioning. There are many types of signal conditioning operations, depending on the sensor's type, signal's type or on the requirements of the measurement system.

2.1 Input coupling

Input coupling is used for conditioning signals which contain both AC and DC components and where only the AC component is of interest. The DC component, which is an offset of the signal, usually equal with the signal's mean amplitude, is removed by using the so called capacitive coupling, placing a capacitor between the signal and the rest of the measurement system (figure 16).

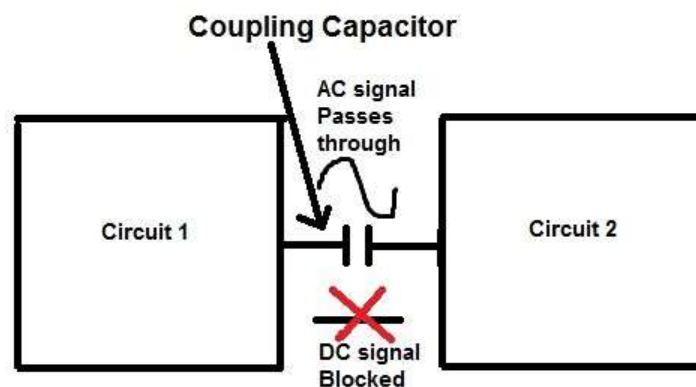


Figure 16. Input coupling circuit.

In simple circuits, the capacitor can be replaced by a **gimmick loop**, a capacitor made by two twisted insulated wires, having a capacitance on the order of 0.5 to 1 pF/cm. The capacitance of a gimmick loop may be changed by tightening or loosening the winding or by changing the wires length.

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2.2 Filtering

Filtering is a type of signal conditioning which removes the signal's components having certain frequencies. One criteria to classify the electronic filters is according to the frequencies they are allowing to pass further in the measurement system: **high-pass filters** allow only the signal component having a frequency above a certain value (cutoff frequency), **low-pass filters** allow only the frequencies below the cutoff frequency, **band-pass filters** allow only the frequencies belonging to a certain interval and **band-stop filters** remove the frequencies belonging to a certain interval. Figure 17 shows an example of composition between a 10 Hz signal and a 2 Hz one, both sinusoidal.

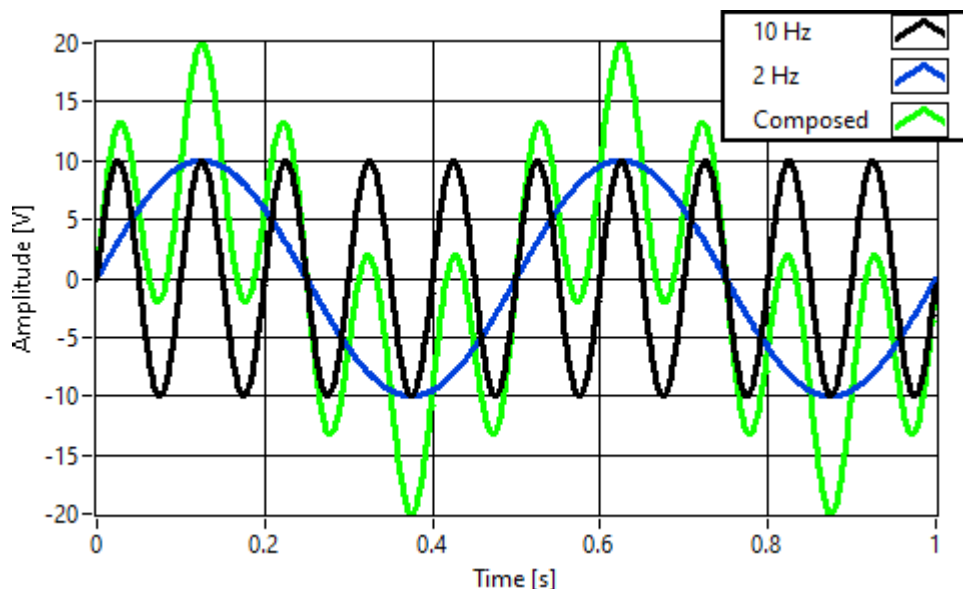


Figure 17. Signals composition.

In figure 18 there are pictured the results of applying two filters on the composite signal. When applying a high-pass filter with the cutoff frequency of 3 Hz, the 10 Hz sinusoidal signal is extracted from the composite signal, while when applying a low-pass filter at 4 Hz the 2 Hz is extracted. It can be observed that, due to the specific design of the applied filters, the extracted signals can suffer various distortions, like an amplitude reduction in the first case or a form distortion in the second one.

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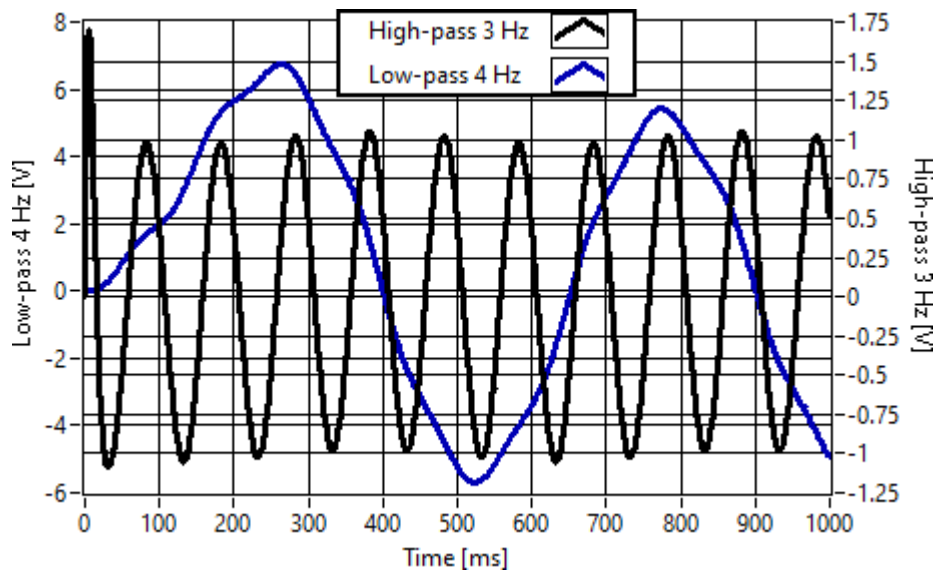


Figure 18. Signal filtering results.

2.3 Amplification

Amplifying a signal means increasing its amplitude (voltage or current), which is useful, for example, for reducing the influence of the electrical noise on the signal quality, the so called **signal-to-noise ratio** increasing. Increasing the signal's amplitude is performed by increasing its power, so the amplifier needs an own power source to deliver the additional energy in the electrical circuit. One very often used application is encountered in temperature measurements using thermocouples, where the millivolts range signal generated by the thermocouple has to amplified in the volts range to better fit with the measurmeent range of the analog-to-digital converter.

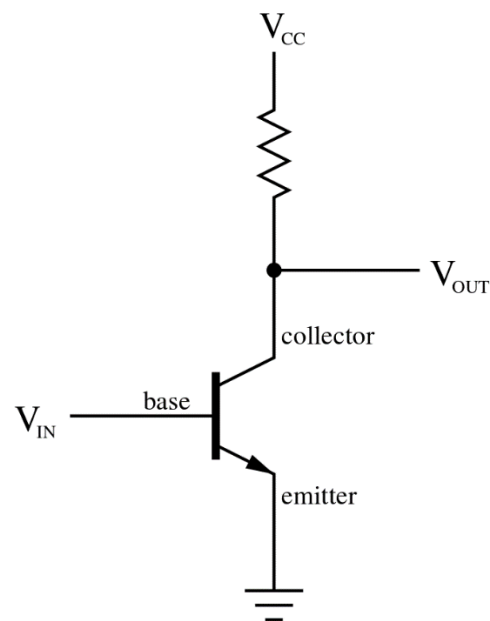


Figure 19. A transistor's circuit.

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An **amplifier** can take the form of a separate equipment, like audio amplifiers, a part of an electronic circuit or an integrated circuit. In all these forms, **transistors** are used as the main amplifier components, based on their functioning principle: controlling the high amplitude of the current flowing between their **collector** and **emitter** terminals, based on the small amplitude current received at the **base** terminal and flowing also to the emitter (figure 19).

2.4 Attenuation

Attenuation represents the decreasing of a signal's amplitude (the opposite of amplification) and is often used when the amplitude is greater than the maximum accepted by the analog-to-digital converter. The most used design of an **attenuator** is that of a so called voltage divider (figure 20), where the ratio between the output and the input voltages is determined by the values of the two resistors.

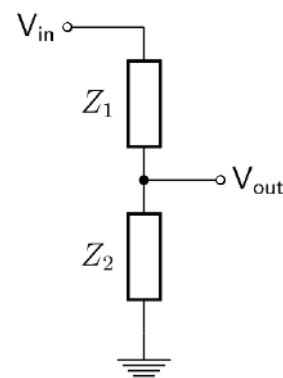


Figure 20. Voltage divider circuit.

$$V_{out} = \frac{Z_2}{Z_1 + Z_2} \cdot V_{in} \quad (4)$$

2.5 Excitation

Excitation consists in providing external energy, from a voltage or from a current source) to a parametric sensor. A very well known case when excitation is used is when measuring with strain gages. A special circuit is used, called the **Wheatstone bridge**, consisting of four resistors from which either one, two or all four can be strain gages (figure 21).

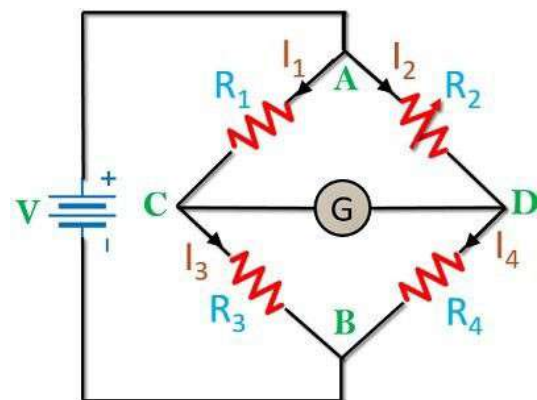


Figure 21. The Wheatstone bridge.

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If a voltage is applied between points A and B, the voltage measured between points C and D depends on the values of the four resistors.

$$V_{CD} = V_{AB} \cdot \left(\frac{R_3}{R_1 + R_3} - \frac{R_2}{R_2 + R_4} \right) \quad (5)$$

Equation (5) shows that, when all the four electrical resistances are equal (balanced bridge), the output voltage is zero. If some or all of the four resistors are replaced with strain gages, when their electrical resistances are changing, the value of the output voltage can be written as in equation (6), so is dependent on the resistances' variations.

$$V_{CD} = k \cdot V_{AB} \cdot \left(\frac{\delta\delta R_1}{R_1} - \frac{\delta\delta R_2}{R_2} + \frac{\delta\delta R_3}{R_3} - \frac{\delta\delta R_4}{R_4} \right) \quad (6)$$

It can be seen in equation (6) that the ratios corresponding to **adjacent sides** of the Wheatstone bridge (1 and 2, 2 and 3, 3 and 4, 4 and 1) have **opposite signs**, while the ratios corresponding to **opposite sides** (1 and 3, 2 and 4) have the **same sign**.

This means that, if same sense variations of the electrical resistance appear on adjacent sides, their effects on the V_{CD} measured voltage will compensate each other, so the total effect will be null. If same sense variations appear on opposite sides, their effects will be added, so the total effect will be doubled.

The first conclusion is useful, for example, when force has to be measured and the effect of the temperature variation has to be eliminated (figure 22). The R_1 strain gage, placed on an object which is deforming when an F force is applied to it, is sensing not only the strain due to the applied force, but also the strain due to the dilating or contracting of the object due to temperature variation.

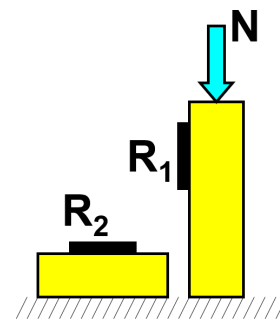


Figure 22. Compensating temperature variation effects.

If a strain gage R_2 (placed on an adjacent side to R_1) is placed on a second object, made from the same material (to have the same dilatation coefficient) and placed close to the first object (to suffer the same temperature variations), then the effects on R_1 and R_2 due to

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temperature variations (having the same sign) will compensate each other and the total effect at the Wheatstone bridge output will depend only on the strain sensed by R_1 .

Another design is used when force signal amplification is needed (figure 23). If the R_1 and R_2 resistors (on adjacent sides of the Wheatstone bridge) are placed on the opposite faces of a body on which the force to be measured is acting, due to object's bending to the left, the length of R_1 will decrease and the length of R_2 will increase, so the variations of their electrical resistances will have opposite signs, but the effects on the Wheatstone bridge output will have the same sign, so the output will be double, so more precise.

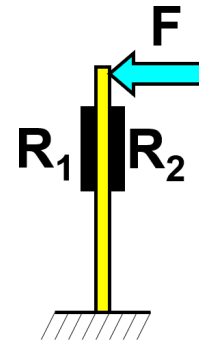


Figure 23. Sensitivity doubling.

2.6 Linearization

Linearization is a type of signal conditioning used when the sensor's output signal is not linearly proportional with the value of the measured physical quantity. Figure 24 shows the variation of the Seebeck coefficient (output voltage vs Temperature) for different types of thermocouples, while figure 25 shows a thermistor's characteristic curve.

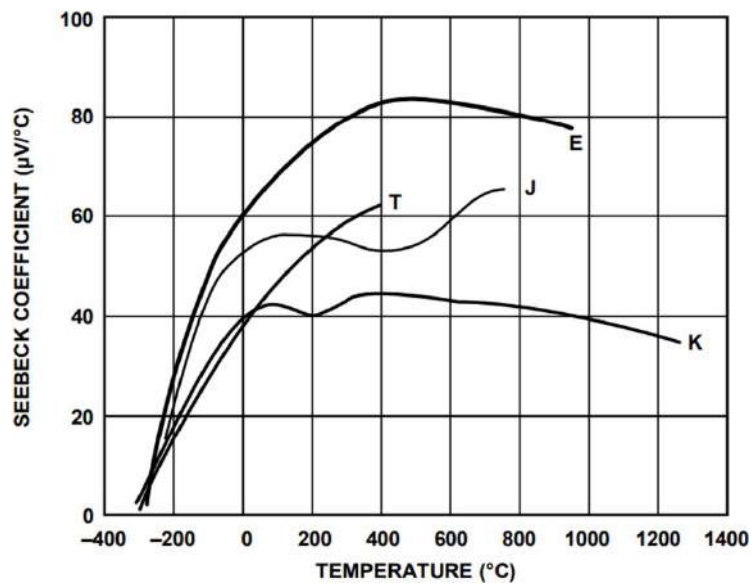


Figure 24. Seebeck coefficient.

Both cases indicate a non-linearity between the temperature value and the output voltage.

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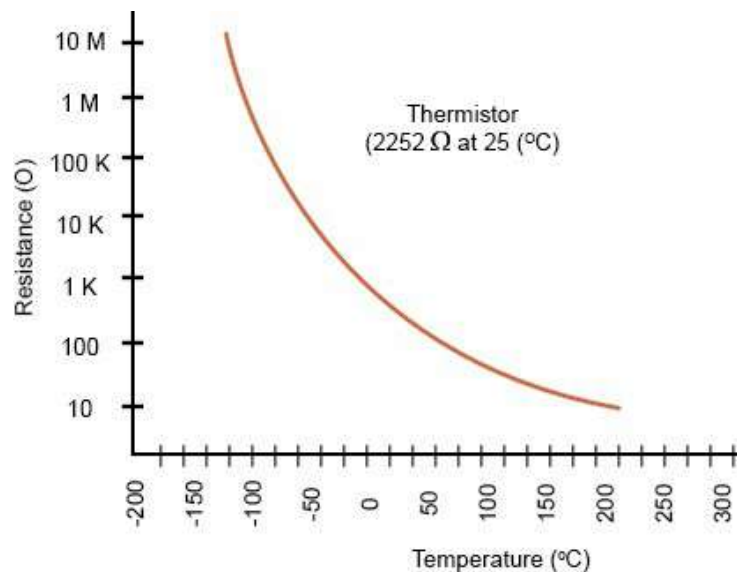


Figure 25. A thermistor's characteristic curve

Different solutions can be used for compensating the non-linearity and providing a linear ratio between the output voltage and the measured temperature.

For example, thermistor signal linearization can be performed by using a cheap analog signal conditioning circuit which consists of a single resistor in parallel with the thermistor [4]. The resistor's value has to be about equal to the thermistor value at the centre of the range of interest. To be noted that only an approximation of a linear relation will be obtained, but this may prove to be enough in certain cases.

More precise linearization solutions are represented by integrated circuits containing instrumentation amplifiers and thermocouple cold junction compensators. Such a circuit, built by Analog Devices Corp, is AD8495, shown in figure 26 on a breakout provided by Adafruit.

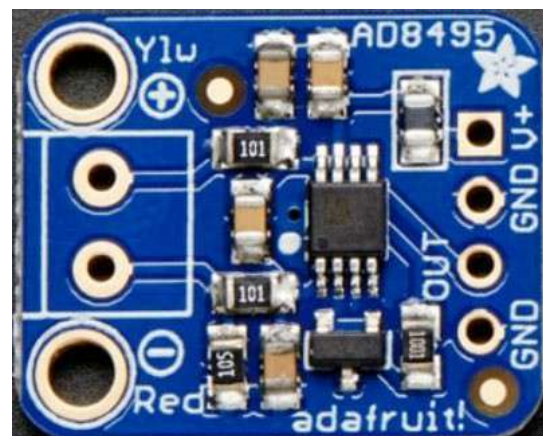


Figure 26. Adafruit breakout with AD8495 IC.

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2.7 Isolation

Signal conditioning by **isolation** is used when the signal has to be passed further in the measurement system without a physical connection, either for avoiding the electrical noise which may appear in the connection lines, or for protecting the next components from potential damaging perturbations.

Most used solutions consist either of a magnetic isolation, which converts the signal into a magnetic field which is further transmitted in the measurement system, or of an optical isolation, which is modulating an electronic signal using the sensor's signal to be transmitted. In both cases, magnetic or optical signals have to be decoded and transformed back into electrical signals, before being passed to the analog-to-digital converter.

Magnetic isolators for analog signals, called **transformers**, consists of two coils which are magnetically coupled using an iron core (figure 27). Transformers are very well avoiding energy spikes, but low-frequency energy increases are harder to be filtered, because transformers are working in the AC domain, so DC analog voltages cannot be isolated. The same principle of transmitting the energy through a magnetic field is also used in current transducers, when the amplitude of the measured signal (current intensity) is very high. The **current transducers** (figure 28) are containing only the secondary circuit, the primary circuit being represented by the wire in which the current has to be measured.

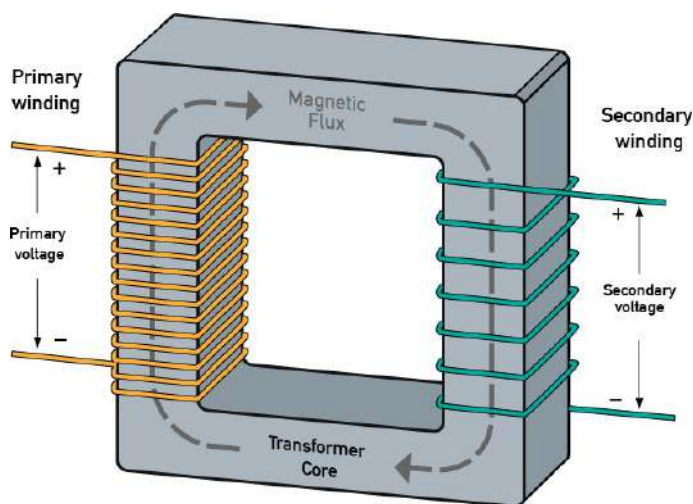


Figure 27. Current transformer.

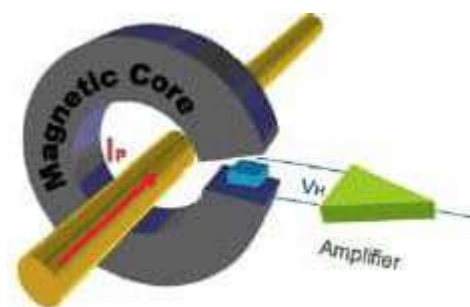


Figure 28. Current sensor.

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For isolating digital signals, **optical isolators** are mainly used, consisting in a LED and an optical sensor (a photoresistor, a photodiode, a phototransistor, a silicon-controlled rectifier (SCR) or a triac.), both working in the infrared domain (figure 29).

The LED converts the electrical signal input into light, while the photosensor detects the light and converts it back into an electrical signal.

The same principle is used in the solid-state relays, where the photosensor is replaced by a pair of MOSFETs (metal-oxide-semiconductor field-effect transistor) which are opening or closing an electric circuit.

A method for **isolating DC analog signals** consists in first converting the analog signal to a digital pulse width modulation (PWM) signal, whereby the duty cycle of the PWM represents the analog value. This PWM signal, being digital, is then isolated using an optoisolator and the output of the optoisolator is then converted back into an analog signal using an RC circuit [5].

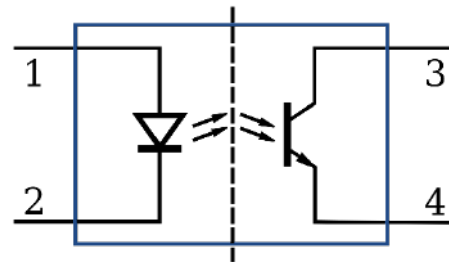


Figure 29. An optoisolator diagram

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3 Analog-to-digital converters

An **analog-to-digital converter (ADC)**, as its name suggests, is converting an analog signal into a digital one. It is an integrated circuit whose very simplified block diagram is looking like in figure 30.

The analog signal input has to be contained in a certain interval, named ADC's **measurement range**.

The number of bits on which the ADC is outputting the voltage value is called **resolution**.

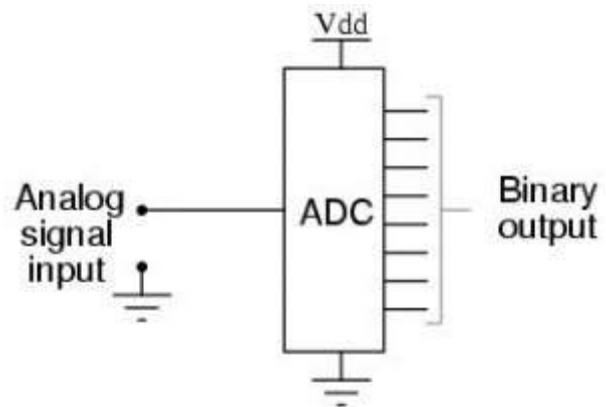


Figure 30. An ADC's diagram

A value belonging to the measurement interval can be expressed in digital format using only the number of bits represented by the resolution (let's call it **N**), which means that the ADC is dividing the measurement interval into 2^N subintervals. As an example, in figure 31 it is represented the conversion of a sinusoidal signal in the [0, 10] Volts interval, using a three bits ADC. The ADC is dividing the [0, 10] Volts interval into eight subintervals, each 1.25 Volts high. The amplitude of one subinterval represents the ADC accuracy, the precision with which the ADC can transform the analog input into a digital value.

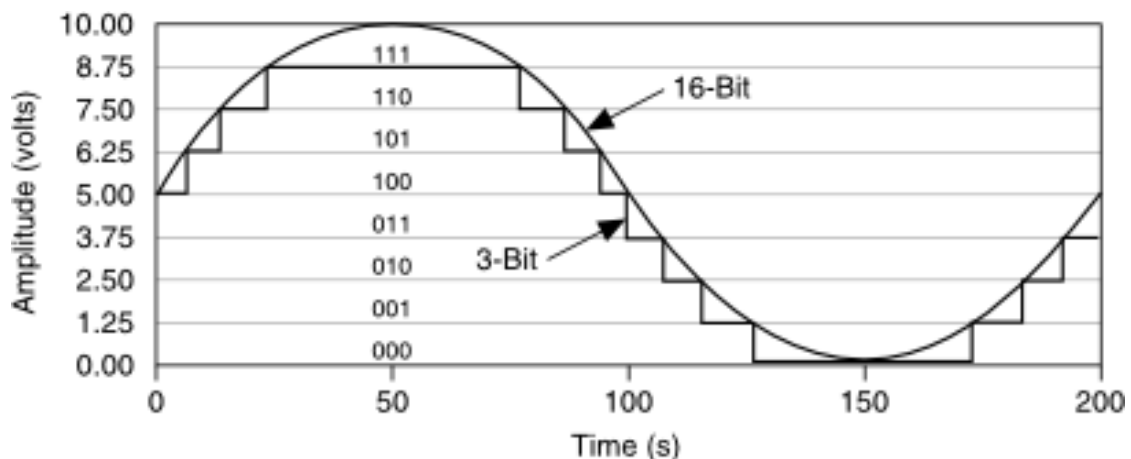


Figure 31. Dividing the measurement interval.

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An input voltage between 0 and 1.25 V will be represented as 0, between 1.25 and 2.5 V as 1, between 2.5 and 3.75 V as 2 and so on. It is clear that the measurement interval and the resolution are directly determining the accuracy of the ADC: when the measurement interval is larger, for the same resolution, the accuracy is lower and when the resolution is increasing, for the same amplitude of the measurement interval, the accuracy is higher.

The measurement interval of an usual ADC is typically between -10 and 10 V or sometimes between -5 and 5 V. Advanced ADCs has configurable measurement intervals, going down to [-0.1 ... 0.1] V.

A low performance ADC has a resolution of 10 bits. Measuring with this resolution in a [0 ... 5] V interval will allow a maximum accuracy of $5 / 2^{10} = 4.88$ mV. Measuring with a high performance ADC, with a resolution of 16 bits, in the [-0.1 ... 0.1] V interval, will provide a maximum accuracy of 3.05 μ V, which is 1,600 times more precise.

For performing the conversion, an ADC is repeatedly increasing an internal voltage and is comparing this with the voltage to be converted, till these two voltages are falling in the same subinterval (figure 32). While increasing and comparing, the ADC is counting the number of increasing steps, each step having an amplitude equal to the ADC's accuracy.

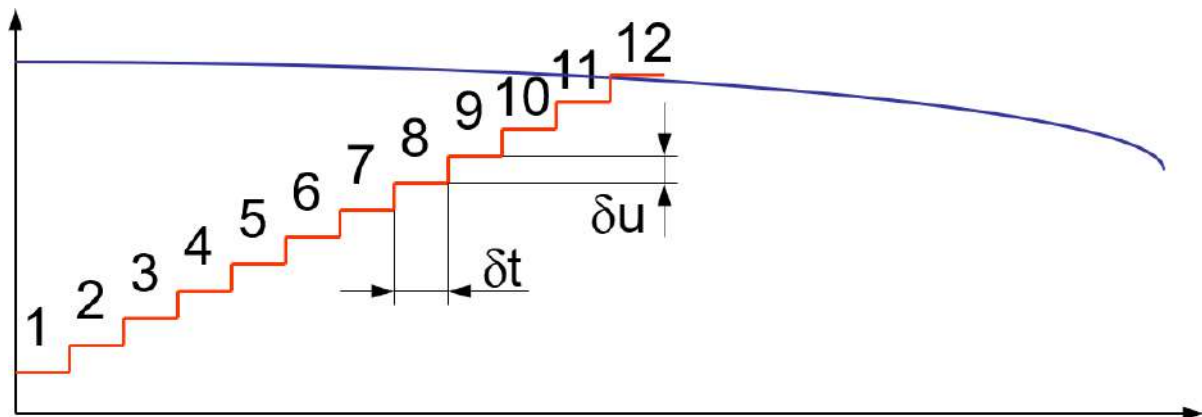


Figure 32. Performing the comparison for conversion.

It is clear that the ADC needs a certain time for performing one conversion, and the number of conversion which can be performed in one second is called the **scan rate**. Usual ADC scan rates are from 10 kHz, for cheaper solutions, up to several MS/s (mega samples per second).

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4 Summary

A **measurement system** is a set of devices, apparatus, equipments etc, used for extracting information from a process and to pass that information further. In most cases, information refers to the values of one or more physical quantities: mechanical, thermal, electrical, chemical, optical etc. As information can not be transmitted without a transfer of matter and without an energy transfer, some material connection has to be established between the observed process and the measurement system. This material connection does not necessarily has to be thought as a mechanical one. Matter means also electrons or photons, so this connection could also be in the form of an electro-magnetical wave, either radio, infrared or visible light. For a connection to exist, some part of the measurement system has to be in contact with the observed process. In figure 2, this component is described as the **sensor**.

When interacting with the observed process, some sensors are changing some of their parameters without generating any amount of energy. These are called **parametric (passive) sensors**. Another category of sensors are those which are generating a certain amount of energy when interacting with the observed process. These are called **generative (active) sensors**.

Discussing only about electrical parameters based sensors, parametric sensors can be further classified, according to the variable parameter, in **resistive** (strain gages, Resistance Temperature Detectors etc) **capacitive** (e.g. proximity sensors, MEMS accelerometers etc) and **inductive** sensors (proximity sensors, LVDT sensors etc). Generative (active) sensors are usually classified according to the physical quantity they are measuring: thermocouples, piezoresistive pressure sensors, accelerometers, piezoelectric temperature sensors, photodiodes, photodetectors, rotary encoders etc).

Signal conditioning represents the transformation of an analog signal in such a way that this becomes compatible with the next components of the measurement system. Extracting only the useful part of one signal also represents a category of signal conditioning. There are many types of signal conditioning operations, depending on the sensor's type, signal's type or on the requirements of the measurement system.

An **analog-to-digital converter (ADC)**, as its name suggests, is converting an analog signal into a digital one.

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Output	O1 - EMERALD e-book for developing of biomimetic mechatronic systems
Module	Module – Biomechatronics
Authors	Filippo SANFILIPPO

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1. Introduction to Biomechatronics

Biomechatronics is a multidisciplinary field that combines biology, mechanics, and electronics to design and develop innovative technologies that enhance human performance and function [1]. The combination of these complementary fields is shown in Figure 1 [2].

It involves the integration of biological systems, such as the human body and its movement, with mechanical and electronic devices to create advanced hybrid systems [3]. These systems can be used for a wide range of applications, including medical devices, prosthetics, and rehabilitation technologies [4].

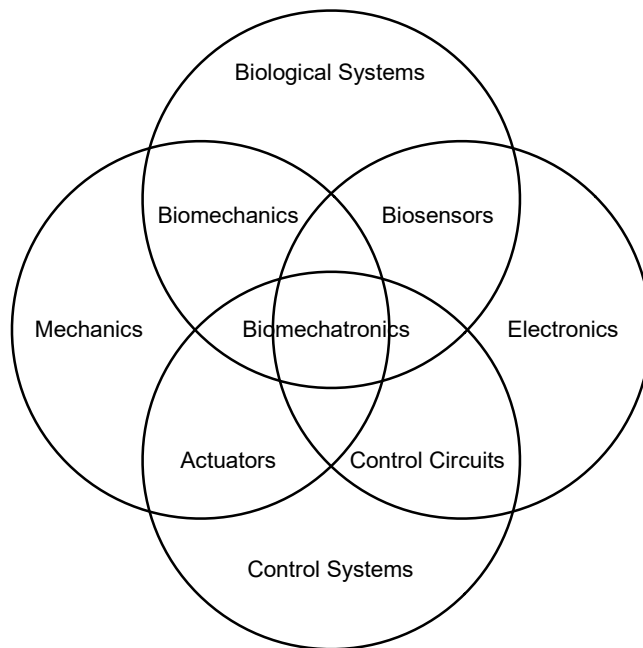


Figure 1: Biomechatronic is a combination of complementary fields.

One of the main goals of biomechatronics is to improve the quality of life for individuals with disabilities or impairments [1]. The development of artificial limbs, or prosthetics, has allowed individuals with amputations to regain mobility and independence. Biomechatronic devices can also be used in the medical field to assist with surgeries or to monitor and treat patients [5]. In addition, biomechatronic devices can be used to enhance

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the performance of individuals without disabilities, such as athletes and military personnel [6].

The field of biomechatronics is constantly evolving and has the potential to revolutionize the way we interact with technology and improve the human experience [7]. In this chapter, we will provide a brief overview of the history and development of biomechatronics, as well as its current and future applications [8].

2. The History and Development of Biomechatronics

The origins of biomechatronics can be traced back to the early 20th century, with the development of prosthetic devices that used mechanical components to mimic the movement of natural limbs [4]. In the 1960s and 1970s, the field of biomechanics emerged, which focused on the study of the mechanics of human movement and its applications in the design of artificial limbs and other devices [1]. In the 1980s and 1990s, the field of biomechatronics emerged, which combined the principles of biomechanics with electronics and control systems to create more advanced and sophisticated technologies [3].

One of the major developments in the field of biomechatronics has been the use of electromyography (EMG) to control artificial limbs and other devices using the electrical signals produced by the contraction. This allows individuals with amputations or other disabilities to control their artificial limbs using their own muscle signals, providing them with a greater degree of control and independence [9].

In recent years, there have also been significant advances in the development of exoskeletons, which are wearable devices that can assist with movement and support the body's weight [10]. Exoskeletons can be used to assist individuals with spinal cord injuries or other mobility impairments to walk, as well as to enhance the physical capabilities of individuals without disabilities, such as military personnel or athletes [6].

3. Current and Future Applications of Biomechatronics

Biomechatronic technologies have a wide range of applications in the medical, sports, and entertainment industries [1]. In the medical field, biomechatronic devices are used to assist with surgeries, monitor and treat patients, and rehabilitate individuals with

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disabilities or impairments [5]. Examples of medical applications of biomechatronics include artificial limbs, exoskeletons, and assistive devices for individuals with spinal cord injuries [11].

In the sports industry, biomechatronic technologies are used to design advanced athletic training equipment and to enhance the performance of professional athletes [6]. These technologies can be used to improve strength, endurance, and speed, as well as to prevent injuries [9]. In the entertainment industry, biomechatronic technologies are used to create realistic special effects and to design interactive experiences [10].

Looking to the future, it is likely that the field of biomechatronics will continue to evolve and expand into new areas. One promising area of research is the development of brain-machine interfaces (BMIs), which could allow individuals to control artificial limbs or devices using their thoughts [1]. Other areas of research include the development of wearable technologies that can monitor and improve physical performance, and the integration of biomechatronic technologies into military and emergency response systems [3].

4. Ethical Considerations

As the field of biomechatronics continues to grow and advance, it is important to consider the ethical implications of these technologies, such as the potential for misuse or abuse, as well as the potential for unintended consequences or negative impacts on society [7]. It is crucial for researchers and developers to carefully consider these ethical considerations as they continue to push the boundaries of what is possible with biomechatronic technologies.

5. Conclusion

In conclusion, biomechatronics is a rapidly growing and evolving field that combines biology, mechanics, and electronics to create advanced technologies that enhance human performance and function. It has a wide range of current and future applications in the medical, sports, and entertainment industries, and has the potential to revolutionize the way we interact with technology and improve the human experience. As the field continues

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to develop and advance, it is important to consider the ethical implications of these technologies and to ensure that they are used in a responsible and beneficial manner.

6. Examples of biomechatronic systems

In the following, a collection of examples of biomechatronic systems will be outlined.



Figure 2: The all in one servo lab (AIOSL).

6.1. Teaching Motion Control in Mechatronics Education Using an Open Framework Based on the Elevator Model

This paper proposes a new open prototyping framework, shown in figure 2, for teaching motion control in mechatronics education using low-cost commercial off-the-shelf components and tools. The framework contains theoretical lectures as well as hands-on laboratory projects that mix surface and deep learning components to help students to create connections and enhance their knowledge. The course structure and main themes are described, and the suggested framework, which incorporates an elevator model, is detailed.

- Teaching Motion Control in Mechatronics Education Using an Open Framework Based on the Elevator Model [12, 13]

6.2. A Novel Adaptive Sliding Mode Controller for a 2DOF Elastic Robotic Arm

A two-loop adaptive controller for a 2-DOF robot arm, shown in figure 3, with compliant actuators is presented in this study. In complex situations, elastic joints are likely to

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outperform stiff ones. For the outer control loop, an adaptive sliding mode controller (ASMC) is utilised to address uncertainties and disturbance on the load side, while model reference adaptive controllers (MRAC) are employed for the inner loops to handle uncertainties on the motor side. The suggested controller has a lower average RMS error and a shorter settling time than a conventional sliding mode controller (SMC), according to simulation experiments and comparisons.

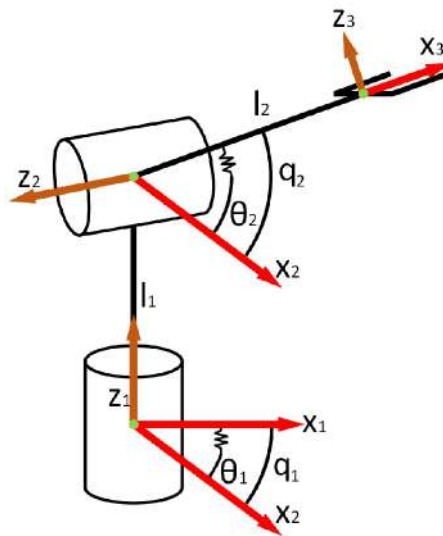


Figure 3: Diagram of the elastic robot arm.

- A Novel Adaptive Sliding Mode Controller for a 2-DOF Elastic Robotic Arm [14]

6.3. Forward Kinematic Modelling with Radial Basis Function Neural Network Tuned with a Novel Meta-Heuristic Algorithm for Robotic Manipulators

A forward kinematic model for a manipulator, shown in figure 4, is proposed in this research utilising a Radial Basis Function Neural Network (RBFNN) architecture optimised via a Cooperative Search Optimisation Algorithm (CSOA). Based on the observation of the input-output connection, the suggested architecture can automatically learn the kinematic features of the manipulator. The suggested model is validated using multiple metrics after simulations on a 3DOF manipulator in ROS. The effectiveness of the CSOA-RBFNN model is compared to that of other models, such as the artificial neural network, support vector regression model, PSO-RBFNN, and GWO-RBFNN, demonstrating the superiority of the suggested approach.

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- A Forward Kinematic Modelling with Radial Basis Function Neural Network Tuned with a Novel Meta-Heuristic Algorithm for Robotic Manipulators [15]

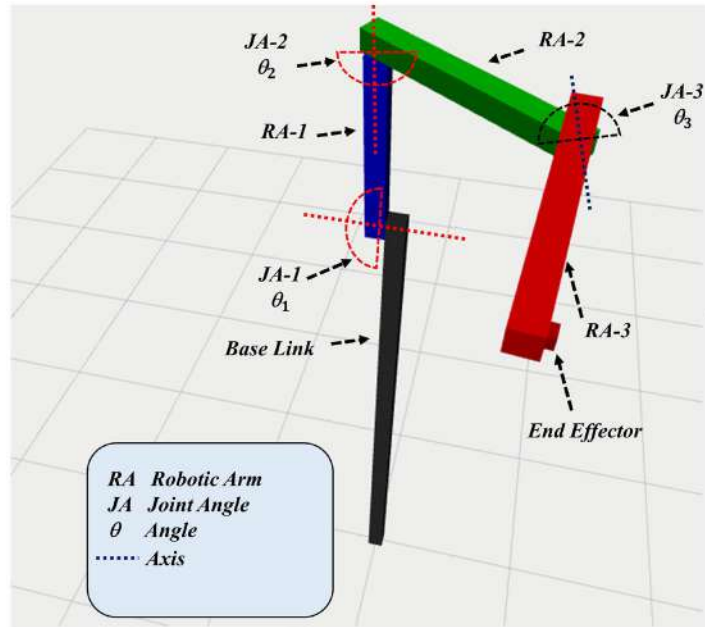


Figure 4: Kinematic model of the 3-DOF manipulator designed in ROS-RVIZ. JA represents the the joint angles while RA represents the arm length.

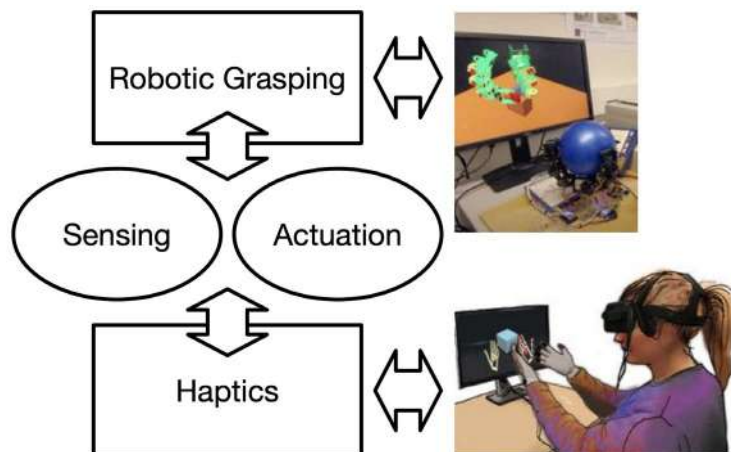


Figure 5: The combination of the advancements in sensing/actuation technology with the betterment of haptic rendering represents a promising opportunity towards the achievement of an effective human-robot interaction (HRI).

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6.4. A Review of the State-of-the-Art of Sensing and Actuation Technology for Robotic Grasping and Haptic Rendering

This study provides an overview of current sensor and actuation technologies for robotic grasping and haptic rendering, as shown in figure 5. After a categorisation of robotic grippers and gripping methods, a study of haptic rendering methodologies and problems, including rigid body, deformable/rigid, fluid, image/video-based, and VR-based interactions, is presented. The latest sensing technology, including touch and optical sensors for robotic hands and grippers, is examined. Lastly, contemporary actuation technology is discussed, with emphasis on soft, micro and nano, multi-fingered, and underactuated grippers. The goal of this study is to offer a foundation for future research and development in this area, as well as to advance attempts to accomplish a broad variety of robotic grasping and haptic technology applications.

- A Review of the State-of-the-Art of Sensing and Actuation Technology for Robotic Grasping and Haptic Rendering [16]

6.5. Mixed reality (MR) Enabled Proprio and Teleoperation of a Humanoid Robot for Paraplegic Patients

As shown in figure 6, his study describes a proprio and teleoperation framework for a humanoid robot that can be controlled by a paraplegic person utilising inputs from an mixed reality (MR) headset. The framework allows for different and unscripted manipulation tasks to be performed in a realistic environment,

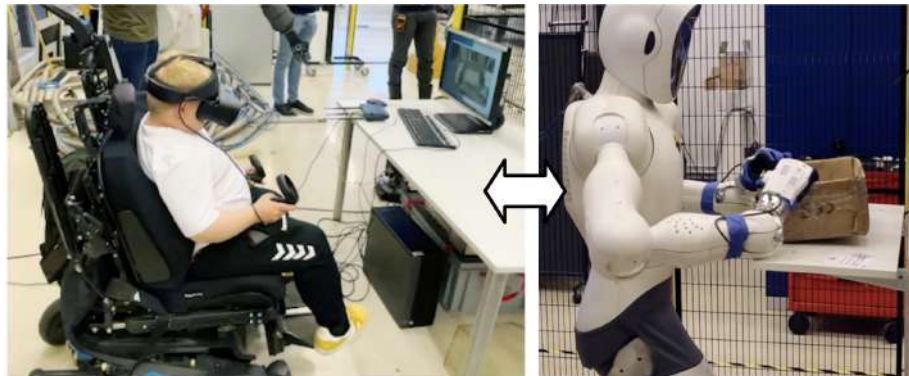


Figure 6: A mixed reality (MR) enabled proprio and teleoperation of a humanoid robot for paraplegic patients.

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including navigation, perception, manipulation, and grasping. A human subject research is provided to exemplify the potential of the proposed framework, demonstrating how the MR-enabled system increases patient engagement and the illusion of presence.

- Mixed reality (MR) Enabled Proprio and Teleoperation of a Humanoid Robot for Paraplegic Patients [17]

6.6. Investigating the User Experience of a Virtual Reality Rehabilitation Solution for a Biomechatronics Laboratory and Home Environment

The purpose of this paper is to offer a feasibility study on the use of virtual reality (VR) technology in physical rehabilitation. As shown in figure 7, the authors built a biomechatronics laboratory with a VR setup and a motion platform for patient training, and they also looked at the possibilities of reproducing this setup in a home-based training system with commercially accessible components. To evaluate the usability and user experience of the VR solutions, user studies were undertaken. The results indicate that the suggested VR solutions are practical; nevertheless, individuals using the home-based system suffered greater cybersickness and unbalance than those using the laboratory solution. Future research will concentrate on developing a safe environment for first patient investigations as well as activities to enhance diagnosis and progress throughout rehabilitation.

- Investigating the User Experience of a Virtual Reality Rehabilitation Solution for a Biomechatronics Laboratory and Home Environment [5]

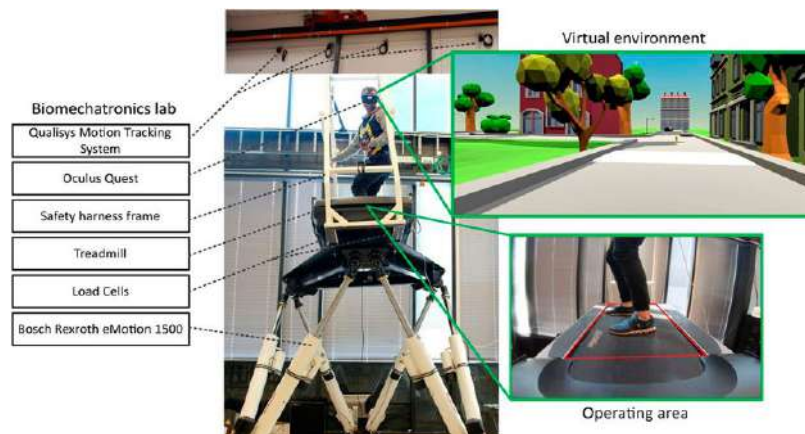


Figure 7: Biomechatronics lab.

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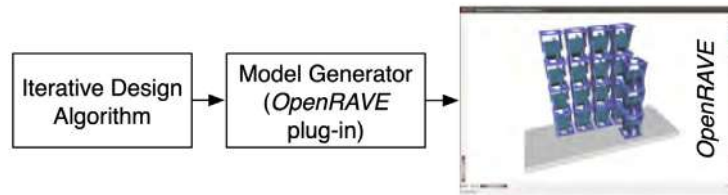


Figure 8: The idea of realising a plugin for OpenRAVE that allows for a fast and automated generation of different modular hand models.

6.7. OpenMRH: a Modular Robotic Hand Generator Plugin for OpenRAVE

OpenMRH, an open-source plugin for OpenRAVE is presented in this study, as shown in figure 8. OpenMRH builds several modular hand models from dynamically produced code and a user-defined input Interface. The models created can be used to test, develop, and deploy grip or motion planning algorithms. Two case studies are used to validate the model generator’s efficiency.

- OpenMRH: a Modular Robotic Hand Generator Plugin for OpenRAVE [18]

6.8. The New Architecture of ModGrasp for Mind-Controlled Low-Cost Sensorised Modular Hands

The purpose of this paper is to present an upgraded version of the open-source ModGrasp framework for designing, modelling, and controlling low-cost sensorised modular hands, as shown in figure 9. The updated version has separate

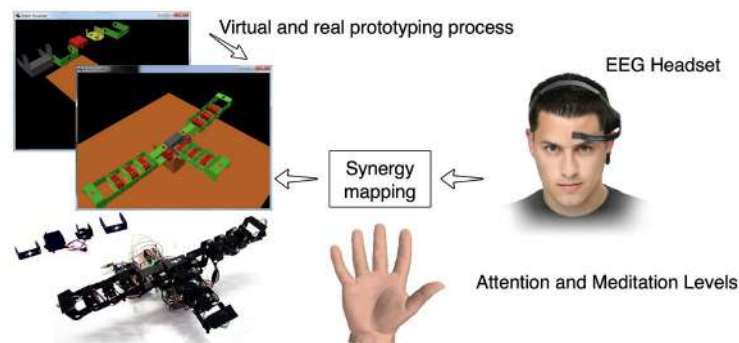


Figure 9: To show the potential of the new ModGrasp control architecture, a mind-controlled, three-fingered modular manipulator is presented. A demo video is available on-line at

<http://youtu.be/2CIYboez9r0>.

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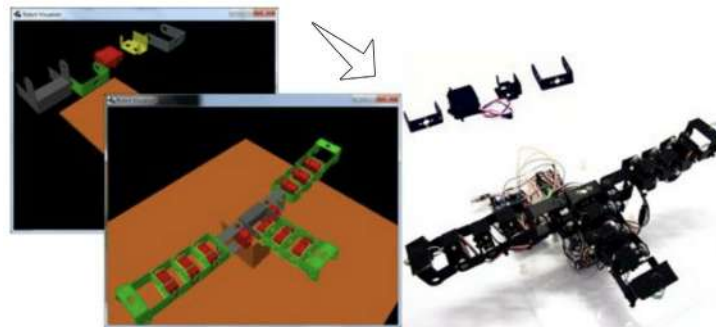


Figure 10: The idea of realising an integrated virtual and physical rapid prototyping framework for the design, simulation and control of low-cost sensorised modular hands.

controller boards for each finger link, as well as a revamped software architecture with a hierarchical logical organisation. A case study of a mind-controlled low-cost modular manipulator that employs an EEG headset to detect the user's levels of attention and meditation to control the hand is shown. The manipulator has 11 degrees of freedom, and a synergistic control strategy is used to match inputs to outputs.

- The New Architecture of ModGrasp for Mind-Controlled Low-Cost Sensorised Modular Hands [19]

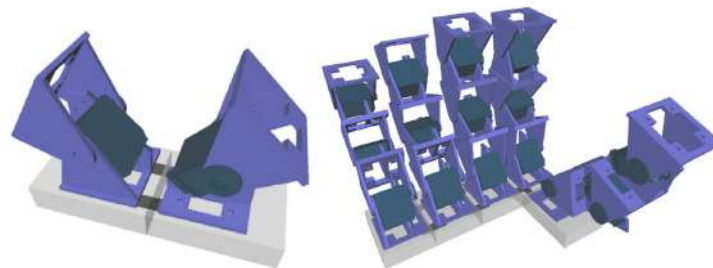


Figure 11: The modular grasping idea: thanks to its flexibility, the device can reproduce both simple grippers and more sophisticated kinematics like anthropomorphic robotic hands.

6.9. ModGrasp: an Open-Source Rapid-Prototyping Framework for Designing Low-Cost Sensorised Modular Hands

ModGrasp, an open-source framework for developing, simulating, and controlling low-cost modular hands, is introduced in the study, as shown in figure 10. Several manipulator configurations may be represented and operated using different algorithms by combining fast prototyping with the modular approach. Joint torque sensing, collision detection, and

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joint compliant control are all possible with low-cost sensors. Visual feedback is provided through a 3-D visualisation environment. A case study of a three-fingered manipulator is shown, and accompanying simulations demonstrate the framework's efficiency and flexibility.

- ModGrasp: an Open-Source Rapid-Prototyping Framework for Designing Low-Cost Sensorised Modular Hands [20]

6.10. Efficient modular grasping: An iterative approach

This research describes a modular approach to robotic grasping that uses simple, resilient, and adaptable modules to mimic human grasping and competent inhand motions, as shown in figure 11. The investigation of the design of modular grasping devices that may adapt to diverse requirements and scenarios, as well as the presentation of an algorithm for selecting optimal modular configurations for efficient object grabbing, is provided. Related simulations were run to test the algorithm's efficiency, demonstrating the modular approach's adaptability in developing grippers.

- Efficient modular grasping: An iterative approach [21]

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MODULE BIOMECHATRONICS APPLICATIONS

Project Title	European network for 3D printing of biomimetic mechatronic systems 21-COP-0019
Output	O1 - EMERALD e-book for developing of biomimetic mechatronic systems
Module	Module – Biomechatronics Applications
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1. Introduction

Biomechatronics is an interdisciplinary field that combines mechanical, electronic, and biological elements to create innovative devices and systems. It is a subfield of biomedical engineering that focuses on the interaction between mechanics and electronics with human biology [1]. Biomechatronic systems can interact with the human muscle, skeleton, and other biological tissues, such as nervous system, to enhance or replace their functions. It is a key area of study in biomedical engineering.

The term "biomechatronics" is derived from the words "biomechanics" and "mechatronics". Biomechanics is the study of the mechanical aspects of biological systems, while mechatronics involves the integration of mechanical, electrical, and computer engineering to create advanced systems [2]. The goal of biomechatronics is to create devices that can restore or enhance the function of the human body.

Examples of biomechatronic devices include prosthetics that can mimic the movements of natural limbs, exoskeletons that can help people with physical disabilities to walk or stand upright, and neuroprosthetic implants that can restore motor function to people with paralysis [2]. The components of a biomechatronic system typically include a human subject, which represents the biological aspect of the system, and a stimulus, which is the input delivered to the system [3].

Biomechatronics is an exciting field that holds great promise for improving the lives of people with disabilities and medical conditions. By combining knowledge from engineering, biology, and medicine, researchers in this field are working to develop innovative solutions that can help people overcome physical limitations and achieve greater independence and mobility. It is a discipline that has the potential to revolutionize healthcare and enhance human performance.

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2. Basics of biomechatronics technology

2.1 Basic definitions and concepts

Mechatronic engineering can be defined as the synergistic combination of electronic, mechanical, control, and computer systems, while biomechatronics is its application in human biology [3]. Below, some basic definitions and concepts pertaining to biomechatronics are presented.

1. **Biomechatronics:** It is an interdisciplinary science that draws concepts and knowledge from various fields of science, such as biology, mechanics, electronics, and mechanical engineering. It deals with the interaction between human organs and electromechanical devices or systems [4].
2. **Applied Interdisciplinary Science:** Biomechatronics is an applied interdisciplinary science that aims to integrate biology and mechatronics, including electrical, electronics, and mechanical engineering. It also encompasses the fields of robotics and neuroscience.
3. **Therapeutic, Assistive and Diagnostic Devices:** Biomechatronics technology researches and designs devices that can be used for therapeutic, assistive, and diagnostic purposes, with the potential to compensate and eventually replace human physiological functions. This includes prosthetics, exoskeletons, and assistive devices for individuals with disabilities.

Biomechatronics is closely related to other concepts, such as biomechanics, electronics, biomimetics and bionics. Relations of these concepts are presented in Figure 2.1, as devised by Witte (2022). Some definitions of the related concepts are presented below:

1. **Biomechanics** is the study of the mechanical properties of biological systems. Biomechatronics devices must be designed to interact with the body in a way that is safe, effective, and natural.
2. **Robotics:** Biomechatronics often incorporates concepts from robotics, including the use of robotic exoskeletons to assist with mobility, and the development of robots with biological characteristics, such as soft, compliant materials and actuator systems that mimic biological muscle.

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3. **Bionics** is defined as the development of modern systems or functions based on similar systems that exist in nature. It involves the study of biological systems and the implementation of their features into engineering design. This approach can be used to create products that are more efficient, adaptive, and versatile than traditional designs.
4. **Biomimetics** is the study of the formation, structure, or function of biologically produced substances and materials such as enzymes or silk, and biological mechanisms and processes such as protein synthesis or photosynthesis. Biomimetics involves copying or synthesizing natural substances and structures to create new products that have improved properties or functions. The aim is to develop artificial products that are compatible with nature and can provide sustainable solutions to various problems.
5. **Biomimicry**, a term closely related to biomimetics, specifically focuses on applying nature-inspired designs to solve human problems.

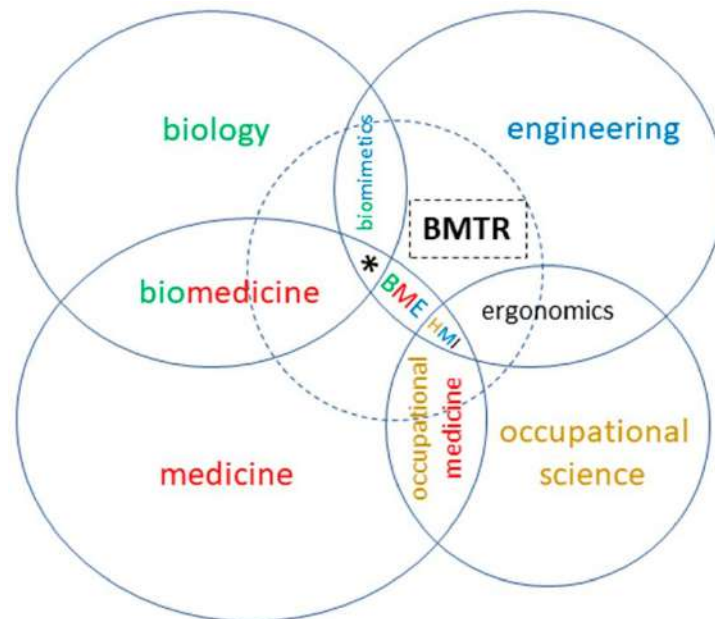


Figure 2.1. Activities of biomechatronics in relation to the related scientific fields. BMTR: biomechatronics; BME: biomedical engineering; HMI: human–machine interaction; Asterisk *: engineering for biology (“E4B”) [5]

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Biomechatronics describes the integration of the human body with engineered, mechatronic devices, to:

- emulate and replace natural human function lost through disease or accident and/or
- augment natural human function to generate superhuman abilities.

Examples of some biomechatronic devices are presented in Figure 2.2.

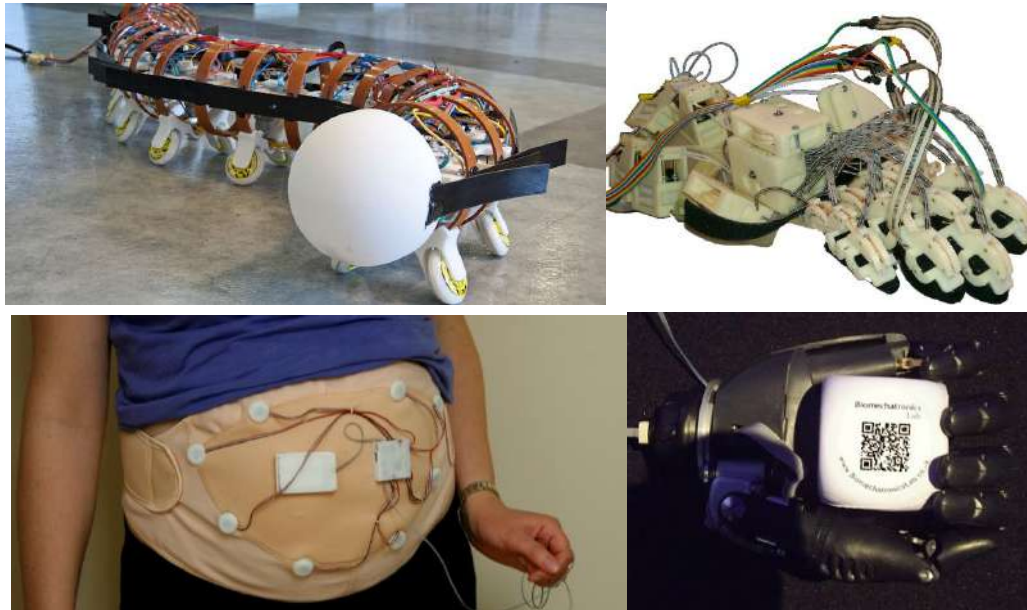


Figure 2.2. Examples of biomechatronic devices [6][7]

2.2 Biomechatronic systems

2.2.1 Basics of biomechatronic systems

A biomechatronic system is a complex system that incorporates biological and mechanical components to achieve a specific function. These systems can be used for a variety of purposes, including rehabilitation, prosthetics, and medical devices. Biomechatronics can be used to restore or enhance the function of the human body, as well as to create entirely new functions that are not possible with biological systems alone.

A scheme of work of a biomechatronic system is shown in Figure 2.3. It is noteworthy that the prominent element in the system – as opposed to typical mechatronic systems – is a human being (that could be replaced with any biological system). The human subject adds *bio*

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to the mechatronic control and monitoring process. The human element is not only the most complex and least understood, but also the most difficult to interface to [1].

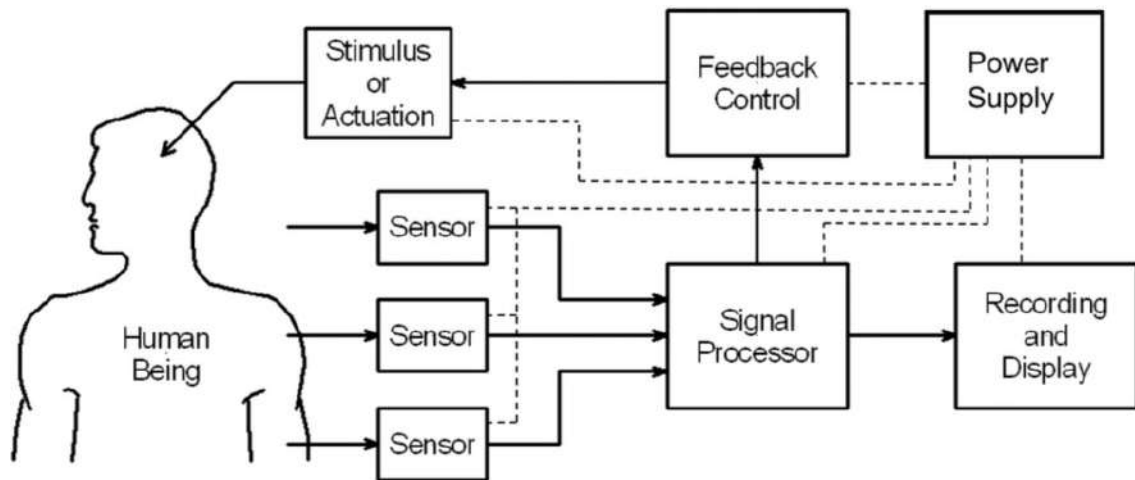


Figure 2.3. Principle of operation of biomechatronic system [1]

Basic elements of mechatronic systems, as mentioned in previous chapter, are:

- actuators (e.g. robotic arms or other powered devices),
- sensors (biosensors),
- signal processors,
- devices for recording and display,
- power supplies.

Some of these key concepts are described below.

1. Actuation: This refers to the ability of biomechatronic devices to create motion, either through the application of force or the generation of a torque. Examples of actuators used in biomechatronics include electric motors, pneumatic systems, and hydraulic systems.
2. Sensors: Biomechatronic devices require sensors to detect changes in the environment or within the human body, such as changes in temperature, pressure, or muscle activity. These sensors may be invasive, such as implantable electrodes, or non-invasive, such as surface electromyography.

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3. Control systems: Biomechatronic devices require sophisticated control systems to regulate and adjust their behavior based on input from sensors. Control systems may use feedback or feedforward mechanisms to ensure the device behaves as intended.
4. Human-machine interface: A key aspect of biomechatronics is the interaction between the human body and the biomechatronic device. Human-machine interfaces can take many forms, including direct neural interfaces, haptic feedback systems, and visual displays. The human subject represents the bio part of biomechatronic systems and makes them unique [1].
5. Signal conditioning elements: Signal conditioning elements are used to amplify, filter, or modify the electrical signals generated by the transducers and sensors to make them suitable for processing by the system.
6. Recording and display: Recording and display elements are used to store and visualize the data generated by the system, which is useful for monitoring and analyzing the system's performance.
7. Feedback elements: Feedback elements are used to adjust the system's output based on the measured performance, which is useful for improving the system's accuracy and stability.

One example of a biomechatronic system is a prosthetic limb. A prosthetic limb is a device that replaces a missing limb and provides the user with the ability to perform tasks that they would otherwise be unable to do. Biomechatronic prosthetics incorporate sensors and microprocessors that allow the device to communicate with the user's nervous system, providing feedback on the position and movement of the limb. This feedback allows the user to control the prosthetic limb in a natural and intuitive way, allowing them to perform tasks such as walking, running, and gripping objects.

Another example of a biomechatronic system is an exoskeleton. An exoskeleton is a wearable device that is designed to assist the human body in performing physical tasks. Biomechatronic exoskeletons incorporate sensors and motors that provide assistance to the wearer's muscles and joints, allowing them to perform tasks that would otherwise be too difficult or impossible. These devices can be used for rehabilitation, enabling individuals with

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injuries or disabilities to regain strength and mobility, or for military applications, providing soldiers with enhanced strength and endurance.

Biomechatronic systems can also be used for medical applications. For example, implantable medical devices such as pacemakers and artificial organs incorporate mechatronic components that allow them to interact with the human body in a controlled and precise way. These devices can be used to treat a variety of medical conditions, including heart disease, kidney failure, and diabetes.

One of the key challenges in developing biomechatronic systems is the need to integrate biological and mechanical components in a seamless way. This requires a deep understanding of both the biology of the human body and the engineering principles that underpin mechatronic technologies. Biomechatronics researchers must be skilled in a wide range of disciplines, including biology, mechanical engineering, electronics, and computer science.

2.2.2 Biosensors

Biosensors are analytical devices that are used to detect and quantify biological and chemical compounds in various applications. In biomechatronics devices, biosensors are used to measure physiological signals such as heart rate, body temperature, and blood glucose levels. These devices can be implanted or worn externally and provide continuous monitoring of a patient's health status. The development of biosensors has opened up new possibilities for monitoring health conditions and improving patient outcomes.

Biosensors used in biomechatronics devices generally consist of three main components: a biological sensing element, a physicochemical detector or transducer, and a signal processing system [8]. The biological sensing element interacts with the analyte of interest, and the physicochemical detector converts this interaction into a measurable signal. The signal processing system then converts this signal into a meaningful output for the user (Figure 2.4).

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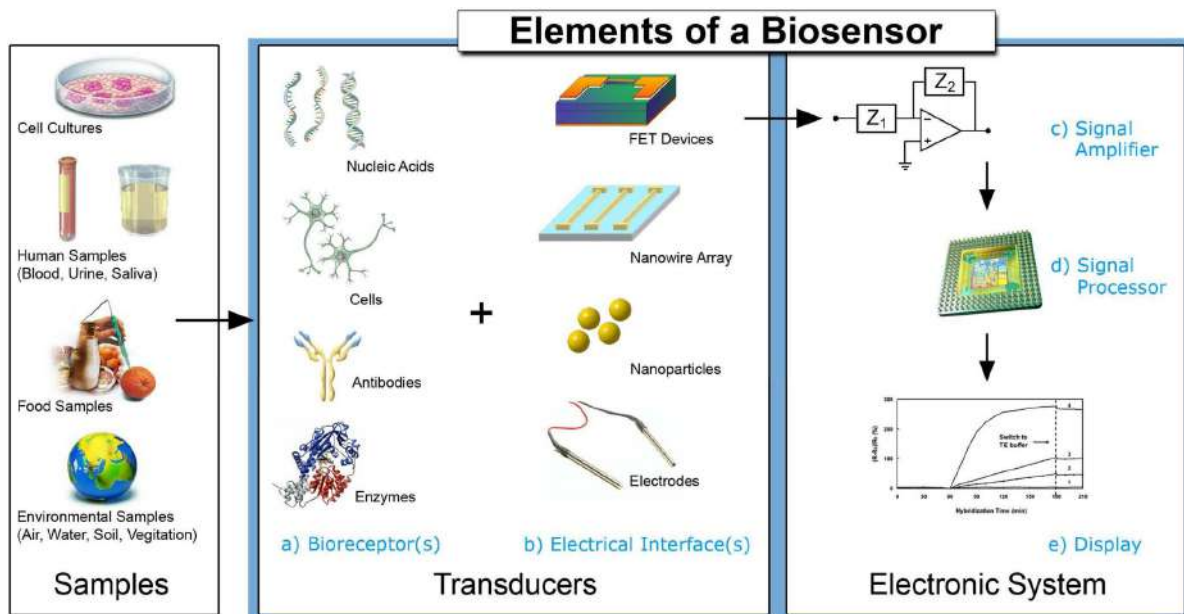


Figure 2.4 Principle of operation of biosensors [10]

The biological sensing element in a biosensor used in biomechatronics devices can be any type of biomolecule that interacts with the analyte of interest. The most common types of bioreceptors used in biosensors are (1) antibody-antigen interactions, (2) enzymatic interactions, (3) cellular (microbial) interactions, (4) nucleic acid interactions, and (5) synthetic bioreceptors (biomimetic) [9]. Each of these bioreceptor types has its own advantages and disadvantages, and the selection of the appropriate bioreceptor depends on the specific application.

Antibody-antigen interactions are commonly used in biosensors for the detection of proteins and other large molecules. The antibody is specific to the antigen of interest, and the interaction between the two molecules generates a measurable signal. Enzymatic interactions are used to detect small molecules such as glucose and cholesterol. In this case, the enzyme catalyzes a reaction that generates a measurable signal. Cellular (microbial) interactions involve the use of living cells to detect analytes. These cells can be genetically engineered to produce a specific response to the analyte of interest. Nucleic acid interactions are used to detect DNA and RNA sequences. In this case, the biosensor uses a complementary sequence

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of nucleic acids to bind to the target sequence. Synthetic bioreceptors are designed to mimic the function of natural bioreceptors and are often used when a natural bioreceptor is not available [8].

The physicochemical detector or transducer in a biosensor used in biomechatronics devices converts the biological interaction into a measurable signal. There are many different types of transducers, including electrochemical, optical, and mechanical. Electrochemical transducers are the most commonly used in biosensors for biomedical applications. They work by measuring the electrical properties of the biological interaction, such as changes in voltage or current. Optical transducers work by measuring changes in light intensity or wavelength, and mechanical transducers work by measuring changes in pressure or flow [8].

The signal processing system in a biosensor used in biomechatronics devices converts the signal generated by the transducer into a meaningful output for the user. This can be done using various techniques, including amplification, filtering, and digital signal processing [8]. The output can be displayed on a screen or transmitted wirelessly to a remote monitoring system for further analysis.

Biosensors used in biomechatronics devices can be used for a variety of applications, including monitoring glucose levels in diabetic patients, measuring heart rate and blood pressure, and detecting the presence of certain biomarkers for disease diagnosis. These devices can be implanted or worn externally and can provide continuous monitoring of a patient's health status. In addition to medical applications, biosensors can also be used in environmental monitoring, food safety, and other fields.

An example might be a wearable biosensing device, involving machine learning techniques for hand gesture recognition, as described by Moin et al. (2020) [11]. Principle of work of this device is shown in Figure 2.5.

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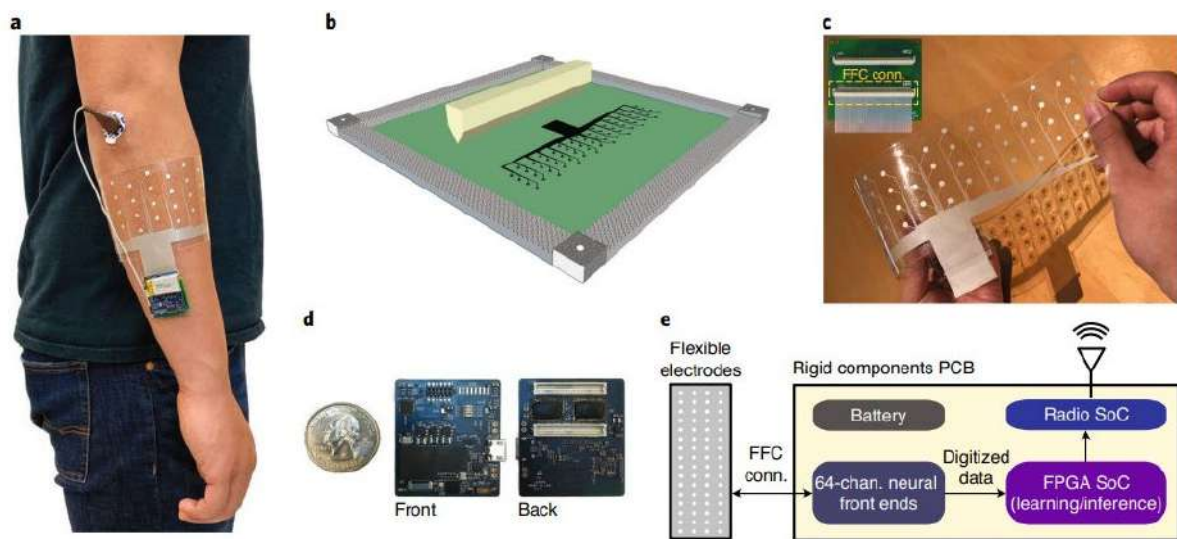


Figure 2.5. Example of wearable biosensing system for sEMG [11]

Here are some examples of the use of biosensors in biomechatronics devices, along with details about their operation and benefits.

- 1 **Prosthetic Limbs:** Biosensors are being used to help amputees control their prosthetic limbs more effectively by providing feedback on muscle activity and other physiological parameters. In one study, researchers used electromyography (EMG) biosensors to detect muscle activity in the residual limb of amputees, which was then used to control a robotic prosthetic hand [12]. The biosensors were able to accurately detect the intended movements of the amputees and translate them into movements of the prosthetic hand. This technology has the potential to greatly improve the quality of life for amputees, allowing them to perform tasks that were previously impossible.
- 2 **Wearable Sensors:** Biosensors can also be integrated into wearable devices to monitor various physiological parameters, such as heart rate, blood pressure, and body temperature [13]. These sensors can provide real-time feedback on the wearer's health and can be used to track changes over time. For example, researchers have developed a wearable biosensor that can detect dehydration in athletes by monitoring changes in skin conductivity [14]. The biosensor was able to detect

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dehydration in real-time, allowing the athletes to take action to prevent further dehydration.

- 3 Biofeedback Systems: Biosensors can also be used in biofeedback systems, which allow users to monitor their physiological parameters and use that feedback to control various devices or systems. For example, researchers have developed a biofeedback system that uses EMG biosensors to detect muscle activity in the user's forearm, which is then used to control the movement of a robotic arm. The user is able to control the movement of the robotic arm simply by flexing their muscles, without the need for any external controllers.
- 4 Brain-Computer Interfaces: Biosensors can also be used in brain-computer interfaces (BCIs), which allow users to control devices or systems using their thoughts (Fig. 2.. The state-of-the-art biosensors are able to accurately detect the user's intent to perform certain actions, such as moving a cursor on a computer screen. BCIs have the potential to greatly improve the quality of life for people with disabilities, allowing them to control devices and interact with the world in ways that were previously impossible.

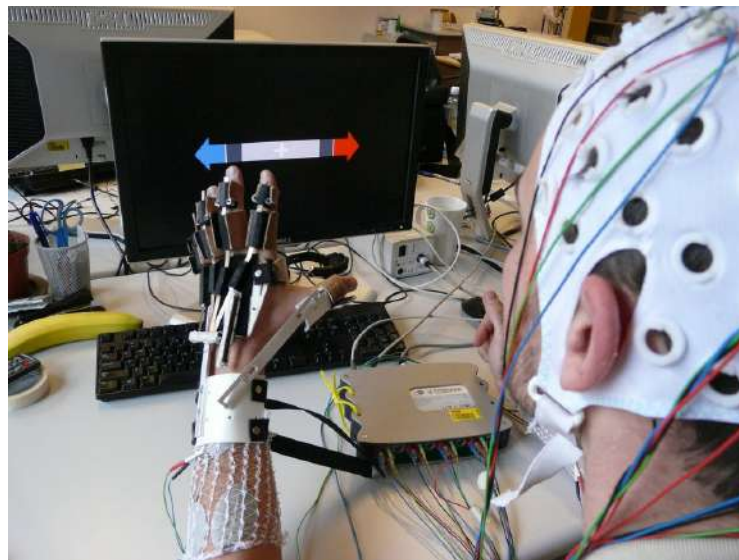


Figure 2.6. Example of a Brain-Computer Interface [15]

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2.2.3. Actuators

Actuators are devices that convert energy into mechanical motion, allowing for movement and control in biomechatronic devices. In biomechatronics, actuators are an essential component of prosthetic and orthotic devices, helping to replace or augment natural muscle function [16] (Figure 2.7). There are several types of actuators used in biomechatronics, including electric, hydraulic, and pneumatic actuators.

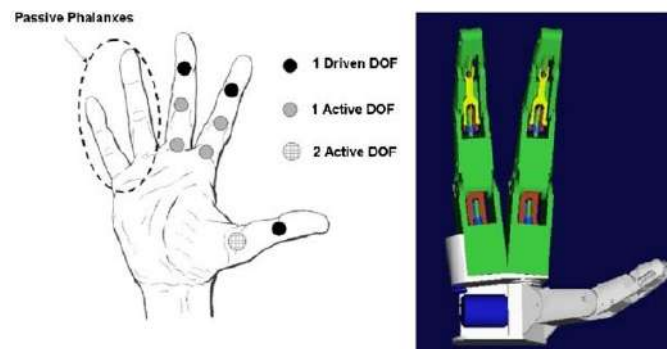


Figure 2.7. Example of a biomechatronic hand with actuated fingers [16]

Electric actuators, such as DC motors or stepper motors, are commonly used in prosthetic devices to control the movement of joints or limbs. These actuators work by converting electrical energy into mechanical energy, allowing for precise control over movement. Some prosthetic devices also incorporate hydraulic actuators, which use pressurized fluid to generate force and motion. Hydraulic actuators are capable of producing high forces and are often used in more advanced prosthetic devices.

Pneumatic actuators, which use compressed air or gas to generate movement, are also used in biomechatronics. These actuators are often used in soft robotics, as they are lightweight and flexible, making them ideal for applications that require a high degree of compliance and adaptability. Pneumatic actuators can be used to create soft robotic grippers or manipulators, which can be used in biomedical applications such as surgical robots or exoskeletons.

Nowadays, a paradigm shift can be observed in biomechatronics actuators, towards use of soft robotics approach, with quasi-direct drives controlled by force rather than position, with

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lightweight components, able to be implemented mostly in orthotic and prosthetic devices for people with special needs [17] (Figure 2.8).

Quasi-Direct Drive: A New Actuation Paradigm

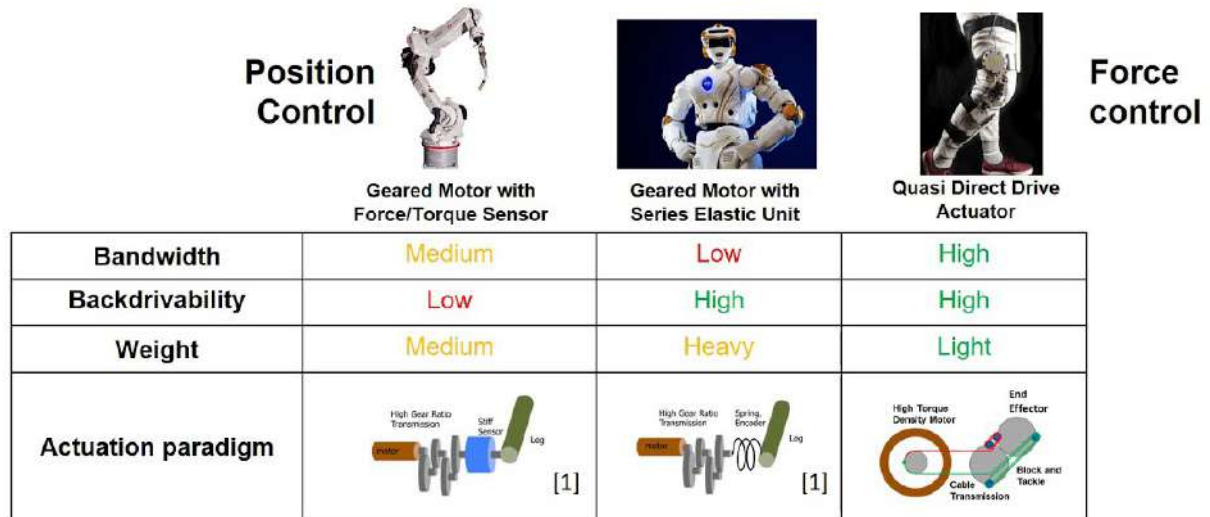


Figure 2.8. Quasi-direct drive in biomechatronic devices: paradigm shift [17]

Overall, actuators are a crucial component of biomechatronic devices, allowing for precise control over movement and enabling the development of advanced prosthetic and orthotic devices as well as soft robotics applications. The choice of actuator type depends on the specific requirements of the device and the intended application.

2.2.4. Signal conditioning and processing devices

Signal processing in biomechatronics is a crucial part of operation of these devices, especially in terms of safety and functionality in aiding human users in operations they need to perform. Processing of signal is realized as shown in Figure 2.9. Output from conditioning elements are in the form of DC/AC voltage / current. Certain calculations (processing) need to be performed on these signals, in order to establish value of variable being measured, which will be then interpreted and send for further use, e.g. to the actuators.

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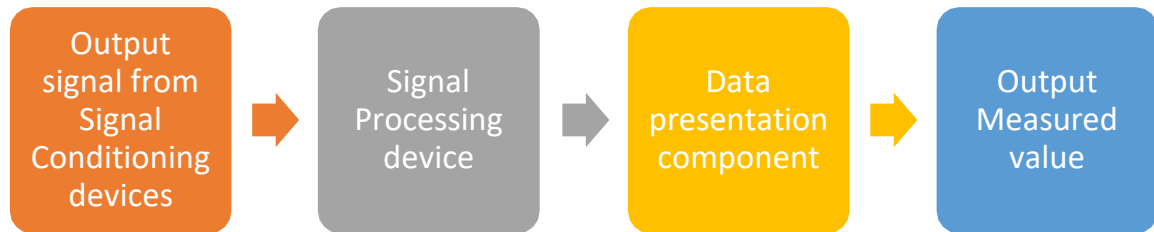


Figure 2.9. Signal transferring in biomechatronic devices

Signal conditioning elements are used in biomechatronics to manipulate signals from various transducers and sensors to prepare them for further processing. These elements are responsible for amplifying, filtering, and converting signals to a form that can be easily interpreted and analyzed by the system. Some common examples of signal conditioning elements used in biomechatronics include:

1. Amplifiers: used to amplify low-level signals from sensors to a level that can be easily processed and analyzed by the system.
2. Filters: used to eliminate noise and unwanted frequencies from the signal.
3. A/D converters: used to convert analog signals to digital signals that can be easily processed and analyzed by digital systems.
4. Instrumentation amplifiers: used to amplify low-level signals while rejecting common-mode noise and interference.
5. Signal isolators: used to electrically isolate the input signal from the output signal to prevent any unwanted coupling.

Examples of transducers and sensors that require signal conditioning in biomechatronics include accelerometers, thermocouples, thermistors, resistance thermometers, strain gauges, and bridge sensors. Signal conditioning is a critical aspect of data acquisition and analysis in biomechatronics, as it ensures accurate and reliable measurement of biological signals.

Signal processing devices are an essential component of biomechatronic systems. These devices are responsible for collecting and processing data from the biosensors and mechanical sensors that are integrated into biomechatronic devices. The collected data is then analyzed to extract features that can be used to control the movements of the actuators. The signal

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processing devices also enable the extraction of useful information from wearable physiological signals, such as ECG, EEG, EMG, BP, and PPG, which are crucial for monitoring the user's physiological responses. The signal processing devices must be designed to operate in a low-power environment to conserve battery life and enable the development of autonomous, intelligent, and connected biomechatronic devices. Overall, signal processing devices are critical to the functionality of biomechatronic systems, as they enable the real-time processing and analysis of data, which is necessary for the precise control of the actuators and the detection of the user's physiological responses.

Example of signal flow in a biomechatronic device is shown in Figure 2.10.

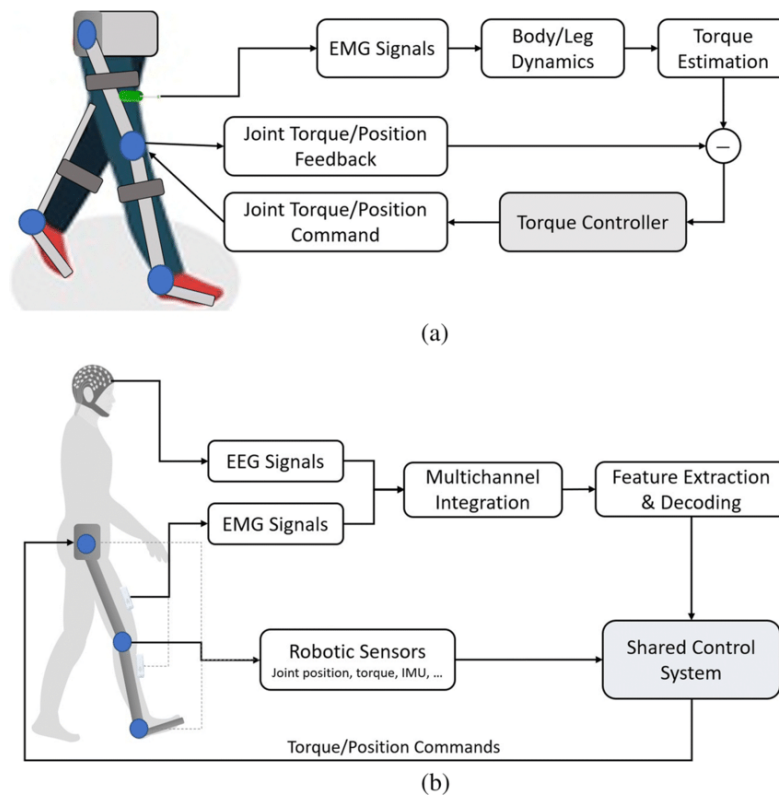


Figure 2.10. Lower limb exoskeleton control scheme [18]

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3. Examples of biomechatronic applications

3.1. Review of applications of biomechatronics

The biomechatronics has many biomedical applications. Some of them are listed below:

- Bio-interfaces for diagnostics and control
- Robotics for high-speed screening and analysis
- Passive and active prosthetic limbs and joints
- Bio-electrical signal processing
- Sensing and biofeedback
- Medical imaging and diagnostics
- Rehabilitation systems
- Neural and brain stimulation
- Tele and robot-assisted surgery
- Mobility aids
- Home care and elderly care
- Implants [3]

In the future, biomechatronics could also be used in [3]:

- Brain prostheses
- Autonomous hospitals
- Memory down/upload
- Nano-machines and micro-robots
- Powered exoskeletons
- Hyperspectral vision – artificial eyes
- Pervasive neural interfaces

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3.2. Biomimetic example – hand prostheses

3.2.1. Introduction

Hand prostheses are a great example of biomimicry, where engineers and designers create products and technologies that imitate nature's solutions to various problems. Hand prostheses are designed to mimic the functionality of natural hands, enabling individuals who have lost their hands or fingers due to injury or illness to perform daily activities with greater ease and independence.

Biomimetic hand prostheses use advanced technologies such as sensors, motors, and microprocessors to mimic the movements of natural hands. The sensors detect the movements of the user's remaining muscles or residual limb, and translate these signals into movements in the prosthetic hand. The motors and microprocessors then coordinate the movements of the fingers and hand to perform various tasks such as grasping, holding, and releasing objects. Some modern hand prostheses use myoelectric sensors to detect the electrical signals produced by the remaining muscles in a person's arm, which are used to control the movements of the prosthetic hand. This is similar to how the human hand is controlled by electrical signals from the brain that travel through the nerves and muscles.

Additionally, some hand prostheses are designed to mimic the movement and grip strength of a real hand. They may use mechanisms like pulleys and cables to achieve this, similar to the tendons and muscles in the human hand.

Biomimetic hand prostheses can provide individuals who have lost their hands with more natural movements and greater functionality, allowing them to perform a wider range of tasks with greater ease and precision. Some biomimetic hand prostheses are designed to look and feel like natural hands, with skin-like coverings and realistic-looking fingers. Others are designed to be more functional and practical, with a more mechanical appearance and greater durability.

3.2.2. Soft biomimetic prosthetic hand

The figure 3.1 presents the soft biomimetic prosthetic hand. The child's prosthetic hand contains six independent, soft and flexible pressure-driven actuators. Each finger uses one

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actuator and can be controlled independently of the other fingers. The thumb is equipped with two actuators that allow it to bend and change its position between opposition and recumbent. The hand is designed so that it can be easily manufactured without expensive equipment. It is made of two types of two-component silicone reinforced with polyester thread. The main part of the device, the rubber exoskeleton, is made of the relatively rigid SmoothOn SmoothSill 940 (Shore A40) silicone, while the actuators are made of the much softer SmoothOn EcoFlex 0050 (Shore 00 50) material. This combination of materials allows the mechanical properties of the fingers to be pre-programmed into the hand structure and transform the linear deformation of the actuators into the required retraction motion of the fingers.

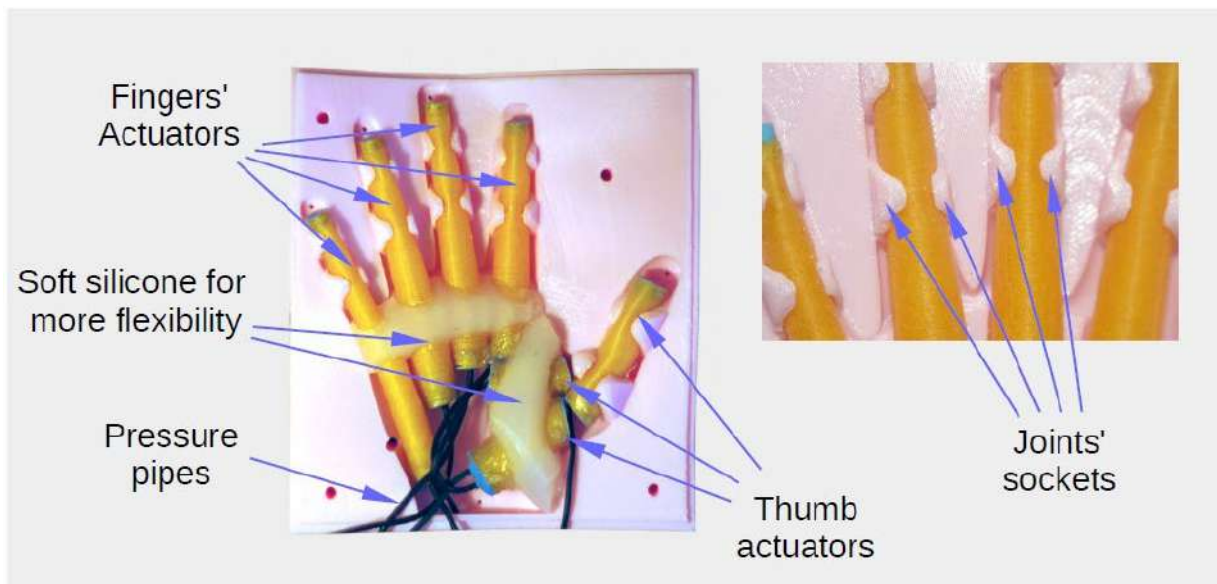


Figure 3.1 Alignment of pneumatic actuators in the main mould [20]

The valves are controlled by providing voltage signals in a range from 0 to 10 V. In our case the voltage signal is emulated by a PWM signal generated by a Raspberry PI running a Python script.

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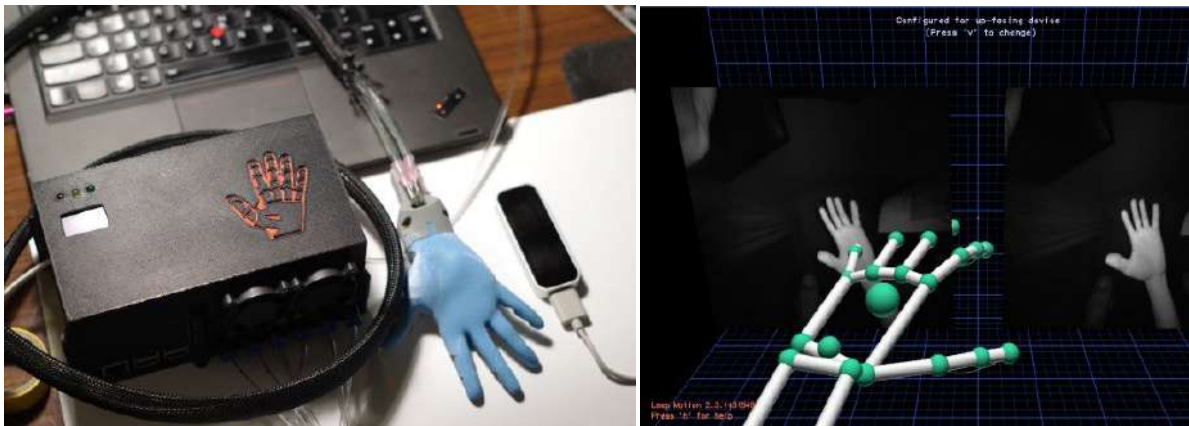


Figure 3.2 (a) The control unit and the LeapMotion controller, (b) LeapMotion-based hand tracking [20]

3.2.3. Rigid prosthetic hands

The figure 3.3 presents the next type of custom hand prosthesis. a biomimetic prosthetic augmentation attachment that interfaces with human body to serve as an additional limb. The project consists of an open source 3D printed prosthetic hand mounted on an aluminum pylon dressed with biomimetic fairings that interfaces with forearm through a mount with micro adjustable tensioners and an adjustable elbow joint. Thumb opposition, pinch-release, and power grasp movements of the prosthetic hand are mediated through three servo motors controlled by an Arduino that translates muscle movements sensed by an infrared proximity sensor into open hand and close hand commands.

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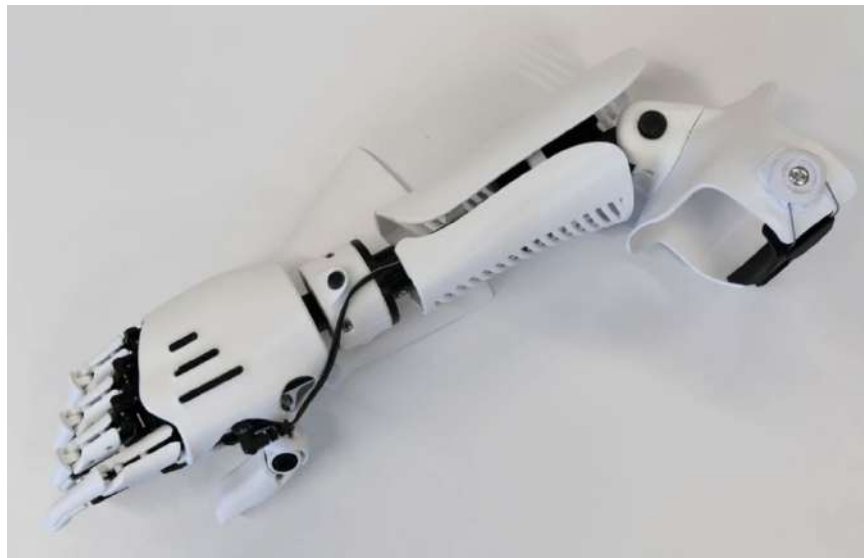


Figure 3.3. A view of the fully assembled prosthetic hand made by Rodolfo Antonio Salido Benítez [19]

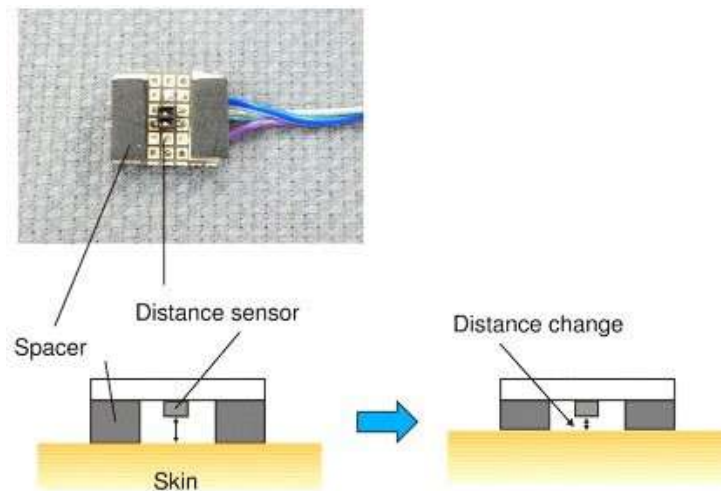


Figure 3.4. Method of operation of the proximity sensor used [19]

- prosthesis with surface electromyography

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The figure 3.5 shows a prosthesis with surface electromyography (EMG) capability. The device has a small surface EMG sensor that detects myoelectric signals in the stump (Figure 3.5 b). The maximum voltage difference when the patient contracts the flexor or extensor muscles of the wrist was used as the reference myoelectric signal to control the device (Fig. 3.5c). In each patient, the EMG sensor site in the support socket showing the maximum voltage difference was identified and used (Fig. 3.5 c). Manipulation of the prostheses was performed using the EMG signal produced by the patterns formed during each voluntary muscle contraction.

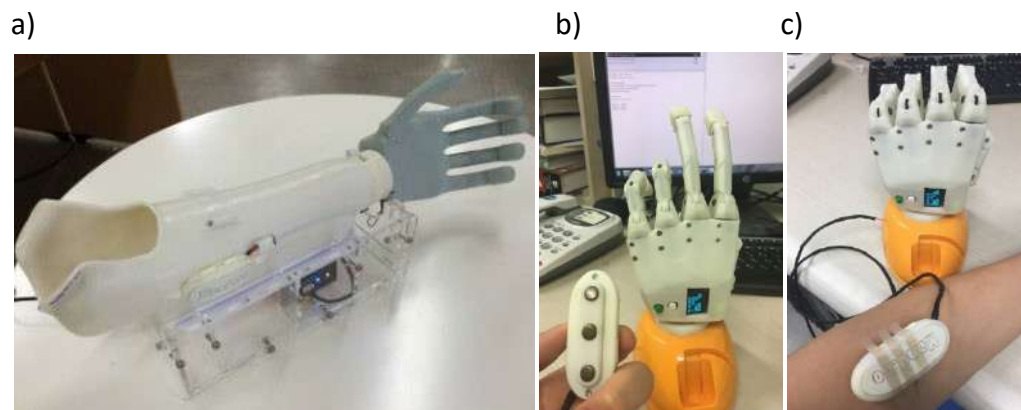


Figure 3.5. (a) A single-channel electromyography (EMG) sensor was installed in the socket where the maximum voltage change in the amputated forearm was checked. (b, c) A prosthesis model with a surface EMG sensor detects the site of the largest voltage change in the myoelectric signal in the stump when the patient moves the rest of the forearm muscle. The voltage change is displayed on a screen on the hand. This model can be used for pre-application testing and for patient observation, three-dimensionally [21]

- prosthesis arm

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Figure 3.6. A prosthesis simulator for use in anatomically intact individuals. The socket is designed to fit over the forearm and fist. Straps allow the socket to be pressed against the person's arm. It is not possible to customize the electrode placement for each person [22]

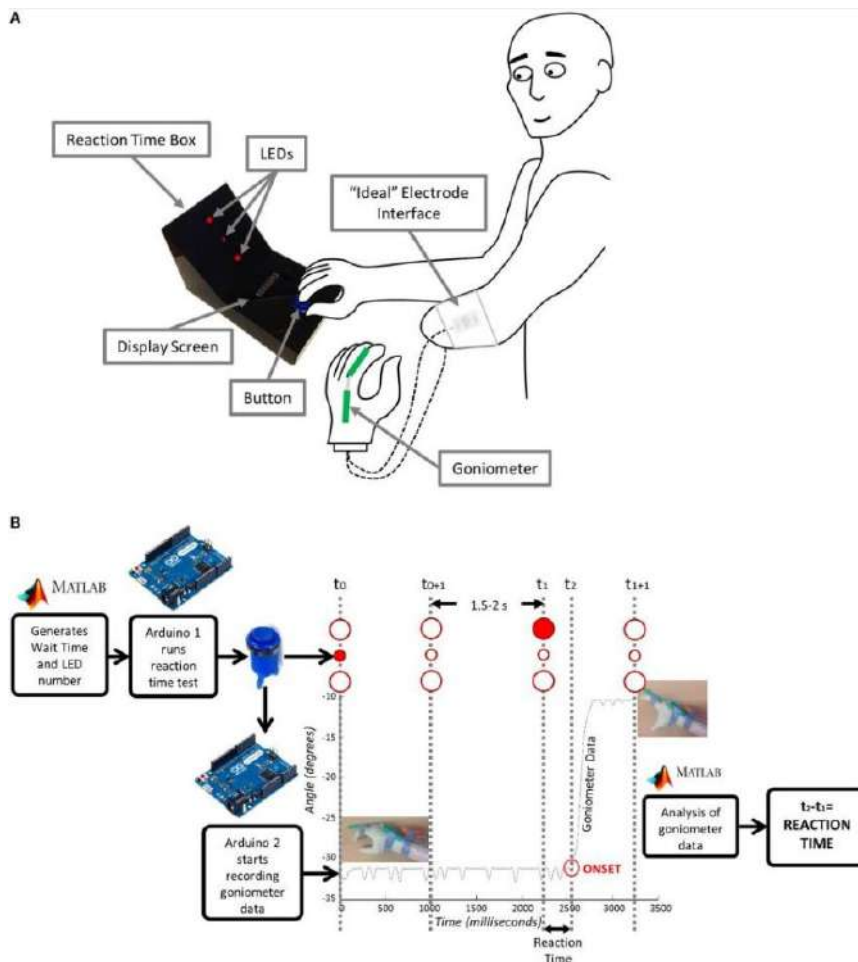


Figure 3.7. Reaction time test: (A) Experiment setup and (B) basic instrumentation [22]

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The figure 3.7. presents, how Matlab generates the wait time and LED number and sends them to Arduino1, which starts the test. The user confirms its readiness by pressing a button. The goniometer starts recording and the central LED lights up for 1 s. After a period of 2.5-3 s, one of the larger LEDs lights up and the user performs a hand movement. An Arduino2 connected to the goniometer sends the motion data to Matlab, where it is analyzed and the reaction time is sent back to the user.

The Figure 3.8 shows a multifunctional myoelectric prosthetic hand system for upper limb amputees. The hand has five fingers, each of which can be actuated by a controller with a six-axis motor driver to perform flexion and extension movements. In the case of the thumb, adduction and abduction movements can be performed manually or automatically by driving the motor at the temporomandibular joint. Two EMG signals are used to perform various hand gestures and grip movements of the developed hand. The electrical signal is output as an envelope according to the movement of the muscle.

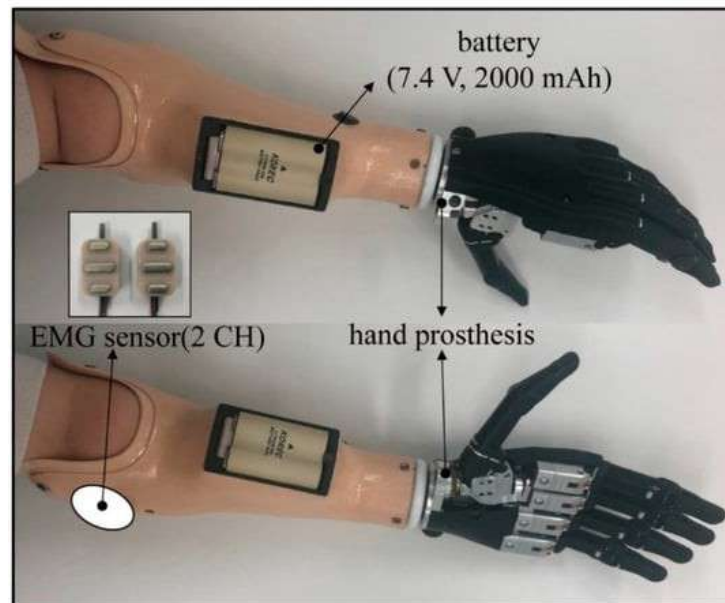


Figure 3.8. The developed multifunctional myoelectric hand prosthesis system [23]

A rechargeable lithium-ion battery with an input voltage of 7.4 V and a capacity of 2000 mAh was used to drive the hand.

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The human hand can perform various grasping movements. The developed system can perform four hand gestures - thumb up, OK, win and point - and four grasping movements - strong grasp, hook grasp, side grasp and peak grasp - using an easy and effective control algorithm (see Figure 3.9).



Figure 3.9. The hand gestures and grip motions performable by the hand [23]

3.3. Bioinspired robotic hands – modular grasping (ModGrasp)

Mimicking the human hand’s ability, one of the most challenging problem in bio-inspired robotics due to large gap in terms of performances. Classical approach, analysis of the kinematic behavior of the human hand involves simplified human hand models with minimum and optimal degrees of freedom. A promising solution is modular grasping, as it provides minimum number of degrees of freedom necessary to accomplish the desired task.

Modular grasping is a trade-off between a simple gripper and more complex human like manipulators. It adheres to the principle of minimalism: choose the simplest mechanical structure, the minimum number of actuators, the simplest set of sensors, etc. In modular grasping, identical modules are used to build linkages to realize the grasping functions. The modular grasping meets the requirements of standardization, modularization, extendibility and low cost [24].

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Figure 3.10 Modular grasping – a) possible functions, b) modular structure

ModGrasp is an open-source rapid-prototyping framework for designing low-cost sensorised modular grasping hands, developed by author of this module [25]. The rapid-prototyping approach is combined with the modular concept so that different manipulator configurations can be rapidly modelled. This method consists of an immersive design process that involves mechanics, hardware and software. A real-time one-to-one correspondence between virtual and physical prototypes is established. The on-board, low-cost torque sensors provided within each module allow for evaluating the stability of the obtained grasps. An intuitive visual feedback is also provided during the designing phase by means of a 3-D visualisation environment. Moreover, both the virtual models and their physical counterparts can be controlled by using the same input device [26].

Architecture of the system is presented in Fig. 3.11. It is based on master-slave communication. Each module is controlled by a slave controller board, which communicates with a master controller board. The controlled manipulators are simulated in a 3-D visualisation environment that communicates with the master controller. If one or more modules break or are disassembled from a prototype, the manipulator keeps working with the remaining functioning joints.

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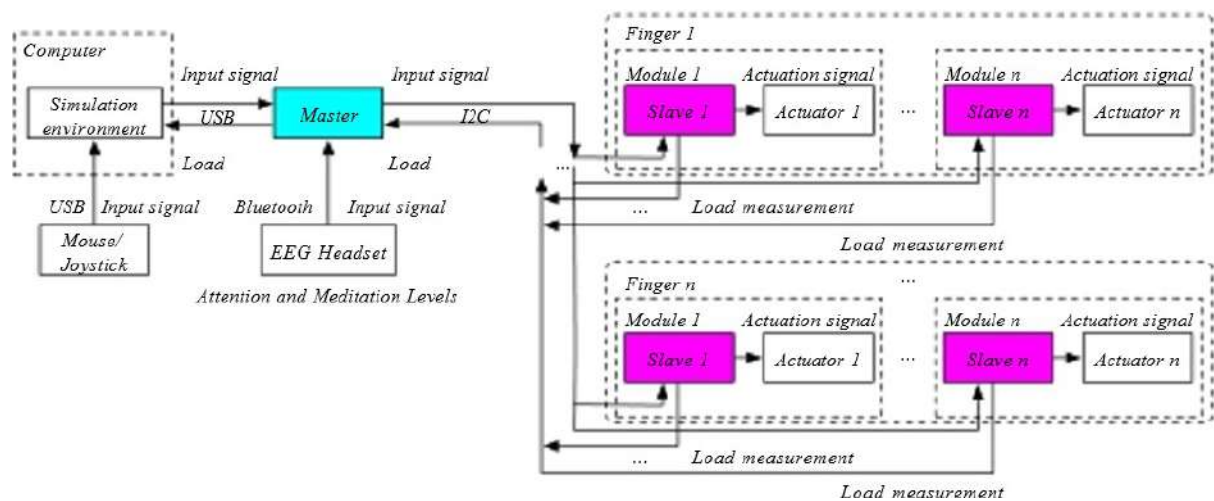


Figure 3.11. ModGrasp architecture

For control of the modular grasping device, open hardware with Arduino is used. An Arduino Uno board based on the ATmega328 micro-controller is used as the master, while one Arduino Nano board is used as a slave to control each finger joint. Support for different input devices is assured – device can be directly controlled from the simulator environment by means of a computer mouse/joystick or work stand-alone and be controlled by means of a set of potentiometer shafts that are used as input controllers. The standard I2C is used as a communication protocol. The physical manipulator models communicate with the simulation environment through the serial interface. Example of implementation is shown in Fig. 3.12.

As method of input is irrelevant, various sources can be used for controlling of the grasping device. In spirit of biomechatronics, human biology can be directly used, via means of brainwaves registered and transmitted real-time through EEG headset. This allows to obtain a low-cost sensorized modular hand controllable by human mind (Fig. 3.13.)

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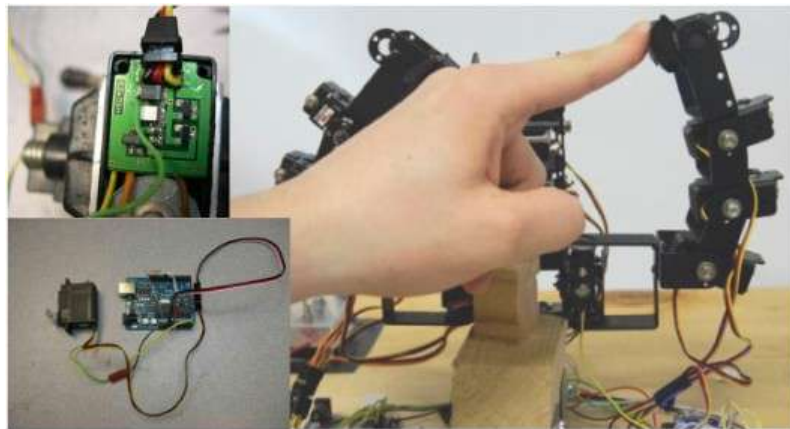


Figure 3.12. ModGrasp implementation – sensing of torque

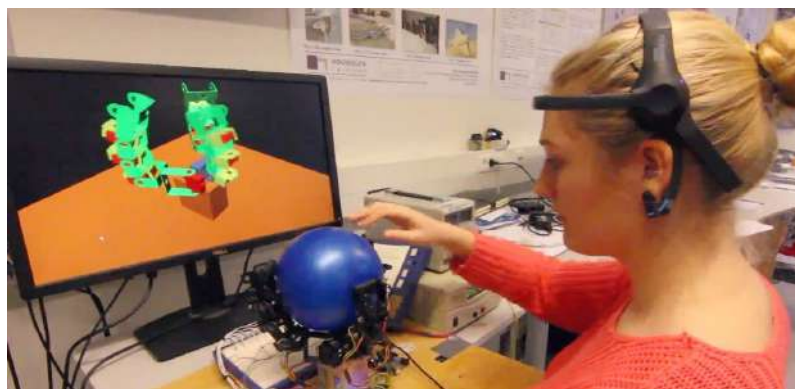
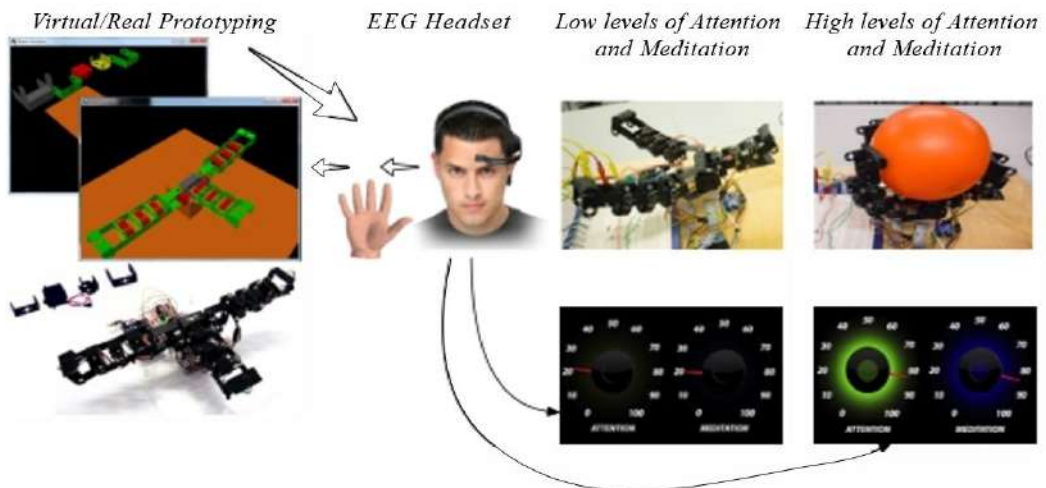


Figure 3.13. ModGrasp implementation – mind control – concept (top) and experiment (bottom) [27]

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3.4. Biomechatronic exoskeletons

An exoskeleton is an external support structure that provides protection and support for an organism's body. In biology, exoskeletons are found in many invertebrates such as arthropods, crustaceans and insects. These organisms have a tough, protective outer layer that serves as both armour and structural support for their bodies.

In recent years, exoskeletons have also been developed that can be used in robotics and human assistance. These exoskeletons are typically made of lightweight materials, such as carbon fibre, and are designed to increase the user's strength and mobility. They are used to help people with disabilities or injuries to walk, and to assist workers in physically demanding occupations such as construction or manufacturing.

Exoskeleton technology is still developing, but it has the potential to significantly improve the quality of life for people with limited mobility and increase the productivity and safety of workers in physically demanding jobs.

The figure 3.14 shows an example of an exoskeleton that also has wheelchair functions. Wheelchair mode allows the skateboard to move on smooth surfaces at high speed with increased safety and reduced energy consumption. Compact wheel modules using skateboard hub motors can be stowed away to prepare for walking. Considering that the backward movement of the exoskeleton's joints is a major concern for safe physical human-robot interaction, the parameters of the wheelchair were designed based on a simplified human model, so that the torque limitation of the actuators is still sufficient to support seat-motion to standing.

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Figure 3.14. Alpha prototype of a wheelchair-exoskeleton hybrid robot in standing position (for walking over obstacles) and in wheelchair mode (for safe and energy-efficient movement over smooth surfaces) [28]



Figure 3.15. The full appearance of the exoskeleton and the actual wearing appearance, which presents the range of operation. The exoskeleton has three degrees of freedom (DoF). The knee has a flexion/extension DoF, the angle of which is indicated by θ . In addition, the ankle has a passive rotation DoF and a passive prismatic DoF. The range of motion of the exoskeleton is 145° . The compliant structure allows the user to sit completely [30]

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The figure 3.16 shows a model of an upper limb exoskeleton that provides motion support for the elbow joint. A stepper motor with a torque of 1 Nm was used as the drive. In order to increase the torque of the drive system, an additional gear ratio was used and a pinion gear was used. A stepper motor was used to drive the exoskeleton, the housing of which was connected to the exoskeleton's "arm". On the axis of the motor, a gear wheel was used, which cooperated with a gear wheel connected to the exoskeleton's "forearm". This resulted in a toothed gear with a ratio of 1:5, increasing the torque transmitted by the stepper motor. Since the minimum travel of the motor is 1.8 degrees at full-step operation, the minimum movement of the forearm is 0.36 degrees. At ½ step setting, the minimum movement is 0.18 degrees.



Figure 3.16 Prototype of upper limb exoskeleton [29]

The exoskeleton is controlled by a TB6560 controller (Fig. 3.17) connected to a computer via an LPT port. The whole thing is powered by an industrial power supply unit with a power of 600W, an output voltage of up to 36V and an output current of 16A. The software used was Step2CNC, a program for controlling numerically controlled machine tools. The program allows both manual control using the buttons of the manual control panel and automatic control. Automatic control is performed using a G-code file. The codes used allow control of the angular position of the forearm, the speed of the movement, as well as the programming of breaks in the movement. The control file can be prepared both in the Step2CNC program editor and developed as a text file in any editor (such as Notepad). The control file can be then

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entered from the computer's memory into the program. By using this program in automatic mode, it is possible to apply a certain sequence of movements that will be performed by the stepper motor.

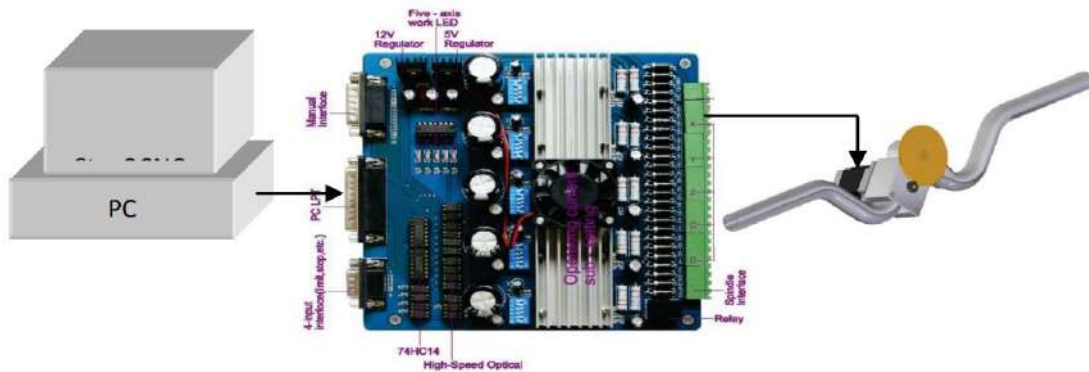


Figure 3.17 Control system of upper limb exoskeleton [29]

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4. Summary

In this e-learning module, basics of biomechatronics were shown. Some key concepts, descriptions of exemplary systems, as well as technical problems, challenges and opportunities were mentioned. The aim of this module was to familiarize the readers with the notion and get their attention to biomimetic, mechatronic systems possible to manufacture using additive manufacturing.

Despite the challenges, the potential benefits of biomechatronic systems are enormous. Biomechatronics has the potential to revolutionize healthcare and rehabilitation, enabling individuals with disabilities and injuries to regain function and independence. In addition, biomechatronic systems could be used to create entirely new functions that are not possible with biological systems alone. This could lead to new opportunities in fields such as robotics and space exploration.

In conclusion, biomechatronics is an interdisciplinary field that holds enormous promise for the future of healthcare and rehabilitation. Biomechatronic systems incorporate biological and mechanical components to achieve a specific function, and can be used for a variety of applications, including prosthetics, exoskeletons, and medical devices. Developing these systems requires a deep understanding of both biology and mechatronic engineering, and researchers in this field must be skilled in a wide range of disciplines. The potential benefits of biomechatronic systems are enormous, and this field is likely to continue to grow in importance in the coming years.

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MECHATRONIC SYSTEMS

MODULE 3D PRINTING and RAPID TOOLING METHODS

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1. Introduction

Additive manufacturing technology (AMT), also known as 3D printing, has revolutionized various industries, including medicine. It is transforming the way medical devices and implants are manufactured, leading to significant advancements in patient care. 3D printing has the ability to create intricate and complex structures, which was not possible with traditional manufacturing techniques. This has opened up new possibilities for medical professionals and researchers to explore and improve upon existing treatments and procedures.

The medical applications of 3D printing are numerous and include the creation of prosthetics, implants, surgical tools, and even human tissues and organs. In the field of prosthetics, 3D printing allows for the production of custom-made, patient-specific devices that are designed to perfectly fit the individual. This has significantly improved the comfort and functionality of prosthetics, allowing patients to lead more active and fulfilling lives.

Another area where 3D printing is making a significant impact is in the creation of implants, such as spinal and joint replacements. Traditional implant manufacturing techniques have limitations, leading to standardized, one-size-fits-all devices. With 3D printing, implants can be created that are tailored to the specific requirements of each patient. This leads to improved patient outcomes and reduced recovery times, as the implant fits more precisely and functions better.

In the operating room, 3D printing is also playing a crucial role in the development of surgical tools and instruments. Surgeons can now create custom-made instruments that are specifically designed for the task at hand, improving the accuracy and efficiency of their procedures. Additionally, the use of 3D printing in surgical planning is allowing for more accurate preoperative simulations, allowing surgeons to visualize and practice complex procedures before they are performed on a patient.

One of the most exciting areas of research in the medical field is the development of 3D printed tissues and organs. Although still in its early stages, researchers have made significant progress in creating functional 3D printed tissues and even entire organs. The eventual goal is to provide patients with functional replacements for damaged or diseased tissues and organs, reducing the need for organ transplantation and improving patient outcomes.

3D printing is also revolutionizing the field of biomechanics, which combines biomechanics and electronics to develop advanced prosthetics and exoskeletons. The

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aforementioned ability to create complex, custom-fit structures has opened up new possibilities for the design and manufacture of these devices.

One of the most significant benefits of 3D printing in biomechatronics is the ability to create prosthetics that are perfectly tailored to the individual patient. Traditional prosthetics have been limited by their standardized design and one-size-fits-all approach. With 3D printing, prosthetics can be designed and manufactured to meet the specific needs of each patient, leading to improved comfort and functionality.

Exoskeletons, which are wearable devices designed to enhance or augment human movement, are another area where 3D printing is making a significant impact. With 3D printing, exoskeletons can be designed and manufactured to be lighter, more comfortable, and more functional. This is particularly important for individuals with mobility impairments, who require exoskeletons to be as unobtrusive as possible.

This module presents basic knowledge on 3D printing. Some basic concepts and definitions have been presented, as well as some descriptions of fundamental and derivative processes. Along with basic knowledge, also examples of use in the field of personalized prosthetic and orthotic devices are presented.

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2. Basics of 3D Printing technology

2.1 Basic definitions

Below, some basic definitions and concepts pertaining to additive manufacturing are presented.

1. Additive Manufacturing: Also known as 3D printing, this is the process of creating a three-dimensional object by adding material layer by layer.
2. Rapid Prototyping: It is a main application of additive manufacturing - a process of creating a physical model of a product or part in a fast and efficient manner, typically using computer-aided design (CAD) data. The goal is to quickly produce a working model for testing, evaluation, and refinement.
3. Rapid Manufacturing: It is a manufacturing process that utilizes rapid prototyping technologies to produce end-use products in small to medium quantities. This method is faster and less expensive than traditional manufacturing methods and can be used to produce complex geometries and designs that are difficult or impossible to produce using other methods.
4. Rapid Tooling: It is the use of rapid prototyping techniques to produce tooling, such as molds, dies, and jigs, in a fast and cost-effective manner. This approach enables manufacturers to quickly produce low-volume production runs, test and refine designs, and reduce time-to-market.
5. 3D Modeling Software: This is software used to create 3D digital models that can be used in additive manufacturing.
6. Build Volume: This is the maximum size of the object that can be produced in a single build process.
7. Layer Height: This is the thickness of each individual layer that is added during the additive manufacturing process.
8. Resolution: This refers to the level of detail that can be achieved in the final product.
9. Post-Processing: This refers to the additional steps that may be required after the additive manufacturing process to achieve a finished product, such as sanding or polishing.

Basic scheme of additive manufacturing, by Gebhardt [1], is presented in Figure 2.1.

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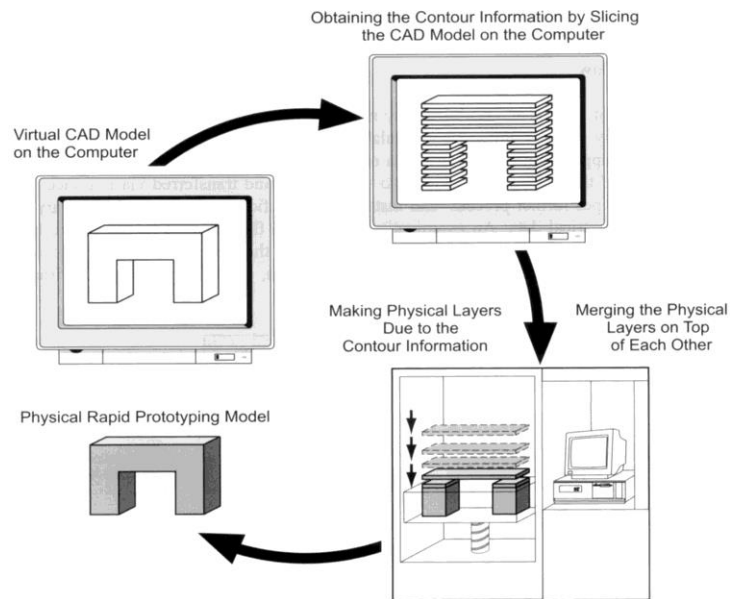


Figure 2.1. Basic scheme of additive manufacturing [1]

2.2 3D Printing technologies

2.2.1 Review of available technologies

The ISO/ASTM 52900 standard defines the following seven categories of additive manufacturing processes (Fig. 2.2):

- extrusion,
- sintering of powders (powder bed fusion),
- photopolymerization,
- material jetting,
- binder jetting,
- sheet lamination,
- directed energy deposition [2].

The first three categories are also the oldest. They gained their popularity on the consumer market mainly due to numerous patents expiring at the beginning of the 21st century by such companies as 3D Systems, Stratasys, MIT, HP, Hitachi.

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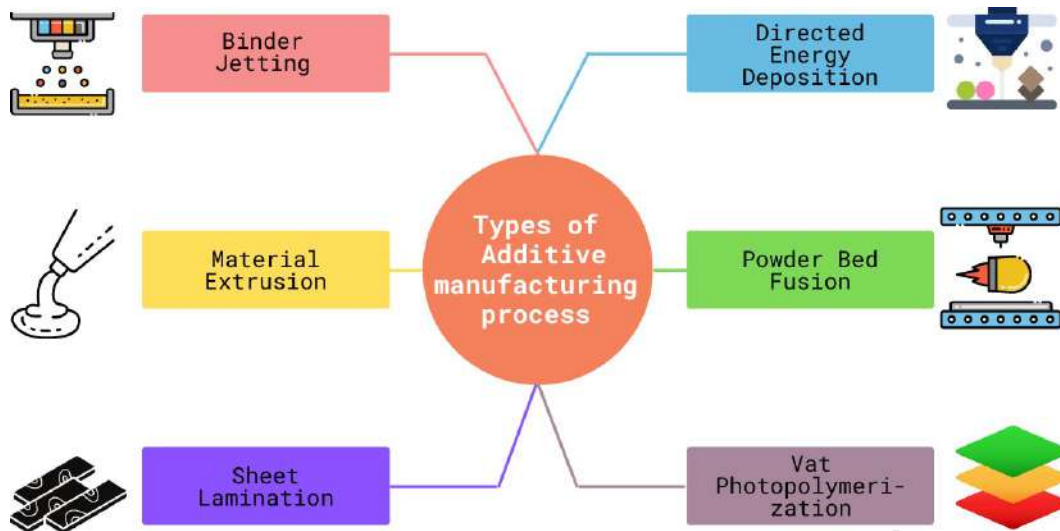


Figure 2.2. Categories of AMTs according to ISO 52900 standard [3]

Of each category, there are several or more distinctively named processes. Some processes are hybrid, i.e. they combine elements from two or more categories. The categories focus more on how the material is stored, deposited and finally joined and less on mechanical and kinematic aspects of realizing these functions. As such, machines realizing processes from one category might look (and also cost) entirely different, depending on the used approach. This is especially visible for the categories, in which original processes lost the patent protection and as such have become “free” technologies – such as Fused Deposition Modeling or stereolithography. These technologies can be implemented in either low-cost, hobby-like machines or in industrial-grade professional devices, ready to be placed in a factory floor or medical facility.

The most popular processes – historically and nowadays – are described in the following subchapters.

2.2.2 Fused Deposition Modelling

Fused Deposition modeling is a process consisting in layered deposition of plasticized build and support material supplied in form of a wire by an extrusion head (see fig. 1 for process schema). Numerically controlled device deposits build and support material on the model base, with data about head positioning coming from horizontal cross-sections of the part, prepared on the basis of the 3D CAD model. The ABS material is frequently used, other

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thermoplastics can be used too, depending on the machine and head type. Obtained models are considerably strong and can be subjected to further treatment by machining, gluing or painting, to obtain desired surface quality. Produced part is ready for use immediately after support material removal [4].

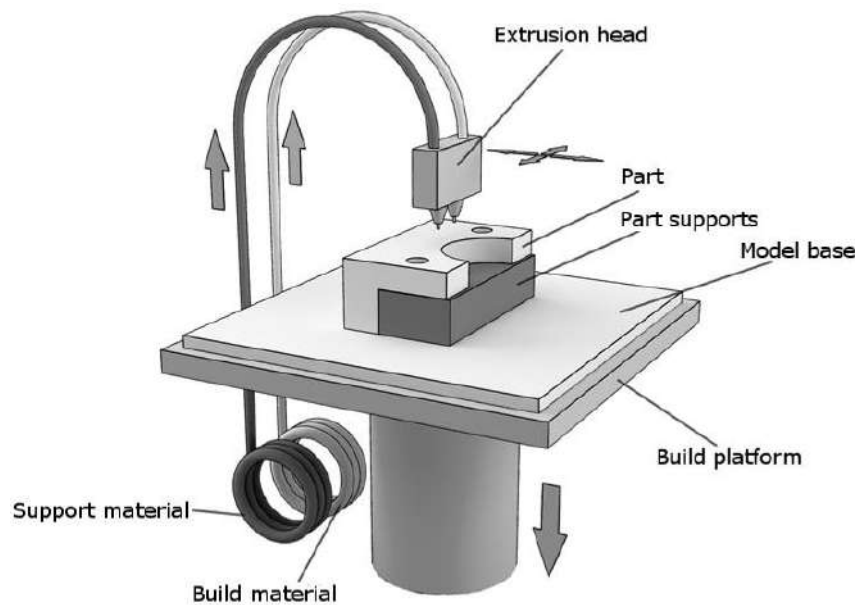


Figure 2.3. Scheme of FDM technology [5]

A very important feature of the FDM technology is the need to use supports. Unlike most additive technologies (e.g. stereolithography or powder methods), the created product does not have any natural supports, so in many cases the applied material could be deformed due to the force of gravity or table or head movements. Hence the need to build support structures that prevent deformation. The most commonly implemented method of building these structures is the use of a double head extruding the plasticized material - apart from the building material, it will be a special support material, usually a polymer material of a similar class, but with slightly different properties. The support must be removed at the end of the process and is the only finishing operation necessary in this manufacturing technique. Due to the method of removal, two types of supports can be distinguished - mechanically removed (by breaking) and soluble, removed by immersing the finished model together with the support in a special liquid.

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The process utilizes mostly thermoplastic materials, or composites based on them. Below, the most frequently used and specific materials are mentioned.

Standard:

- ABS - Acrylonitrile butadiene styrene, (poly(acrylonitrile-co-butadiene-co-styrene))
- the most popular, good strength properties,
- PLA - polylactide, polylactic acid - cheap, biodegradable, easily processed

Often used:

- PETG ("HD glass") - transparent, durable, easy to process,
- TPU ("flex") - thermoplastic polyurethane, flexible, soft
- PA12 (nylon) - abrasion resistant
- HDPE - polyethylene - cheap, available

Specialized:

- PC - polycarbonate – durable
- PPSF - polyphenylsulfone (polyphenylsulfone) - increased resistance
- PEEK (polyetheretherketone) - rigid, durable, resistant to high temperatures

Soluble supports:

- PVA - polyvinyl alcohol, soluble in water
- HIPS - polystyrene - soluble in limonene, can also be used as a building material

Figure 2.4 presents single anatomical product (hand orthosis) made of different materials using FDM technology.

Apart from the material, users of FDM technology can alter almost any parameter of the process, provided that the software and a given machine are open source. Basic parameters are layer thickness, internal filling level (stated in percentage of filling up single layer), velocities of head movement and material extrusion and temperatures of working table and printing nozzles. There are many other advanced parameters, able to be set up in the software. More expensive, industrial-grade machines have the process more automated, with only several choices to be made and other parameters adjusting automatically to a given material.

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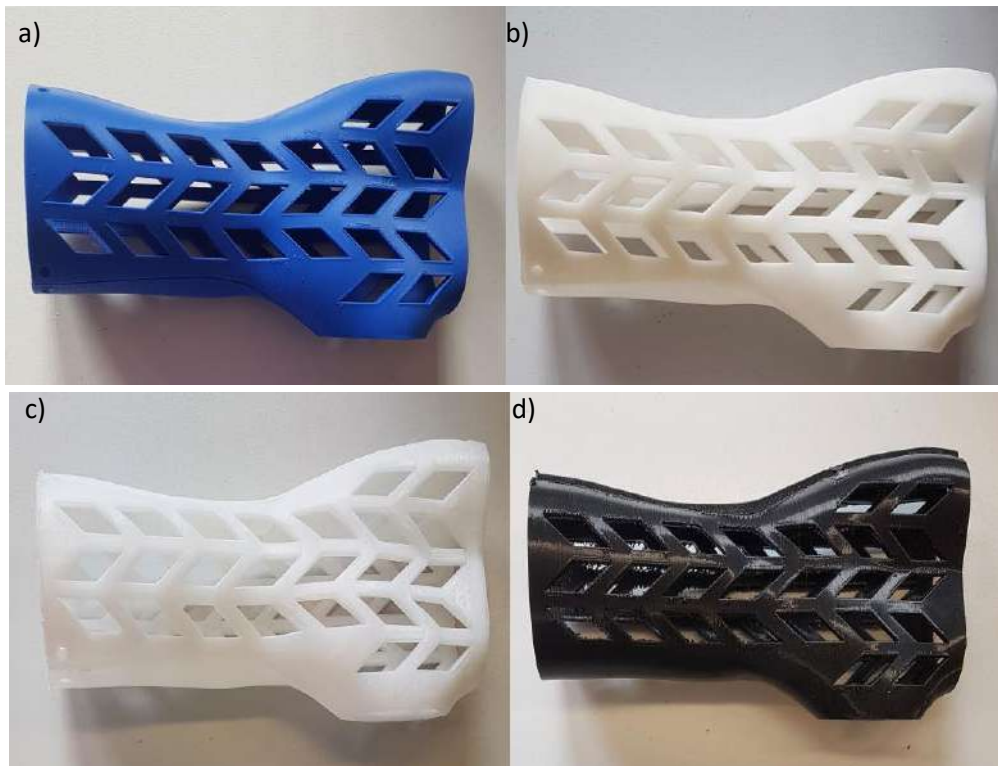


Figure 2.4. Orthosis manufactured in FDM technology, using: a) ABS; b) PLA; c) nylon; d) TPU

Compared to other additive manufacturing techniques with a similar cost and time to obtain a finished product (e.g. SLA, PolyJet, Layered Object Manufacturing), the FDM technique has the following advantages:

- speed of obtaining finished products - immediately after the machine is finished and the supporting structures are removed, the products are ready for use, without the need to keep them in the working chamber of the machine; also the layers are deposited relatively quickly,
- acceptable mechanical properties - products obtained with the FDM technique do not require finishing to obtain satisfactory mechanical properties,
- availability of build material - products are made of thermoplastics that are generally available, easy to process and recover through recycling.

One of the largest disadvantages of FDM is the relatively low mechanical properties of obtained products (tensile & bending strength, impact resistance, elongation at break and others) [6]. Apart from being lower than expected, these properties also often have uncertain,

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hard-to-predict values and are anisotropic on a macroscopic level [7]. The influence of the manufacturing process parameters on mechanical properties of products made using FDM, and economical coefficients of the process have been thoroughly studied worldwide [6-8].

2.2.3 Stereolithography and UV technologies

Stereolithography (SLA) is one of the basic and oldest methods of additive manufacturing. The SLA technology belongs to the group of additive manufacturing techniques that use the photopolymerization process (so-called “UV technologies”). The fabricated object is created as a result of selective hardening of the photopolymer resin with laser light, with the laser operating in a specific range of wavelength (ultraviolet). The resin is poured into the container, into which the work table is immersed. When the table is lowered to the bottom of the container to the height of the predetermined layer, the laser beam, which is focused on a predetermined path by means of a set of special mirrors (known as scanners), hardens the given layer of material. When this is complete, the platform rises to the height of the next layer and the process repeats. Basic scheme of the process is shown in Fig. 2.5.

After printing, the part is not fully cured, requiring repeated exposure. Carrying out additional processing (mainly re-exposure after the completion of the printing process) makes it possible to improve the mechanical and thermal properties of the printed model.

Unlike in the FDM technology, most of the parameters of the process are set automatically by the device manufacturers, without the possibility of changing them. Usually it's not possible to control intensity of the laser, its detailed movements and speed etc. Changeable parameters include the very basic ones: layer height and model position, which determines the location of its support structures. The supports are usually required to some extent, not as bulky as in the FDM, but rather openwork and easily disposable using simple mechanical tools, right after the process.

The typical layer height of the material is 25-100 μm , but both lower and higher values can be found in available systems. The use of lower layer thicknesses allows for better mapping of complex geometries, especially in comparison with the FDM technology – so-called staircase effect, eminent in FDM prints, is usually minuscule or unnoticeable in SLA prints. On the other hand, the manufacturing time is extended, and thus the cost of the production process. 0,1 or 0,05 mm are usual thicknesses of choice in the SLA process.

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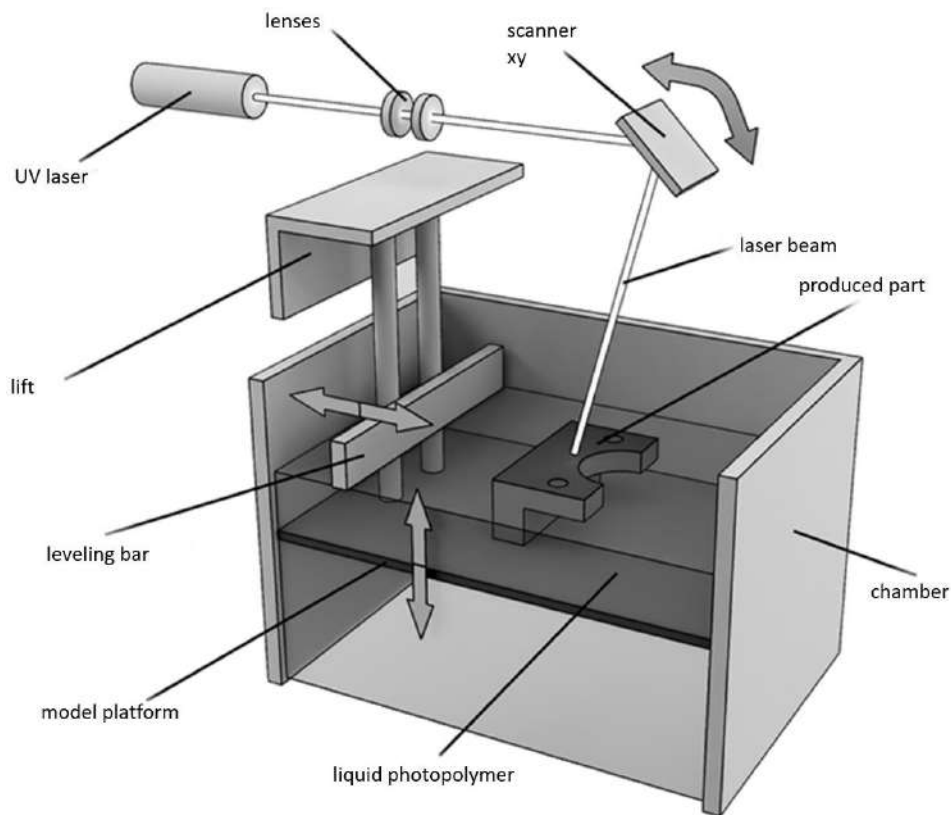


Figure 2.5. Scheme of SLA technology [5]

There are two main kinematic variants of SLA technology:

- standard process, in which laser is positioned above the resin tank (as presented in Fig. 2.5), and the model platform is going down after each layer,
- inversed process, in which laser is positioned below the resin tank and the model platform is rising up after each layer, with the product being fabricated upside down.

The standard process, more difficult to implement and costly, is a domain of professional, industrial printers. The inversed process can be found in most middle class or low-cost machines, offered by various producers. In the inversed process, the support structures are far more important than in the standard process, as they also enable safe and stable manufacturing, without disjoining of the model from the table due to gravity and increasing mass of the produced part.

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Examples of desktop SLA printers with setup are presented in Fig. 2.6. An example of SLA part of anatomical shape is presented in Fig. 2.7.

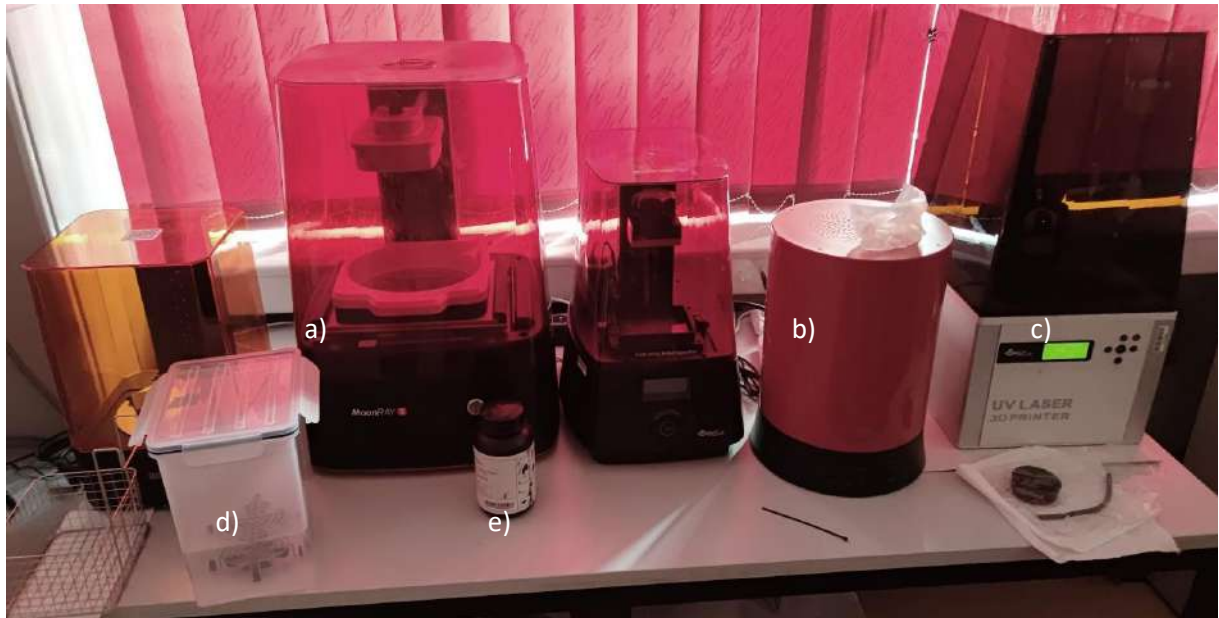


Figure 2.6. SLA technology setup: a) & c) desktop machines with inverse kinematics, b) post-curing station, d) cleaning tank, e) photopolymeric material

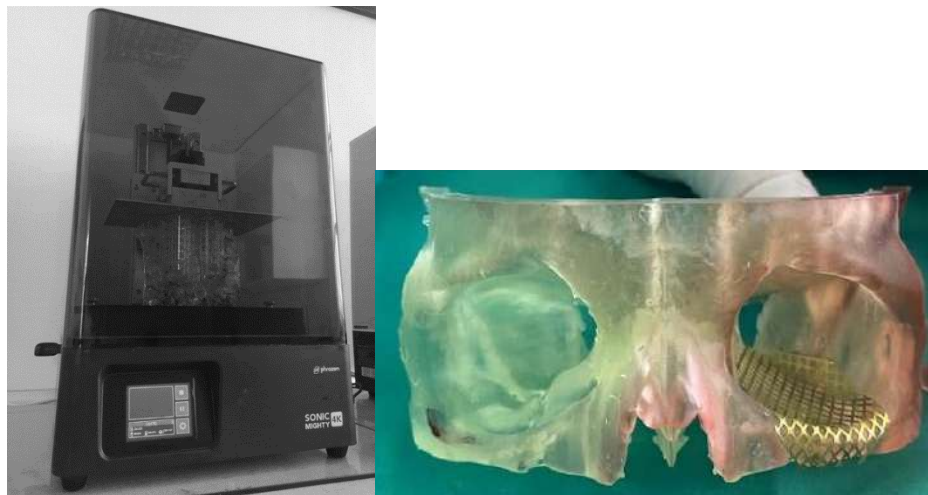


Figure 2.7. Anatomical part printed with SLA (inside the machine) and its clinical use for implant shape adjustment [9]

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Thanks to the use of SLA, it is possible to produce a model with a high degree of complexity of geometry, which has free surfaces with a wall thickness not less than the diameter of the laser beam used. This allows for a very high surface quality. Sterolithography has many advantages, but also weaknesses. SLA is a slow process, which, combined with the high cost of the building material, makes the use of this tool less economical compared to other methods (such as FDM). It should be remembered that during the polymerization process, volumetric shrinkage may occur, which will result in both dimensional and shape errors. However, modern materials and stable conditions of the manufacturing process allow to significantly reduce the risk of such errors. An additional problem may be the fact that elements made of photopolymers differ significantly in appearance and properties from typical engineering plastics. Due to the low mechanical strength, the models produced with the use of SLA mainly play the role of visual and conceptual prototypes, and are rarely used in functional tests [5].

The SLA technology is a basic UV process. There are, however, some variations even more useful than the original process. The most popular is the PolyJet technology, combining photopolymerization principle with kinematics more similar to FDM process, with moving head depositing the material in selected locations at the model table. This improvement allows using multi-material heads and obtaining models with combined properties, either pertaining to color or e.g. hardness or other properties. Basic scheme of the PolyJet process is presented in Figure 2.7. However, kinematics implemented in various machines can be different.

PolyJet technology is very useful for building multi-material, very detailed physical representations of complex intricate shapes, especially anatomical ones. It is suitable for representation of very thin structures and minor details, such as eye socket bone (Fig. 2.9) or arteries and nerves in a brain. Larger machines, such as MediJet J5 (Fig. 2.8) can be used to produce useful structures and objects, such as mechanisms of bioinspired prostheses, as well as large anatomical interconnected structures, such as liver or heart. PolyJet models need support, but as the process is conducted in low temperature, these supports are easily soluble under a jet of pressurized water, and as such are not a topic of concern as in FDM or even SLA. PolyJet is however an expensive technique and not as easily implementable in office or hospital conditions as relatively simpler FDM or SLA machines.

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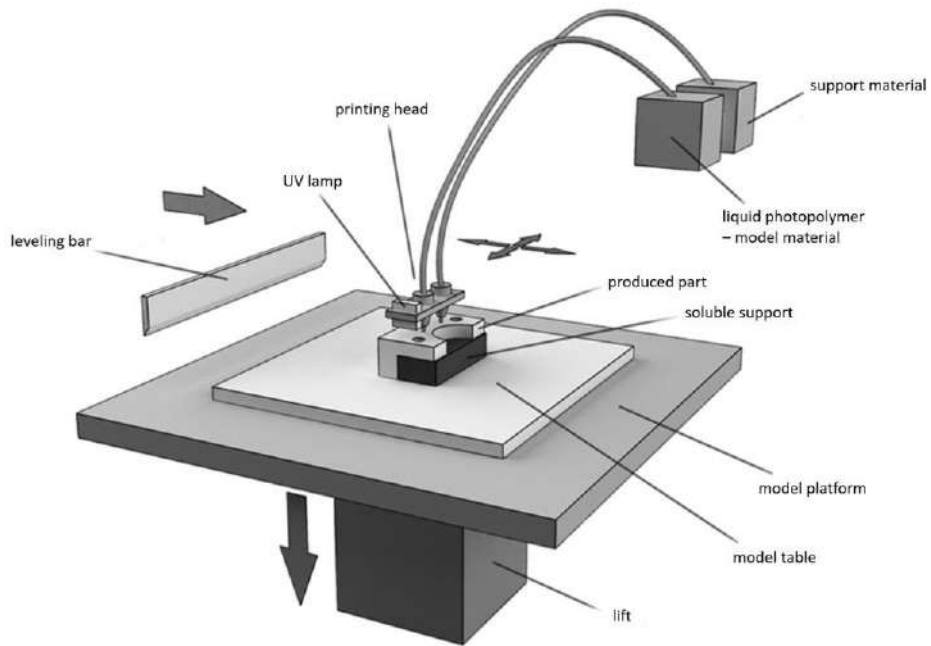


Figure 2.7. Scheme of PolyJet technology [5]



Figure 2.8. PolyJet machine – Stratasys Medijet J5

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Figure 2.9. Example of anatomical models produced by PolyJet [9]

Another noteworthy example of UV technology is DLP, standing for Digital Light Processing. In this technology, idea of partial, point-like curing of liquid material has been replaced with curing of image of a whole layer at once, using special digital light projector (hence the name) and special brand of material, curable in the light of this projector. DLP technologies are often named as “layerless”, as there can be no defined layer thickness – the projector can smoothly project a section plane “traveling” through 3D object model along with corresponding vertical movement of build platform. Support structures are necessary as in the inverse kinematic SLA method, as the projector is located at the bottom of the resin tank (Fig. 2.10). DLP is a useful method for intricate shapes, but current generation of machines have very small build chamber and the process takes very long – its usability is therefore limited.



Figure 2.10 DLP machine and example of anatomically shaped product [10]

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2.2.4 Selective Laser Sintering

Selective laser sintering (SLS) is one of the basic additive manufacturing methods. It was developed at the University of Austin (United States), and the first successful commercial implementation took place in 1991. Intensive development work on the SLS method led to the creation of similar methods: Direct Metal Laser Sintering (DMLS) and Selective Laser Melting - SLM. All three methods are considered as one family. They differ mainly in the range of materials used, as well as in the fact that in the SLS and DMLS method only the outer layer of powder grains is melted, and in SLM the powder grains are fully melted (as in welding processes) [5].

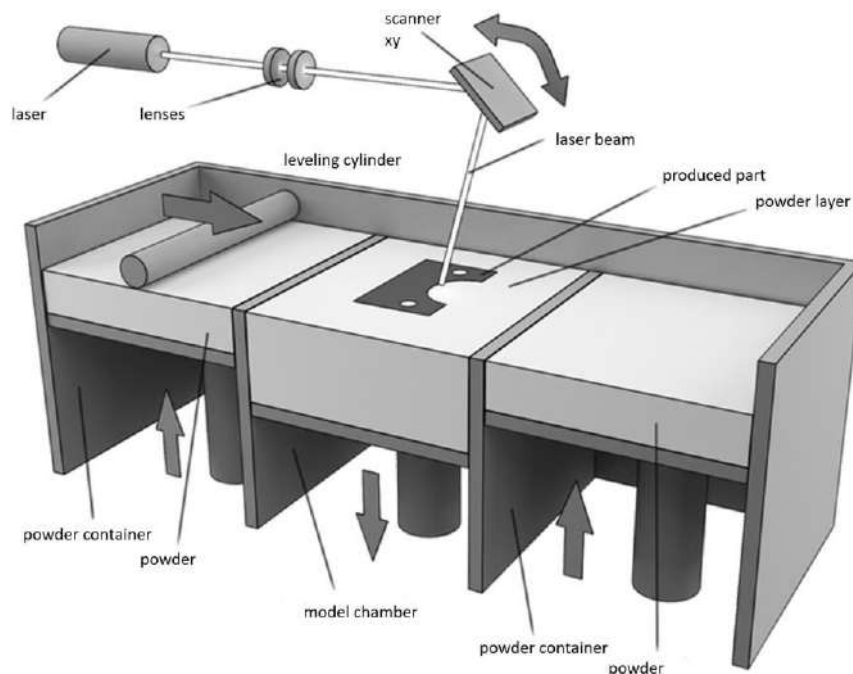


Figure 2.11. Scheme of SLS technology [5]

The additive sintering methods use high-power lasers - most commonly CO₂ (carbon dioxide) for SLS and Yb (ytterbium) for DMLS/SLM - to deliver the necessary energy to the powdered material for fusion. The density of the produced prototypes depends mainly on the maximum instantaneous power that the laser can achieve, and not on the amount of energy delivered to the powdered material. Therefore, pulsed lasers are used, which can deliver short pulses of high power light. Among the materials used to build prototypes, one can find both

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plastics (nylon, nylon with glass microfiber, polypropylene, polystyrene, ABS) and metal powders (steel, stainless steel, tool steel, titanium, bronzes, aluminum, copper, nickel), depending on machine construction and laser type used. The SLS method uses both one-component powders and two-component powders - of which only one component material is a melting binder and the other is a filler. The size of a single grain is usually in the range of 20-70 micrometers, and the smaller it is, the better the strength properties and the greater the dimensional and shape accuracy of the manufactured element.

The temperature in the working chamber is only slightly lower than the melting point of the material from which the powder is made. Thanks to this, the bonding of successive grains requires the supply of a small amount of energy by a laser guided selectively on the surface of a given layer. This shortens the duration of the entire model building process. After the powder fusing process is completed, the produced parts must cool down, and then they are removed from the working chamber and cleaned of loose grains. The use of high-power lasers also necessitates the use of a protective atmosphere inside the working chamber. It is most often filled with nitrogen or argon (with minuscule amounts of oxygen, strictly controlled, desirably below 0,1% or even less), thanks to which there is no danger of ignition and explosion of the powder [5].

The great advantage of the described method is that there is no need to use supports for the elements protruding beyond the outline of the prototype base, because they are supported by the loose, unbound powder. The key advantage of the whole group of technologies is the possibility of using metallic powders, from which it is possible to build fully functional prototypes and series of usable products, such as personalized implants ready for implantation. The disadvantages of laser sintering include a much more complicated mechanical system of the device than in the case of other methods, leading to very high costs of purchase, implementation and maintaining the equipment. What's more, the obtained dimensional accuracy and surface quality of the prototypes is lower than in the case of stereolithography, and sometimes FDM [5].

Examples of anatomically shaped products 3D printed using SLS technique are presented in Figure 2.12.

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Figure 2.12. Example of anatomical object produced by SLS technique [11]

2.2.5 Other noteworthy technologies

Among literal dozens of other additive technologies available on the market, the following might be interesting from the viewpoint of producing biomimetic devices intended for medical use:

- 3D bioprinting is one of the additive manufacturing techniques (Additive Manufacturing) intended for medical applications and tissue engineering. It consists in the layered production of tissues (groups of cells). The produced tissues consist of living cells and specially selected support materials (organic or synthetic), ensuring process stability and shape rigidity. During the manufacturing process of one model, it is possible to use many different materials in its different areas. 3D bioprinting is currently used to test new drugs, study disease processes in a safe environment, and study blood flow processes in artificial vessels. In the future, it is planned to print tissues and complete organs for transplants based on the recipient's own cells. Basic bioprinting processes are based on known additive solutions: the main processes are inkjet printing, embossing, laser printing and stereolithography. The current generation of devices is used mainly for experimental purposes - the stability of the shapes obtained, cell survival, and the complexity and size of the obtained tissues are still not high enough to speak of a breakthrough in the field of tissue engineering and transplantology. However, 3D bioprinting technology can be described as the future of medical printing, especially in the field of biomimetic solutions.

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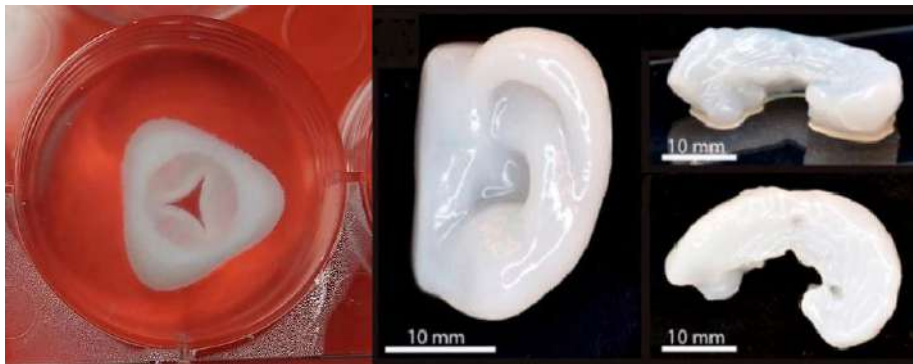


Figure 2.13. Examples of bioprinted objects [12] [13]

- laser powder forming - LPF - this is a group of methods which use a high-power laser beam to deposit metallic materials in a targeted manner. The obtained models do not have a porous structure, so their density is identical to that of elements cast from the same material. Thanks to the very good crystal structure, the strength properties may in some cases be better than for identical castings. The characteristic feature of the LPF is that it is the work table on which the model is formed that moves at most in the XY axes, and does not move in the Z axis. The input material is powder, which is supplied evenly along the circumference of the dosing head outlet opening, through which the laser beam also passes. The light beam is focused on the surface of a given layer of the model and supplies the energy necessary to melt the powder. The head rises in the Z axis after the material is applied in a given layer. In order to protect the applied material against the harmful effects of oxygen, and to facilitate the joining of successive layers, the manufacturing process can take place in a protective atmosphere. The metal powder is supplied to the head by gravity or in a gas stream [5].
- electron beam melting - EBM - allows for the production of models from metal powders melted using an electron beam in high vacuum conditions. The process is carried out at a high temperature (even up to 1000 degrees Celsius), which varies depending on the building material used, which gives a measurable benefit in the form of a model structure free of thermal stresses. Thanks to the presence of a very small amount of oxygen atoms in the working chamber, it is possible to produce models from easily oxidized materials (e.g. titanium). EBM is the most similar to

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SLM, because in both cases the powder is fully melted, thanks to which the elements do not have a porous structure and do not require further heat treatment. An additional advantage of this technology is the relatively high speed of operation and the minimum layer thickness of 0.05 mm. A typical application of this method are medical implants and aircraft engine turbine blades made of titanium alloys [5].

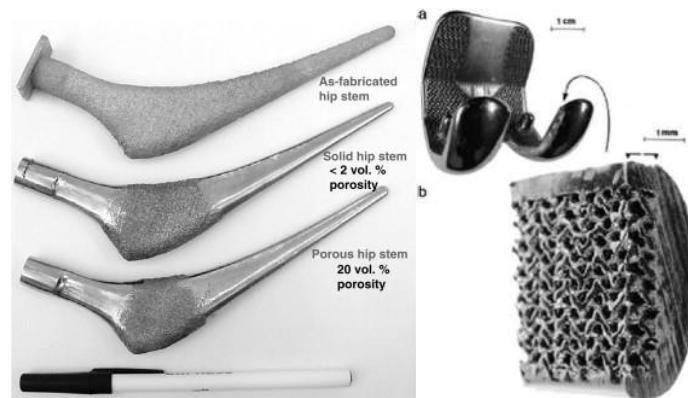


Figure 2.14. Products obtained by laser powder forming (a) [14] and electron beam melting (b) [15]

2.3 Preparing 3D printing processes

2.3.1 Data formats

There are several file formats that are directly related to the additive manufacturing [16]. They differ significantly from one another. Some additive manufacturing software can also import CAD-specific file formats, which is an ongoing trend. The selection of the appropriate data format to use frequently depends on the specific machine and the manufacturing technology. The file format used for 3D printing must accurately represent the design of the object, including its shape, size, and material properties. There are several file formats used in additive manufacturing, each with its own advantages and disadvantages. Currently, STL was still the most widely used data exchange format, developed in the 1980s and accompanying the first technology (stereolithography – hence the acronym, later altered to a different meaning).

STL (initially Stereolithography, now – Standard Triangulation Language) is the first and still one of the most widely used file formats for additive manufacturing. STL files are surface

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models, representing a 3D model as a mesh consisting of series of oriented triangles (facets), making it a faithful representation of a 3D object's geometry provided that these geometry contains straight lines. Otherwise, chordal error is introduced when converting arcs, circles and curves to triangles, but this can be nowadays managed by serious increase in density of tessellation. STL files are widely supported by most 3D printing software and hardware, making them an ideal choice for most applications. STL files are also default format for many optical 3D scanners, what is quite important and convenient in biomedical applications (change of formats during the processing is often not required).

STL is the simplest open-source file format. It supports ASCII encoding (bigger file size) and binary encoding (smaller file size, usually preferred). It can store only information about the geometry of a single object (no assemblies) and an additional 80 bytes of text information in the header. STL is not a topological format and it contains a lot of redundant information but no data on the connectivity of the triangles (this information is computed in real time during processing). STL also does not introduce any data correctness mechanisms by itself (e.g. it is not checked if geometry is “watertight” - object to be additively manufactured should have closed surface with positive volume). However, lots of free software is available for repairing and editing (as mentioned in Module 1 – CAD). Example of an STL file in ASCII encoding is shown in Fig. 2.15. Example of STL file during editing is shown in Fig. 2.16.

```

proteza00_Zosia__stl x
1 solid STL generated by MeshLab
2 facet normal 9.994322e-03 -4.197675e-02 -9.990687e-01
3 outer loop
4 vertex -5.937941e-01 3.377039e+01 3.400025e+01
5 vertex -8.860629e-01 3.359167e+01 3.400483e+01
6 vertex -1.287003e+00 3.360526e+01 3.400025e+01
7 endloop
8 endfacet
9 facet normal 1.001812e-02 -4.128383e-02 -9.990972e-01
10 outer loop
11 vertex -1.287003e+00 3.360526e+01 3.400025e+01
12 vertex -8.860629e-01 3.359167e+01 3.400483e+01
13 vertex -1.880865e+00 3.335046e+01 3.400483e+01
14 endloop
15 endfacet
16 facet normal 1.019512e-02 -4.169602e-02 -9.990783e-01
17 outer loop
18 vertex -1.287003e+00 3.360526e+01 3.400025e+01
19 vertex -1.880865e+00 3.335046e+01 3.400483e+01
20 vertex -1.906565e+00 3.345367e+01 3.400026e+01
21 endloop
22 endfacet

```

Figure 2.15. STL file structure – ASCII encoding

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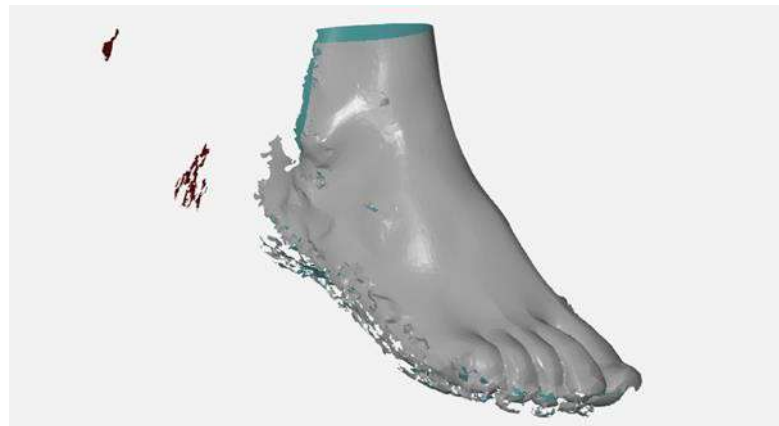


Figure 2.16. STL mesh editing process

OBJ (standing just for Object) is another widely used file format for additive manufacturing. OBJ files are similar to STL files, representing a 3D model as a series of triangles – but can also use polygons (quads) instead. OBJs also include additional information, such as color, texture, and material properties – for these additional MTL file is required (MTL standing for material template library). Also, many parts can be stored in a single file, allowing to process assemblies. OBJ files are widely supported by many 3D printing software these days, making them a good choice for applications that require more information than just the 3D geometry of an object – e.g. in PolyJet manufacturing, where different objects can have different colors or textures and be manufactured in a single process.

AMF (Additive Manufacturing File) is a newer file format that has been developed specifically for additive manufacturing, in 2011. It was called "STL 2.0", as it addresses to many of the shortcomings of the STL format. Despite the advantages of the format, the process of adaptation into additive manufacturing is relatively slow, mostly due to popularity and good usability of older formats in the most popular processes (FFF). AMF files are XML-based and contain a more detailed representation of a 3D object, including its geometry, material properties, and build parameters. In the AMF, geometry is described with triangular mesh (same as STL), but triangles can be curved, so file size can stay low in volume with only a small loss to mapping accuracy of nonlinear geometry. AMF files are becoming increasingly popular, as they provide a more comprehensive representation of a 3D object than STL or OBJ files.

It is also worth mentioning of another file format that is associated with additive manufacturing processes. It is G-Code. G-Code is a file format used primarily in the control of

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CNC (computer numerical control) machines, including 3D printers. G-Code files contain instructions for a machine to follow, including movements, speed, and temperature. G-Code files are not used to represent the 3D geometry of an object but are instead used to control the machine's movement and behavior during the printing process. Usually, software for slicing (CAM) deals with G-Code preparation and the user does not have to interfere or deal with the format in any way. However, there are scenarios in which editing the G-Code might be necessary for a process to succeed, especially if a given machine was customized for a specific purpose – certain instructions can be added or altered manually, to ensure correctness, especially in the beginning or end of the process.

2.3.2 Software – slicers

Slicer software is an essential tool for 3D printing, used to prepare 3D models for printing. It plays a crucial role in the planning and execution of the 3D printing process, as it divides the 3D model into hundreds or thousands of horizontal layers and generates the instructions for the 3D printer to build the model layer by layer, usually in form of NC code.

Slicer software usually allows to adjust various parameters that affect the final quality and accuracy of the 3D printed object, as well as course of the additive manufacturing process. Some of these parameters include layer height, infill density, print speed, and support structures. The sliced model can be also previewed and adjustments can be made if needed, which is particularly useful when working with complex models that require support structures or intricate details.

One of the most significant benefits of using slicer software is the ability to generate accurate estimates of print time and material usage, which can be useful for planning and budgeting purposes. This information can also be used to optimize the print process by reducing material waste and minimizing print time without sacrificing quality.

There are two main variations of slicers, depending on application range:

- universal – not made for any specific brand of machine or manufacturer, rather general and suitable for use for many types of devices,
- dedicated – usually created by manufacturer of a given machine, for that particular machine or a whole series of machines, not suitable for other devices.

The universal slicers usually allow more freedom in terms of selection of process parameters, but they also require more initial effort in order to properly set up and tune

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constant parameters for a given machine and material. The dedicated slicers have the machines and materials profiled from the start, so the user does not have to worry about details of parameter selection.

An example of universal slicer is Simplify3D software, that can be used for almost any FDM machine and material which is available on the market (Figure 2.17). An example of a dedicated slicer is Z-Suite software, made for machines made by Zortrax company, or MakerBot Print software, made for machines of the MakerBot brand (currently owned by Stratasys company).

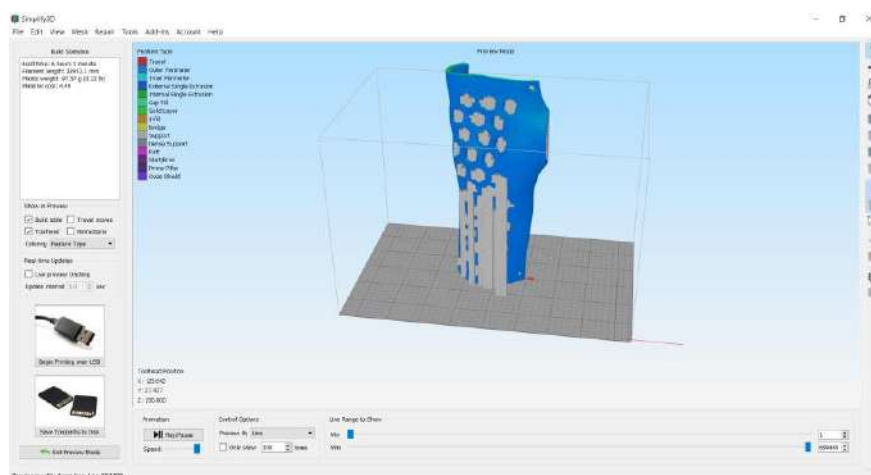


Figure 2.17. Simplify 3D slicer

A very important function of slicer software, mentioned above, is the ability to generate G-code, which is the machine language used by 3D printers to build objects. The G-code produced by the slicer software provides the 3D printer with the necessary information to control the movement of the print head, the extrusion of the filament, and other important aspects of the printing process.

There are many slicer software options available, including both open-source and commercial options. Some popular slicer software options include Cura, PrusaSlicer, and Simplify3D. Each of these options offers a range of features and benefits, and the best choice for a particular application will depend on the user's specific requirements and experience level.

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2.3.3 Guidelines for 3D printing of anatomical shapes

Below, a set of general guidelines is presented for 3D printing of anatomical shapes – including biomimetic products. These are just a general set of remarks, which have to be considered carefully, depending on a specific case of a product suited for people with special needs.

1. Accuracy: It must be ensured that the 3D model used for printing is accurate and has been verified by a medical professional (of a profession corresponding to a given subject, i.e. surgeon, orthopaedist, physiotherapist etc.). The model should have accurate proportions and details to ensure the best possible representation of the anatomy.
2. Material Selection: a material that is safe and appropriate for the intended use should be selected, ideally a biomaterial. Biocompatible materials such as polylactic acid (PLA) or polyamide (PA12, nylon) are commonly used in medical applications.
3. Layer Thickness: The layer thickness should be small enough to produce a smooth surface but not so thin that the print is weak and prone to breakage. A common layer thickness for biomedical and biomimetic applications is 0.1-0.2mm for the FFF technology, although use of very low thickness can result in lengthy prints.
4. Print Resolution: High-resolution prints produce better details and improved accuracy. Using a 3D printer with a high resolution capability should be considered to produce the best results.
5. Post-Processing: Depending on the intended use, it may be necessary to perform post-processing techniques such as sanding or polishing to improve the surface finish and accuracy, especially if surface of a product will be in touch with human body parts.
6. Sterilization: If the 3D print is intended for use in a medical setting, or for people with special needs (e.g. immunocompromised) it must be sterilized to eliminate any potential contaminants or microbes. Common methods of sterilization include autoclaving and exposure to ultraviolet light.
7. Quality Control: Quality control checks before using the 3D print in a medical setting must be performed, to ensure that it meets the necessary standards and

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specifications. This may include measurements, strength tests (static and dynamic), functional tests and material analysis.

8. Legal Considerations: It is important to consider any legal or regulatory considerations when 3D printing anatomical shapes. This may include obtaining necessary certifications and complying with applicable regulations. The 3D printed product must be classified to either class as stated in an appropriate regulation and then, if necessary, certification process should be realized if the product is intended for serious medical use with the patients. Otherwise it can be only used by volunteers in a course of a scientific experiment, but this also should be performed under specific regulations (usually approval of ethics committee is required).

In terms of guidelines for design of 3D printed parts, there are also plenty of things to consider, when switching from conventional manufacturing technologies into 3D printing, mostly regarding easier post processing, strength and usability of fabricated parts. Many guidelines are available in the community of 3D printing professionals, an example is shown in Fig. 2.18.

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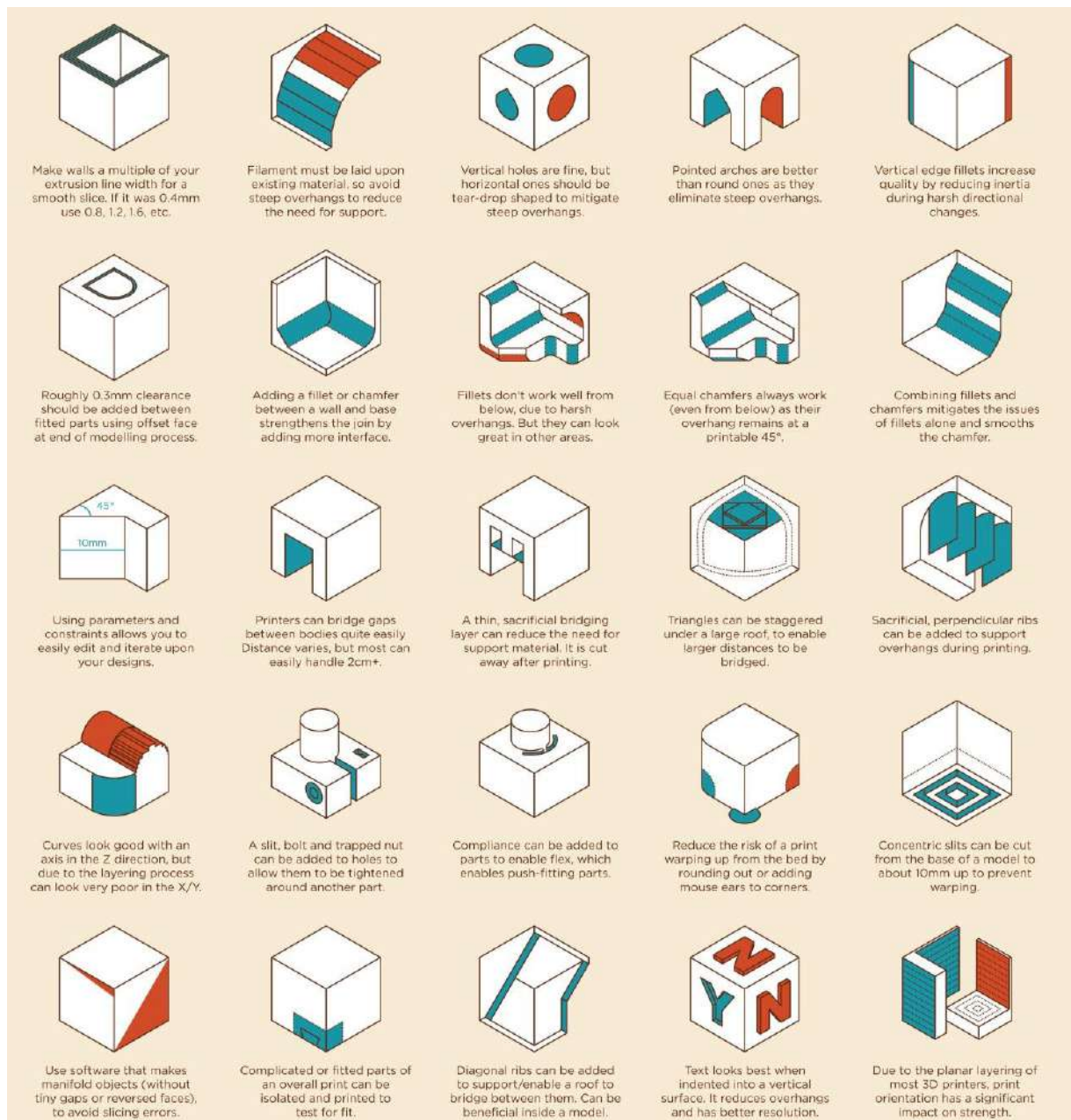


Figure 2.18. Example of guidelines for design for 3D printing [17]

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3. Examples of 3D printed biomimetic devices

3.1 Review of applications of 3D printing for biomimetic devices

3D printing and additive manufacturing, as already mentioned, has plenty of medical applications. Of these, building anatomically shaped and biomimetic devices seems to be a very promising direction, that surely will thrive in upcoming years. Here are several examples of 3D printed biomimetic devices:

1. Artificial Joints: 3D printing is increasingly used to produce customized artificial joints, such as hip and knee replacements, with shapes and structures that mimic the natural anatomy (Fig. 3.1).



Figure 3.1. 3D Printed knee personalized implant versus traditional implant [18]

2. Heart Valves: 3D printing has been used to produce heart valves with structures and materials that mimic the natural anatomy, offering improved functionality and personalization. For example, researchers at Minnesota University created patient-specific model, which includes the anatomy of the damaged leaflets of the aortic valve, where the replacement valve will be inserted. The model includes integrated sensors that helps to guide positioning of the replacement valve (Fig. 3.2) [19].

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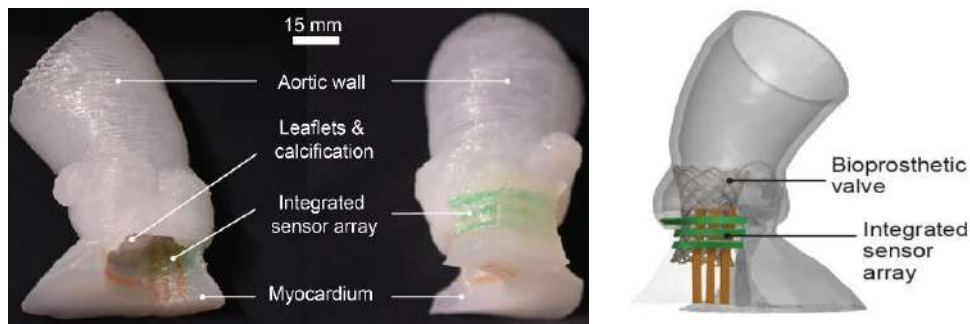


Fig. 3.2. 3D-printed model of a patient's aortic region [19]

3. Skin Tissue: Researchers have developed 3D printed skin tissue that mimics the structure and function of natural skin, offering a promising solution for burn victims and people with skin conditions [20].
4. Bones: 3D printing has been used to produce customized bones for use in medical procedures, such as spinal fusion and cranial reconstruction. The 3D printed bones mimic the structure and mechanical properties of natural bone, offering improved outcomes for patients, e.g. by infusing them with antibiotics (Fig. 3.3) [21]

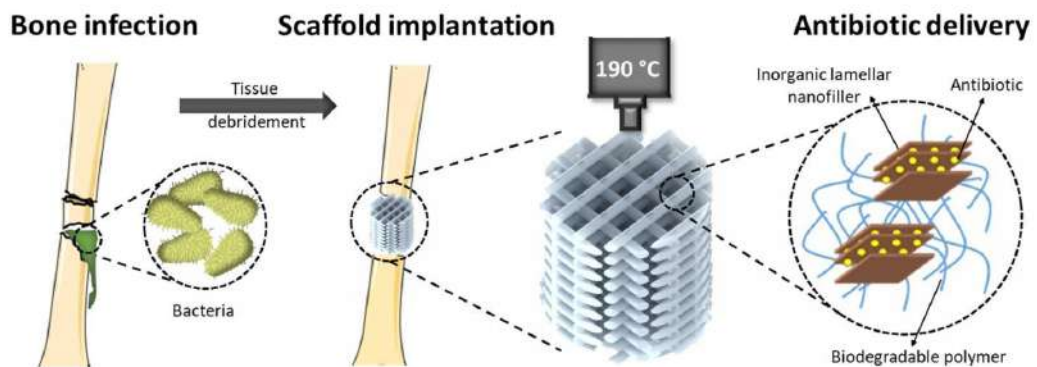


Fig. 3.3. 3D-printed bone scaffold with antibiotics [21]

5. Cartilage: Researchers have developed 3D printed cartilage that mimics the structure and function of natural cartilage, offering a promising solution for people with conditions such as osteoarthritis (Fig. 3.4) [22].

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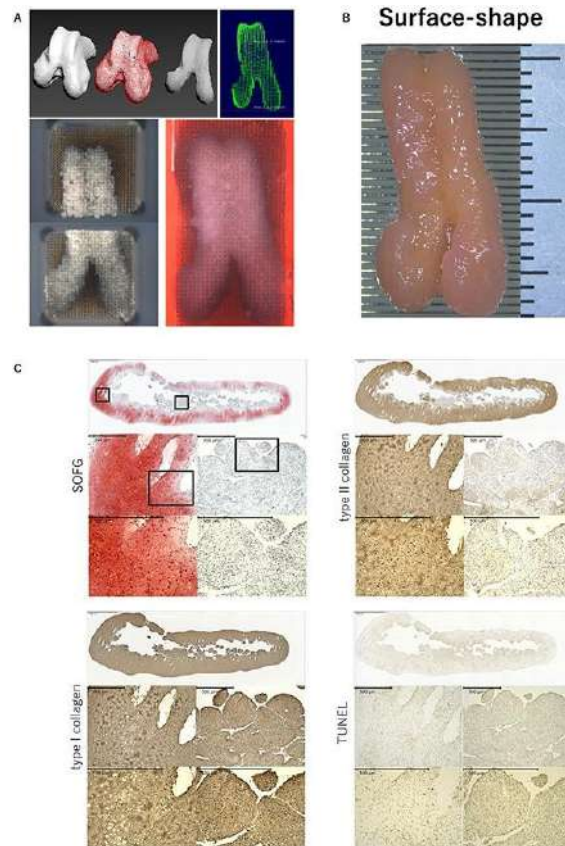


Fig. 3.4. Bio-3D printer design data and images of the articular surface-shape construct of cartilage tissue [22].

6. Blood Vessels: 3D printing has been used to produce functional blood vessels with a structure that mimics the natural anatomy, offering a promising solution for patients with cardiovascular disease [23].
7. Prosthetic Feet: 3D printing has been used to produce prosthetic feet with structures that mimic the natural anatomy, offering improved balance and stability for users [24].
8. Orthoses: 3D printing has been used to produce customized orthoses that mimic the shape and structure of the body, offering improved comfort and function compared to traditional equipment, often by implementation of mechatronic solutions [25].

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These are just a few examples of the many biomimetic devices that are being developed using 3D printing. The technology offers a wide range of possibilities for improving medical outcomes and developing new treatments for a variety of conditions. In the EMERALD project, the focus is on 3D printed mechatronic devices, with biological personalized shapes, made for external use – i.e. orthotics and prosthetics. An example of a 3D printed device taken as a case in the project is presented in the next subchapter.

3.2 Biomimetic example – therapeutic wrist hand orthosis

As a custom example of 3D printed product for people with deficits, a hand orthosis intended for realization of therapeutic and rehabilitation purposes will be described in this chapter. It can be used for wrist joint stabilization in time after an injury (fracture) or for patients with conditions that require stabilization, as rheumatoid arthritis, muscle atrophy and many others. The orthosis is customized on the basis of a 3D scan geometry of patient’s hand and forearm. It can be 3D printed using one of the basic FDM technology materials: PLA, ABS, PET-G and PA-12 (nylon), of which PLA and PA-12 are recommended due to proper combination of mechanical and processing properties, as well as no known issues with skin irritation. Basic information about design process of the orthosis are shown in Module 1 – CAD. Shape of the orthosis is shown in Fig. 3.5.

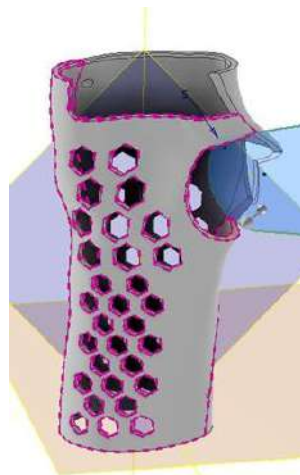


Figure 3.5. Shape of the wrist hand therapeutic orthosis

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For manufacturing of the orthosis, a case of a 13-year old patient is assumed. First of all, finishing the actual design stage, the two parts of the orthosis were exported to STL file format, with maximum detail in order to not lose shapes of geometrical details..

The first stage of the process of additive manufacturing of the orthosis in the FDM technology was the import of 3D models of the STL files to the selected slicer software in order to create instructions for the device in the form of a G-code file. Each part was oriented in the virtual workspace of the Simplify3D software for vertical fabrication, as generally better for this application. Of previous studies [26] it can be concluded the following regarding the orientation selection:

- vertical orientation is good in terms of accuracy and shape representation,
- horizontal orientation is worse in terms of surface roughness and comfort (without additional work-consuming post processing),
- vertical orientation is better economically – if the orthosis can fit vertically into selected machine’s chamber – as it does not require high volume of support structures, which take time to build and later remove in post processing,
- vertical orientation is worse in terms of strength (bending test), although not in a way disqualifying the orthosis from daily use.

Considering all these factors, a default orientation was assumed as vertical, with lower predicted strength being the main drawback, however assuming the orthosis application scenario (several hours of therapeutic use daily), this should not pose a problem.

It was decided to make the prints of two materials: PLA (polylactic acid) by default and also TPU (thermoplastic polyurethane). The TPU orthosis was a proposed concept to obtain certain level of flexibility and easier use during therapeutic activities. Due to appropriate (low) size of the orthosis, a typical closed-chamber machine was used – FlashForge Creator Pro. PLA orthosis was printed in two design versions, with varying offset between patient’s hand and orthosis inner surface (1 mm and 3 mm).

Processes for both materials were executed using similar parameters. Layer thickness of 0,25 mm was used and 30% of internal filling was applied with default pattern. 3D printing of PLA took approximately 4 hours per one part of the orthosis, with TPU taking above 7 hours. First printouts were not subjected to full post-processing, as they were only intended to check

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out the fitting and material – this is a standard way of conduct in low-cost 3D printing of personalized orthopedic equipment.

In Figures below, 3D printed orthoses are shown.

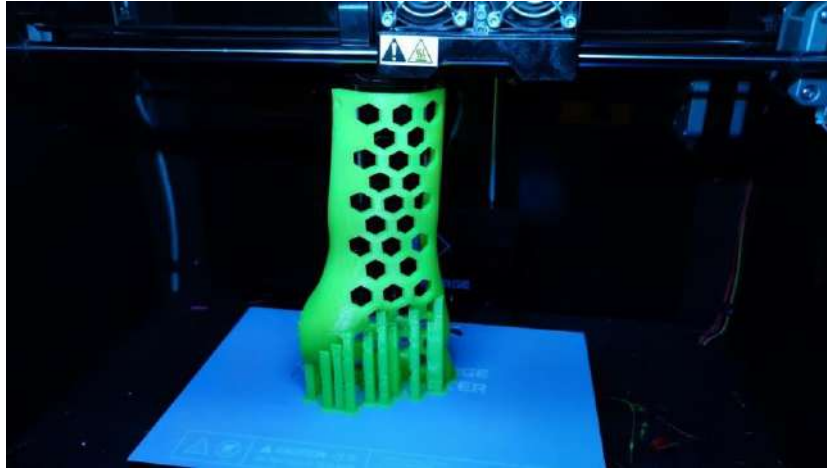


Figure 3.6. 3D printed orthosis (single part) in the machine chamber



Figure 3.7. 3D printed test orthoses, PLA (left) and TPU (right)

Improved final version of the orthosis was 3D printed only of PLA material, in a similar time, approximately 8 hours of continuous printing for both parts (one after another). Full post processing was applied, consisting of the following activities:

- removal of support,
- manual grinding, removing sharp edges,
- lining the orthosis with the EVA medical foam in specific places – mostly around the edges but also in locations where corrective shape of the orthosis would make it squeeze patient's muscle tissue.

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The two printouts of two separate materials were tested simultaneously. The procedure of fitting was performed with a physiotherapist, to ensure proper hand positions during fitting and therapeutic exercise simulation. The PLA orthosis was considered as the preferred variant by both patient and physiotherapist. Slight changes were also proposed in terms of geometry, to make the orthosis more functional and comfortable. Final version of the design was prepared and 3D printed. It was fully post processed and then given to the patient. Appropriate fitting and assembly was achieved.

Figure 3.8. presents the process of testing and fitting with the patient.



Figure 3.8. Tests of orthoses with the patient

The orthosis was evaluated as usable and helpful in therapy. After several months, the patient was 3D scanned again and another version was made, as the previous orthosis was too small (due to patient's growth). Also, orthoses for other patients with similar condition were made. The orthosis produced in this way is equal to, and in many respects even better than typical solutions. The first key aspect here is individualization, the 3D printed one described here is precisely adapted to the human body, which increases its rehabilitation effectiveness. Another important feature is the very short production time - only a week passed from the start of measurements to the first tests of the device by the patient. It also translates to reduction of costs, as the whole process of creating the orthosis costed approx. 50 EUR, including materials, use of machines and human operator time. 3D printing also enables the orthosis to be openwork and lightweight – which is a very important factor in terms of patients with limited muscle strength, typical orthoses are too heavy to operate effectively.

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4. Summary

In this e-learning module, 3D printing technologies were presented. Basic concepts, ideas and principles were described, along with context of biomedical applications, especially having in mind the main topic of the EMERALD project, which is production of biomimetic mechatronic devices using 3D printing. The performed review of processes and applications prove that it is fully justified to use the additive technology as means of fabrication of usable, anatomically personalized (biomimetic) devices for people with disabilities or other special needs.

Basic knowledge contained in this module, along with knowledge on CAD, computer programming and biomechanics should allow the learner to get acquainted with basic set of technologies necessary in the work of modern biomedical engineer, dealing with design and production of customized mechatronic medical devices.

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EMERALD

The Education, Scholarships, Apprenticeships and Youth
Entrepreneurship
EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC
MECHATRONIC SYSTEMS

MODULE INTELLIGENT (SMART) MATERIALS

Project Title	European network for 3D printing of biomimetic mechatronic systems 21-COP-0019
Output	O1 - EMERALD e-book for developing of biomimetic mechatronic systems
Module	Module - Intelligent (Smart) Materials
Authors	Diana BĂILĂ

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1 Introduction in Additive Manufacturing technologies

1.1. The principle of Additive Manufacturing technologies

Additive Prototyping Technologies (AM) differ fundamentally from material removal processing technologies (cutting, EDM, laser processing) and redistribution processing technologies material (casting, injection, forging, stamping) by the fact that the parts are obtained by adding layer by layer material using a CAD file.

These technologies have emerged grace a result of the achievements and advances made in the field of fine mechanics, numerical control, laser technology, computers, software, and the new materials development.

These new Additive Manufacturing technologies have started to grow in importance due to the efforts of manufacturers to reduce design times up to marketing, as well as the costs of assimilating and manufacturing new products. The specificity of these additive manufacturing processes is their ability to make parts and complex three-dimensional objects, starting from a CAD file, without the need for it use of machine tools or certain tools. The basic element of prototype additive manufacturing technologies is "the section". [1-86]

The pieces are quantified in sections and made using a repetitive process of construction, section by section, reducing a three-dimensional problem to one flat. This dimensional reduction leads to a decrease in accuracy and quality surfaces due to the scale effect.

The steps required for the additive manufacturing of a part are as follows:

- designing the three-dimensional (3D) model of the part, using a design program computer aided (CAD);
- transferring the CAD model to the sectioning processor. The best-known method of sectioning is the approximation of the model with flat triangular elements.
- sectioning the 3D virtual model with parallel planes to the working plane of the rapid manufacturing machine of prototypes and generation of orders for control equipment of the machine.
- the construction of the part (material, supports required during the model, how will be added a new layer, marking the contours for each section, marking the area between the exterior and interior contour of a section.

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- cleaning and finishing of the part (operations in which the supports used at construction and excess material are eliminated).

Additive Manufacturing Processes were initially used to produce prototypes, in the case of small, unique series production. Soon, however, these manufacturing processes Additive will directly produce functional parts with high precision and shorter manufacturing time, either metallic or other materials, successfully replacing classical manufacturing technologies that used expensive machine tools.

Regarding solid CAD modelling, Additive Manufacturing systems are becoming an important and motivating factor for companies that produce solid modelling systems, such as: Solidworks, Unigraphics, I-DEAS, Catia, Inventor, Onshape, AutoCAD, Pro / Engineer, etc.

Models obtained by Additive Manufacturing optimize the design of a new model or modernization of an existing one, these models allow the physical visualization of the product and improving communication between producer and beneficiary.

Testing a product manufactured using Additive Manufacturing technologies depends on three factors material, size, and design. The tests performed must lead to a visual acceptance, understanding of construction, product functionality and finalization sizing elements.

Additive manufacturing technologies have and will play an important role in many industrial fields, from the field of Machine Building to medicine, aerospace, architecture, thus giving technology a strategic importance for companies that use these technologies. [1-85]

1.2. Classification of additive manufacturing technologies according to the materials used

Additive prototyping technologies can be classified by materials used (figure 1.1), namely:

- technologies that use liquid polymers as a base material, and solidification is realized by the light impact from a special light source or from a small laser power (stereolithography) or by heating (thermal polymerization);
- technologies based on melting, deposition and resolidification of the material. These allow the use of metals (DMD, LMD technologies) as well as plastics or liquids (FDM process, ballistic particle processing).

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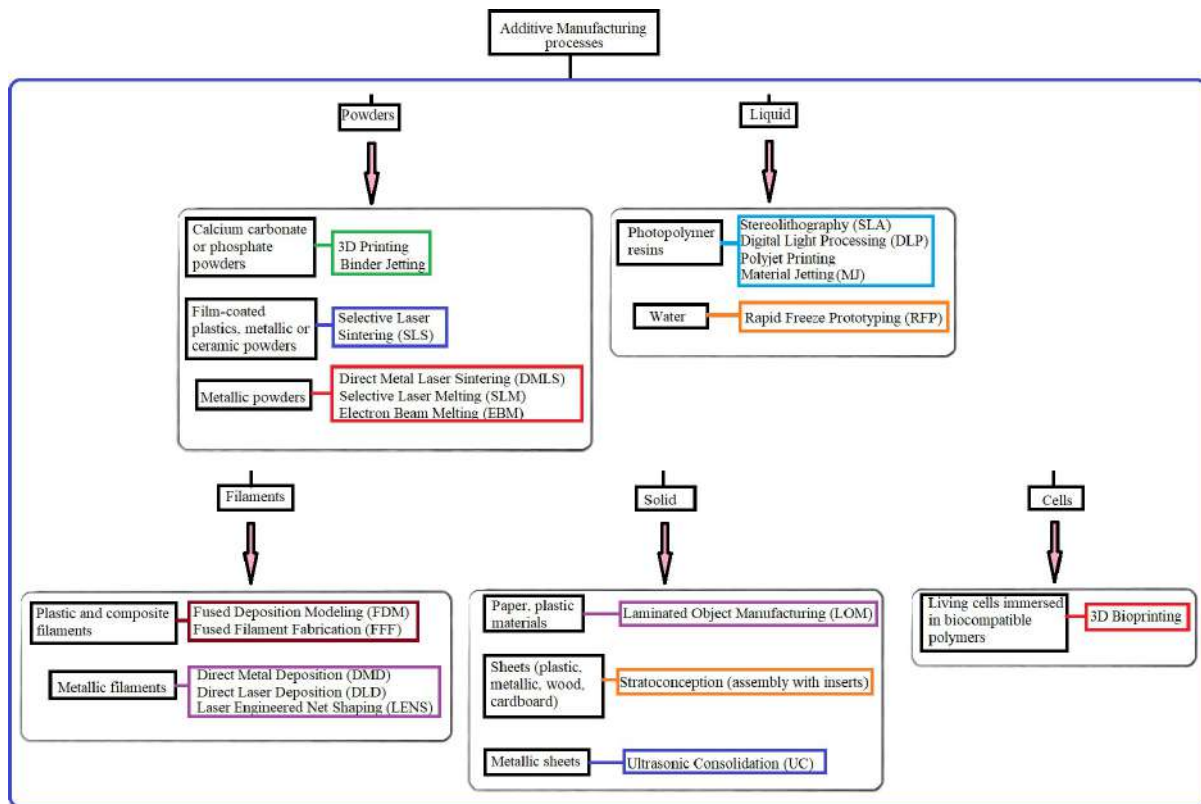


Figure 1. Classification of additive manufacturing technologies according to the materials used

-other processes use powder as raw material. [2] Binding of particles to powder can be made by melting in the contact area between particles of the same kind or with particles of another material which will be constituted as a special complementary material for this process (selective laser sintering SLS, DMLS, SLM), or gluing particles in areas of interest with a special substance (three-dimensional printing or gluing) – Binder Jetting.

-some processes use solid raw material, especially thin foils, as LOM or Stratoconception technologies.

Some processes are made by gluing or welding thick foils to produce the shape requested. Other processes use the semi-polymerization of plastic foils which are fixed together by another light curing. [1-86]

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2. Plastic materials used in Additive Manufacturing

ABS and PLA are the most common FDM (Fused Deposition Modeling) printed materials and are typically similar in cost. ABS has superior mechanical properties but is harder to print compared to PLA. PLA is ideal for 3D prints where aesthetics is important.

Table 1. The mechanical properties of Acrylonitrile Butadiene Styrene (ABS)

Properties	Values	Units
Density	1.0-1.4	g/cm ³
Poisson's Ratio	0.35	-
Shear Modulus G	1,03-1,07	GPa
Melting Temperature	200	°C
Glass transition temperature	105	°C
Thermal Conductivity	0,25	W/m-K
Extruded Temperature	200-230	°C
Heat Deflection Temperature, 1,81 MPa	81	°C
Young's modulus	1,79-3,2	GPa
Tensile Strength	29,8-43	MPa
Compressive Strength	76-78	MPa
Elongation at Break	10-50	%
Flexural modulus	2,1-7,6	GPa
Hardness Shore D	100	
Izod Impact Strength	58	kJ/m ²
Yield Strength	28-120	MPa
Standard Tolerance	+/-0.05	mm
Biodegradable	-	-
Melt flow	12-23	g/10min
Rockwell Hardness	R102-R104	

Due to its lower printing temperature is easier to print with and therefore better suited for parts with fine details. ABS is best suited for applications where strength, ductility, machinability and thermal stability are required. ABS is more prone to warping. The mechanical properties of ABS are presented in Table 1. [1-86]

Other materials used frequently in FDM technology are the filaments of Polyethylene Terephthalate PET (C₁₀H₈O₄)_n and Polyethylene Terephthalate Glycol (PETG). The mechanical properties of PET material are presented in the Table 2 and the comparison concerning mechanical properties between the common materials used in FDM technology, PLA, ABS and

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HIPS is shown in the Table 4. In table 3 are shown the mechanical properties of PLA for 3D printed material.

Table 2. The mechanical properties of Polyethylene Terephthalate PET (C₁₀H₈O₄)_n

No	Mechanical and chemical properties	U.M.	Value (unit)	Obs.
1	Density	g/cm ³	1.455 – cristalin 1.37 - amorphous	1.38 – at 20°C
2	Tensile Strength	N/mm ²	74-cristalin 55-amorphous	-
3	Compressive Strength	N/mm ²	125	-
4	Flexural strength	N/mm ²	90	-
5	Torsion strength	N/mm ²	-	-
6	Shear strength	N/mm ²	-	-
7	Elongation at break	%	50-cristalin 150-300 - amorphous	-
8	Ball penetration hardness	Kg/m ³	1370	-
9	Rockwell Hardness	-	R100-cristalin R90-amorphous	-
10	Charpy shock resistant (uncracked)	kJ/m ²	3.6	-
11	Charpy shock resistant (cracked)	kJ/m ²	2.5	-
12	Melting temperature	°C	260	-
13	Glass transition temperature	°C	67-81	-
14	Notch test	kJ/m ²	3.6	-
15	Vicat Temperature(VST)	°C	82	-
16	Extruded temperature	°C	220-250	-
17	Liniar expansion coefficient	-	7	(*10 ⁻⁵ K ⁻¹)
18	Specific Heat	cal/g°C	0.28	(JK ⁻¹ *kg ⁻¹)
19	Thermal conductivity	W/mK	0.15-0.24	-
20	Boiling point	°C	350	-
21	Volume resistivity	Ω*cm	4*10 ¹⁶ – cristalin 2*10 ¹⁶ - amorphous	-
22	Surface resistivity	Ω	10 ¹³	-
23	Water absorption (ASTM)	%	0.5-0.6 – cristalin 0.6-0.7 -amorphous	/24h
24	Viscosity	cP	75000-90000	Low- viscosity PET at high- viscosity PET
25	Dielectric rigidity	kV/mm	16	-
26	Melt flow	g/10min	35,08	230°C
27	Young's Modulus (E)	MPa	2800-3100	-
28	IZOD Impact strength	J/m2	140	-

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Table 3. The mechanical properties of PLA (Polylactic Acid)

Properties	Values	Units
Density	1.25	g/cm ³
Poisson's Ratio	0.36	-
Shear Modulus G	2.4	GPa
Melting Temperature	173	°C
Glass transition temperature	60	°C
Thermal Conductivity	0.13	W/m-K
Extruded Temperature	160-220	°C
Heat Resistance	110	°C
Young's modulus	3.5	GPa
Tensile Strength	61.5	MPa
Compressive Strength	93.8	MPa
Elongation at Break	6	%
Flexural strength	88.8	MPa
Hardness Shore D	85	A
Impact Strength	30.8	kJ/m ²
Yield Strength	60	MPa
Standard Tolerance	+/-0.05	mm
Biodegradable	yes	-

Table 4. Comparison concerning mechanical properties between the common materials used in FDM technology, PLA, ABS and HIPS

Polymers	HIPS			ABS			PLA		
	OV	SD	SE \bar{x}	OV	SD	SE \bar{x}	OV	SD	SE \bar{x}
MFI (g/10 min)	7.5 ± 0.20	0.16	0.11	8.76 ± 0.16	0.13	0.09	13.52 ± 0.11	0.09	0.06
Young's modulus (MPa)	112.5 ± 0.12	0.09	0.06	175 ± 0.11	0.09	0.06	47.9 ± 0.10	0.08	0.05
Yield stress (MPa)	3.44 ± 0.21	0.17	0.12	0.49 ± 0.21	0.17	0.12	0.27 ± 0.16	0.13	0.09
Glass transition temp (°C)	100.41 ± 0.16	0.13	0.09	109.76 ± 0.2	0.16	0.11	62.57 ± 0.21	0.17	0.12
Peak load (N)	80.8 ± 0.11	0.08	0.06	207 ± 0.2	0.16	0.11	282.4 ± 0.20	0.16	0.11
Peak strength (MPa)	4.21 ± 0.16	0.13	0.09	10.78 ± 0.11	0.09	0.06	14.71 ± 0.16	0.13	0.09
Peak elongation (mm)	1.9 ± 0.20	0.16	0.11	4.75 ± 0.16	0.13	0.09	5.13 ± 0.16	0.13	0.09
Percentage elongation at peak (%)	3.0 ± 0.11	0.09	0.06	6.0 ± 0.15	0.12	0.08	7.0 ± 0.10	0.08	0.05

3. Photopolymerizable resins used in Additive Manufacturing

In the SLA (Stereolithography) and DLP (Digital Light Processing) technologies are used photocurable vinyl- or epoxy- functional oligomers for photopolymerization. In figure 2 are presented the transparent resins used in dental domain, manufactured by SLA. The principle

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of manufacturing for both technologies is presented in figure 3. In table 5 are presented the mechanical properties of Bisphenol A Ethoxylate Diacrylate resin. Other resins used in SLA manufacturing are the polyurethane resins. In figure 4 can remark the SEM image for the resin sample. [1-86]



Figure 2. Transparent resins used in dental domain manufactured by SLA

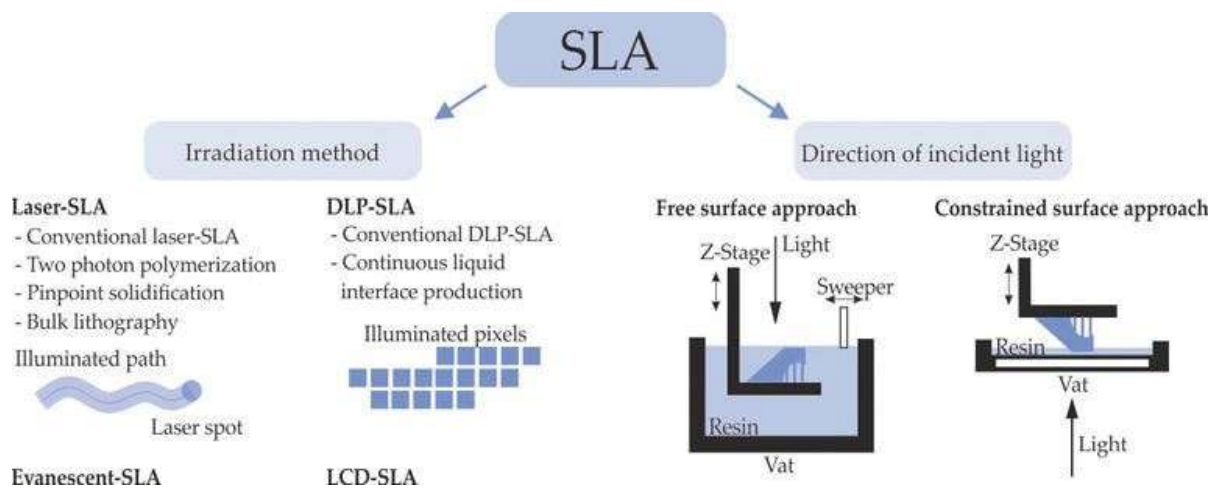
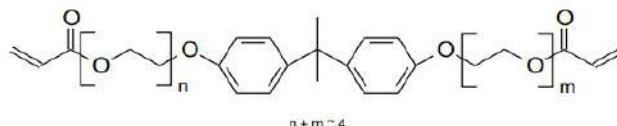


Figure 3. The principle of manufacturing for both technologies: SLA and DLP

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Table 5. The mechanical properties of Bisphenol A Ethoxylate Diacrylate

Bisphenol A Ethoxylate Diacrylate



INTRODUCTION

EBECRYL 150 is an ethoxylated bisphenol A diacrylate commonly used as reactive diluent in UV/EB cure applications. EBECRYL 150 can improve the cure response, hardness, and chemical resistance of UV/EB curable coatings and inks while maintaining good adhesion, and without imparting brittleness.

PERFORMANCE HIGHLIGHTS

EBECRYL 150 is characterized by:

- High reactivity
- Moderate viscosity
- High refractive index

UV/EB curable formulated products containing EBECRYL 150 are characterized by:

- Hardness
- Chemical resistance
- Good adhesion
- Improved wetting

The actual properties of UV/EB cured products also depend on the selection of other formulation components such as oligomers, additives and photoinitiators.

SPECIFICATIONS⁽¹⁾

	VALUE
Acid value, mg KOH/g, max.	5
Appearance	Clear liquid
Color, Gardner scale, max.	2
Viscosity, 25°C, cP/mPa s	1150-1650

TYPICAL PHYSICAL PROPERTIES

Density, g/ml at 25°C	1.14
Flash point, Setflash, °C	>100
Functionality, theoretical	2
Refractive index (n _D at 20°C)	1.5294
Vapor pressure, mm Hg at 20°C	<0.01

TYPICAL CURED PROPERTIES⁽¹⁾

Tensile strength, psi (MPa)	6300 (43)
Elongation at break, %	9
Young's modulus, psi (MPa)	180000 (1241)
Glass transition temperature, °C ⁽³⁾	41

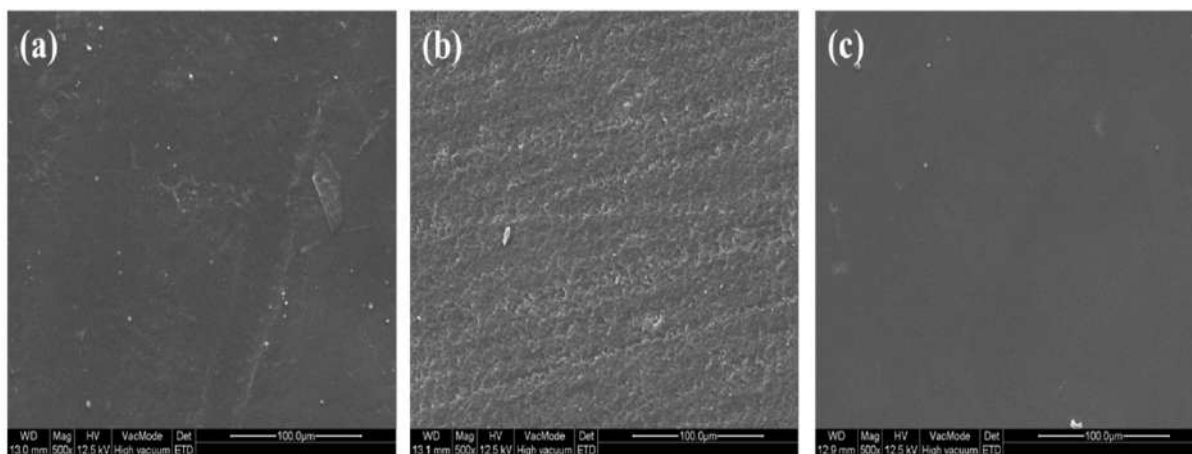


Figure 4. FE-SEM images (x500) of an unpolished resin sample as – SLA fabricated (a) after sanding (b), and (c) after sanding and Chemical Mechanical Polishing

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4. *Metallic powders used in Additive Laser Manufacturing (ALM)*

These technologies have emerged as a result of achievements and progress made in the field of fine mechanics, numerical control, laser technology, computer technology, computer software and new materials.

Laser additive manufacturing is a set of processes that allow layer by layer fabrication by adding material, creating a 3D physical model starting from a numerical model.

Direct laser additive fabrication of metal powders is performed by DMLS, SLM, EBM, DED, LM, LENS, DLF processes and use pure powders metallic, obtaining parts that can be functional immediately, not being necessary always a post-sintering treatment. [1-86]

Classification of the main technologies of Laser Additive Manufacturing, in according to the manufacturing principle is as follows:

I. Melting the metal powder bed

SLM - Selective Laser Melting

LBM - Laser Beam Melting

DMLS - Direct Metal Laser Sintering

EBM - Electron Beam Melting

II. Melting of conditioned metal powders with binder (polymer)

SLS - Selective Laser Sintering

SLA – Stereolithography

LM – Layered Manufacturing

FDM - Fused Deposition Modeling

3D Printing

III. Metal powder design and laser melting

DMD - Direct Metal Deposition

LENS - Laser Engineering Net Shaping

DLF- Direct Light Fabrication

3D Laser Cladding

LFF - Laser Freeform Fabrication

Laser Consolidation

EasyClad

LDT - Laser Deposition Technology

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IV. Wire technologies

Wire Deposition

EBF3 - Electron Beam Freeform Fabrication

DMD - Direct Metal Deposition (NTiC)

WAAM - Wire and Arc Additive Manufacturing

Indirect additive manufacturing of metal powders is carried out by SLS process, because the metal powder is conditioned with a binder for making the green piece, after which a post-sintering treatment is required to improve mechanical properties.

During post-sintering treatment performs depolymerization, burning of the binder used in the first phase of sintering with laser. For this reason, the SLS process is an indirect process of additive manufacturing of metal powders.

Each ALM process has its advantages and disadvantages concerning the residual stresses in the material after sintering / melting.

It is noted that by processing SLM, DMLS, EBM by melting powder bed, obtaining parts with very fine details with a very high complexity degree, but the speed of the process is low and the parts present mechanical properties quite low compared to the parts obtained by DMD with wire. [1-86]

The DMD (Direct Metal Deposition) process with metal wire is similar in principle FDM (Fused Deposition Modeling) procedure.

SLM, DMLS and EBM technologies are used for parts with fine details, with a high degree of complexity of shapes, but the manufacturing speed of the processes is slow. The mechanical properties are lower than in the case of DMD technology. Use fine-grained powder between 5-30 microns.

LMD technology (Laser Metal Deposition) is used for manufacturing medium complexity parts that present better mechanical properties, than SLM, or DMLS technologies. This technology uses granular powder larger of the order between 50-150 microns.

DMD (Direct Metal Deposition) is used for the manufacture of semi-finished products with simple geometric shapes.

The mechanical properties are good, like the forged parts.

The DMD wire process is mainly used for repair metal parts and has a high manufacturing speed, very good mechanical properties of the parts, but it cannot make complex shapes and very fine details.

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DMD manufacturing systems are similar as CNC centers, having 5 axes and allow 10 depositions of different metal materials on different surfaces of metal parts by performing the movements due to the movements allowed on the 5 axes.

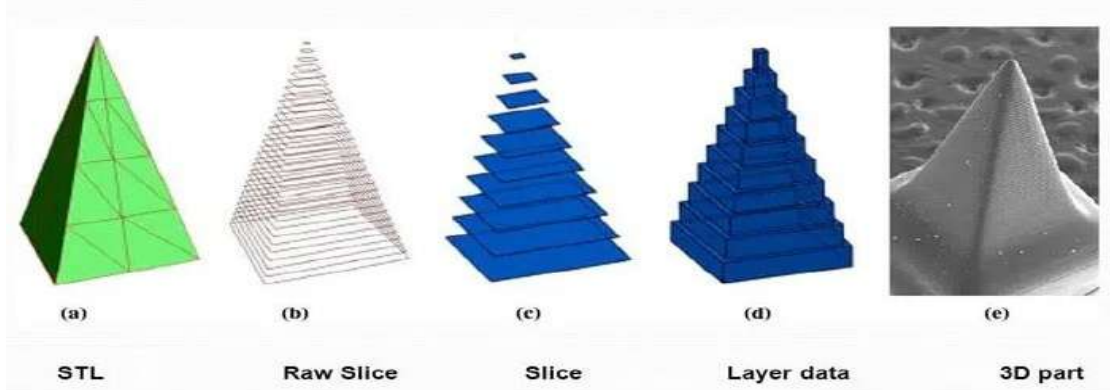


Figure 5. The general processing principle of Additive Laser Manufacturing technologies

The general processing principle of Additive Laser Manufacturing technologies (ALM) is presented in Fig.5.

Laser Additive Manufacturing of Metal Powder (ALM) must hold account for the next parameters:

- 1-temperature profile.
- 2-thermal gradient of metal powder.
- 3-speed solidification.
- 4-speed cooling.

For large series production, manufacturing systems are dotted with 1kW power lasers.

ALM manufacturing systems use different sources concerning the 3D model, namely:

- conversion CAD files (* STEP, * IGES);
- 3D scan (optical, RX,...) of the existing model.
- 3D models designed and exported from various design software (Blender, Catia, Solid Works, ProEngineer,...), saved as * stl or * gcode files.

Main uses of additive laser manufacturing (ALM) technologies are shown in figure 6.

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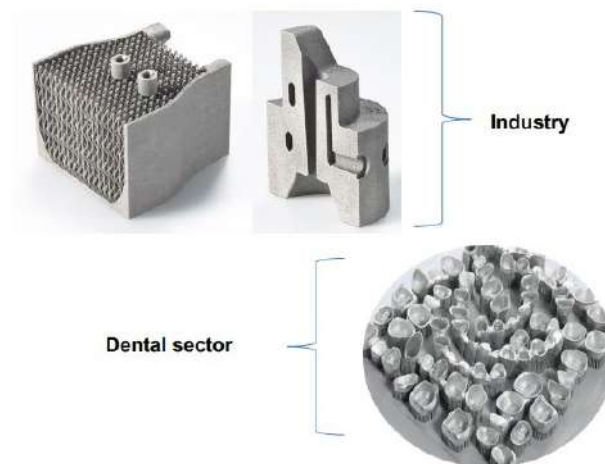


Figure 6. The main uses of additive laser manufacturing technologies (ALM): in industry and in medical domain

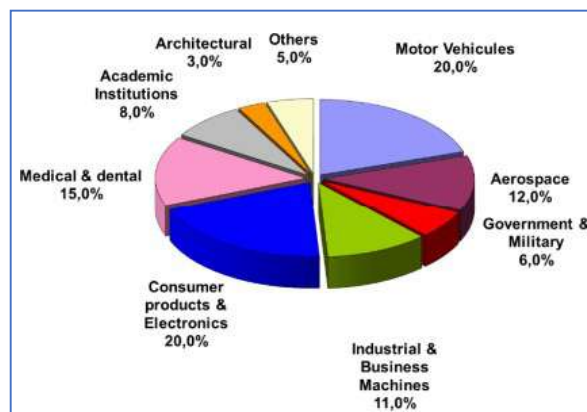


Figure 7. Applications domain of Additive Laser Manufacturing

The technological breakthrough brought by additive manufacturing in the field of manufacturing, by making it possible to rethink the design and production engineering of systems, pushes the industrial sector to increase the share of investment in this sector promising to manufacture. The evolution of the turnover of additive manufacturing to 6/36 Metal additive manufacturing: technologies and opportunities the global scale will be multiplied by 4.9 to reach the sum of \$10,800 million by 2020, as in figure 7. [1-86]

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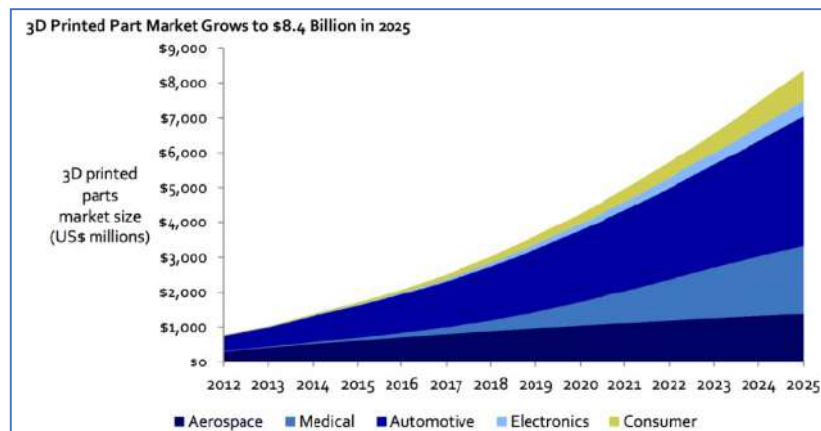


Figure 8. Market development, by industrial field, of additive manufacturing and its evolution

Among the major industrial fields interested in this new technology: automotive, aerospace and to a lesser extent, biomedical and wind power, as in figure 8.

SLS technology using stainless steel powder is a process of indirect sintering, as the powder is conditioned with a binder to lighten the formation of bridges between grains, and the part obtained by SLS sintering, cannot be used immediately, because it does not have the necessary mechanical strength. For this reason, green piece, as it is called, must necessarily endure another fasting treatment sintering in the oven for 30 minutes at 1100°-1200°C, to be realized final sintering between the metal grains of the powder and to increase mechanical strength of the piece. Selective laser sintering uses a high-power laser, generally up to 25W. The laser selectively sinters the powder by scanning cross sections generated from a 3D model, data from a CAD file or from a 3D scan. After each cross-section is sintered, a new layer of powder is applied with the help of a roller, and the process is repeated until the piece is completed. The systems of SLS manufacturing usually use a pulsed laser because the density of the part depends mostly on the laser power and less on the sintering time. SLS systems preheat the powder in the powder bed just below the point of melting, to facilitate laser sintering. Parts manufactured by SLS technology do not require the production of supports to be sintered, because the bed of unsintered powder surrounding the part can be used as a support. This process allows the creation of parts with geometries complex, which are difficult to achieve through traditional technologies. [1-86]

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A noticeable design aspect is the fact that it is impossible to manufacture an element that is hollow inside, but completely closed. This is due to the fact that it is impossible to drain the unsintered powder inside the element completely closed.

SLS manufacturing systems have started to become affordable in the market, but there are still obstacles in terms of high-power consumption up to 5kW and because of the temperatures that must be controlled with a precision of 2°C, for the three preheating, melting and storage steps, before removing the part.

This process is like direct metal sintering technology DMLS laser and SLM selective laser melting technology, the three technologies using the same concept but differing in technical details. For SLS technology, the powder is conditioned with epoxy resin binder, and laser power and sintering temperature is lower than in the case DMLS and SLM technologies. In the case of DMLS manufacturing the metal grains of the powder are not covered with binder, pure metal powder is used which is sintered, and the parts can be used immediately after sintering, without the need for further post treatment sintering.

The metallic powders used in DMLS and SLM processes are obtained by different methods, as: HDH (Hydrate-Dehydrate process), gas atomization, plasma atomization and plasma rotating electrode process.

Selective Laser Melting (Selective Melting Laser) SLM is a technology relatively new and differs from SLS technology because the metal powder is melted due to the high power of the laser beam above 25 W, obtaining a density of the material up to 80-90%, almost identical to the density obtained in the case casting, but they differ in the crystalline structure obtained, as well as the mechanical properties or the porosity obtained.

The SLM process allows parts to be built to form close cumulatively the net shape components. Some SLM machines use the powder with a single component, such as pure Ti alloy powder. Powders are usually produced by ball milling or atomization. [1-86]

The powder bed laser melting/sintering process does not only have advantages with regard to the geometry of the part. Indeed, the powder bed requires a surface plane to be spread by the roller, if the surface is not plane, the roller may hit the part and thus damaging the machine. Another important point is the fact that the laser powder bed fusion constructions most often exhibit anisotropy in the construction direction with an elongated grain along this axis. This phenomenon is due in part to the reflow of layer $n - 1$ when layer n has been integrated. This "natural" orientation therefore leads to an anisotropy of the mechanical

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properties (figure 9). It is however possible to attenuate this phenomenon by applying treatments thermal post manufacturing (TTH) to homogenize the structure.

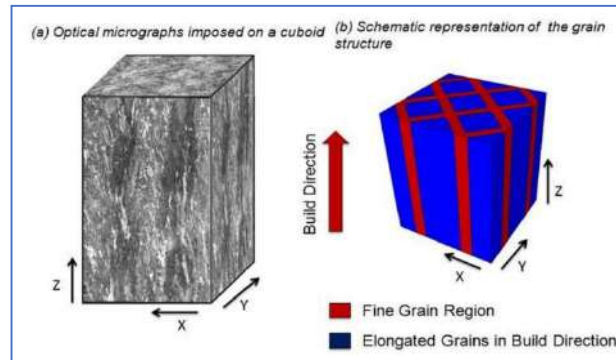


Figure 9. Anisotropy of the microstructure of parts built by SLM

Figure 10 presents additive manufacturing technologies performance concerning surface quality, part size, geometric complexity, manufacturing time, machine availability (number of machines available in the world), static properties, fatigue strength, fabrication cycle in industry, and, as can be noted, the DMLS process assures the best surface quality, geometric complexity, mechanical properties, and machine availability, but cannot be used to obtain large size parts and the manufacturing cycle is low. In comparison with other additive manufacturing technologies, such as EBM (electron beam melting), LMD (laser projection/laser metal deposition), DMD (direct metal deposition), only SLM (selective laser melting) and DMLS technologies can be used in dentistry.

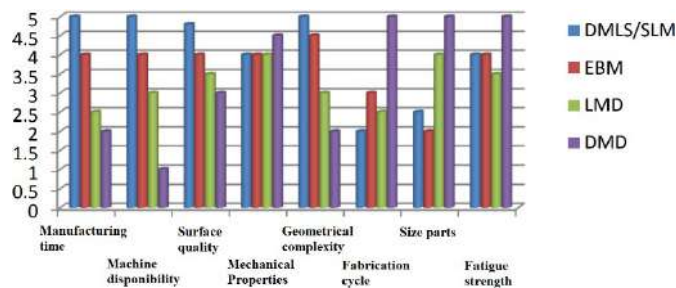


Figure 10. Comparison between the Additive Laser Technologies

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The most used technologies for the manufacturing metallic powders for DMLS are the hydride-dehydride process, water atomization, gas atomization, plasma atomization, electrode induction melting gas atomization (EIGA), plasma rotating electrode process (PREP), centrifugal atomization and plasma spheroidization.

The most common method of metal powder production for DMLS is plasma atomization. The elemental feedstock is melted under an air or inert gas blanket or under vacuum. The chamber is then backfilled with gas to force molten alloy to pass through a nozzle where high-velocity air, N, He, or Ar gas impinges the powder grains onto the flowing melt and breaks it up. The powder is mostly spherical, with some asymmetric particles and satellites present. A satellite is when a smaller particle sticks to a larger one during solidification. Grain size ranges from 0 to 500 microns. The most used powders that can be produced using this method are based on Ni, Co, Fe Ti, and Al alloys.

Characteristics of the powder particles at the end of the manufacturing process, using different standards,-are shown in Table 6.

Titanium cannot be directly brought in the powder state because it presents increased ductility compared to other crystallized metals, crystallinity being defined by the ratio of crystalline c/a over the theoretical value 1.633, which allows splitting grains after multiple plans with an atomic density close to the base or median plane.

Titanium is highly reactive to warm and oxide refractory materials so that the production of powders by mechanical means has the advantage of allowing the possibility to keep it at high purity level without being necessary to take special measures and expensive protection measures. The technology for obtaining titanium powder by hydride-milling-de-hydride systems is based on the behaviour of titanium to hydrogen. The solvus curve in the diagram is steep and provides the diffusion of a large amount of hydrogen in the solid solution. [1-86] Upon heating under equilibrium conditions, for temperatures above 450°C, hydrogen forms a metastable hydride —TiH₂. This can be brought to ambient temperature in the atmosphere without decomposition or by a complex reaction. It is extremely brittle and may be easily sieved to give a particle size fraction distribution range. In the case of vacuum heating, the hydride decomposes, liberating hydrogen. The SEM analyses, using a JEOL JSM-5600, for Ti6Al4V are shown in Figure 11 and Figure 12.

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Table 6. Standards (ASTM, ISO, EN) for powder properties used in additive manufacturing [86]

AM Powder characteristics	Powder Type	Symbols	Techniques	ASMT Standard	ISO Standard	EN Standard
Size and shape	Metallic powders	Φ [μm]	SEM	B822	13322	-
Specific density	Metallic powders	ρ _{specific} [g/cm^3]	Gas pycnometer	B293	12154	-
Apparent density	Non-free flowing metallic powders	ρ_{app} [g/cm^3]	Hall apparatus	B212	3923/1	3923
Apparent density	Non-free flowing metallic powders	ρ_{app} [g/cm^3]	Carney apparatus	B417	3923/1, 4490	4490
Apparent density	Metallic powders	ρ_{app} [g/cm^3]	Arnold meter	B703	-	-
Apparent density	Refractory metals and compounds	ρ_{app} [g/cm^3]	Scott volumeter	B329	3923/2	-
Tap density	Metallic powders	P_{tapped} [g/cm^3]	BT-1000	B527	3953	3953
Average particle size	Metallic powders	d_{60}	Fisher sub-sieve sizer	B330, C72	10070	-
Powder sieve analysis	Metallic powders	-	Sieve analysis equipment Westmoreland	B214	4497,2591	24497
Particle size distribution	Metallic powders and related compounds	d_{10}, d_{60}, d_{90}	Light scattering	B822	13320, 24370	-
Flowing rate	Free-flowing metallic powders	Flow time (s) for 50g	Hall apparatus	B213	4490	4490
Envelope specific surface	Powder bed under steady flow	S_v [m^2/g]	Measurement of air permeability	-	10070	196-6

The analyses emphasized two predominant forms of particles: blocks with flat facets—almost smooth—and sharp edges and peaks and foam particles, with a large number of microscopic cavities. This type of granulometry powder is not good for DMLS, because it influences the powder flowing rate and the sintering process quality.

The main mechanical characteristics of Ti6Al4V powder are: elastic limit 0.2% $R_{p0,2} = 815$ MPa, elongation at break = 10%, Vickers hardness = 375 HV , elastic modulus = 229 GPa, mass density = $8,336 \text{ g}/\text{cm}^3$, corrosion resistance $< 4 \mu\text{g}/\text{cm}^2$, and thermal expansion coefficient = $14,5 \times 10^{-6} \text{ K}^{-1}$.

The SINT-TECH company and ISO 9001 and ISO 13485 standards propose a range of powders suitable for the process developed by Phenix Systems. This powder range was selected to guarantee an optimized result for implementation with the “PX” range and the former “PM” range systems produced by Phenix Systems. [1-86]

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The Co-Cr alloy powder (ST2724G) used for DMLS manufacturing presents the chemical composition: 54.31 %Co; 23.08%Cr; 11.12% Mo, 7.85% W, 3.35% Si, and Mn, Fe < 0.1%. [35-41]. Table 7 presents the mechanical characteristics of the Co-Cr powder used for the DMLS manufacturing process.

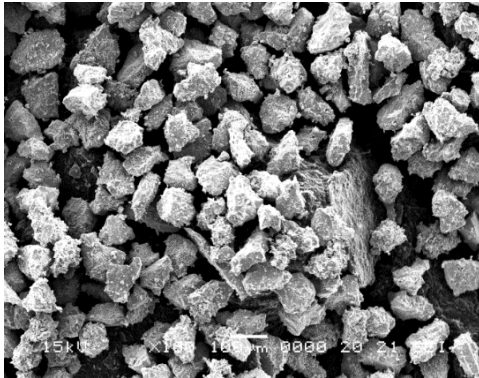


Figure 11. Ti6Al4V powder obtained by hydride-dehydride

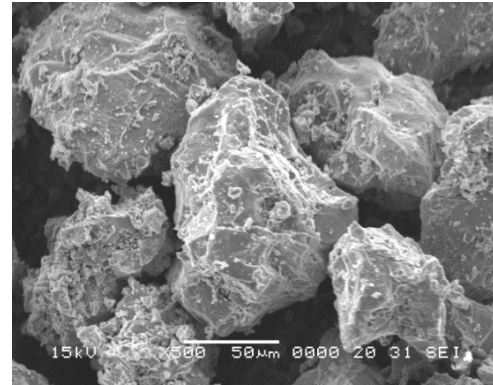


Figure 12. Compact and irregular Ti6Al4V grains

The main mechanical characteristics of Ti6Al4V powder are: elastic limit 0.2% $R_{p0,2} = 815$ MPa, elongation at break = 10%, Vickers hardness = 375 HV , elastic modulus = 229 GPa, mass density = $8,336 \text{ g/cm}^3$, corrosion resistance $< 4 \text{ } \mu\text{g/cm}^2$, and thermal expansion coefficient = $14,5 \times 10^{-6} \text{ K}^{-1}$.

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The morphology investigation and semi-quantitative analysis of powder were performed using a QUANTA INSPECT F scanning electron microscope and x-ray spectrometer for energy-dispersive (EDS) with a 133 eV resolution at MnK.

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The DLMS process consists of sintering a powder material using a laser that binds powder grains to materialize a solid structure by welding. The un-sintered or loose material is removed after the sintering process is finished on the machine and can be recycled for future use, making it both economical and environmentally friendly.

Table 7. Mechanical characteristics of Co-Cr powder

Minimum layer thickness	20 μm
Surface roughness	Ra=10 μm , Ry=40-50 μm Ra=0,39 μm , Rz=1,6 μm After polishing Rz<1 μm
Density with standard parameters	8,3 g/cm ³
<i>Mechanical properties</i>	
Tensile strength	1100MPa
Yield strength	600 MPa
Elongation at break	20%
Young's modulus	200 GPa
Hardness	35-35 HRC
Fatigue life	>10 million cycles
<i>Thermal properties</i>	
Maximum operating temperature	1150 °C

The Co-Cr alloy powder has low granulometry, and the spherical grain size is approximately 20 μm , as shown in Figure 13a). Figure 13b) shows the DMLS sintered structure of a dental part; this image also shows the specific porosity. The EDAX analysis of the Co-Cr powder is illustrated in Figure 14.

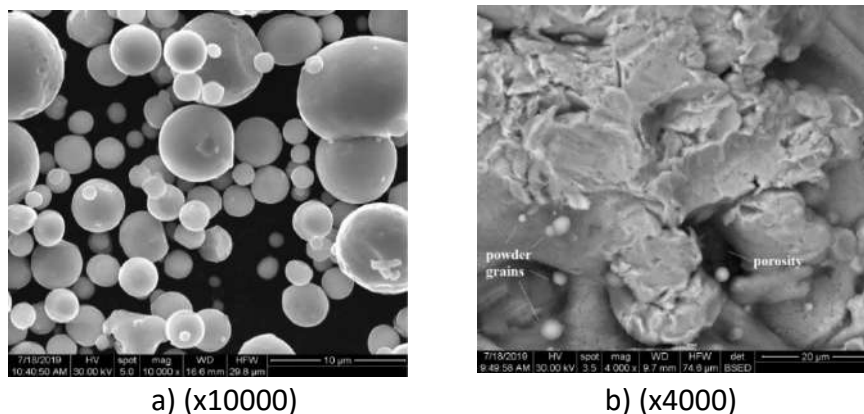


Figure 13. SEM analysis of a) Co-Cr powder; b) DMLS sintered structure

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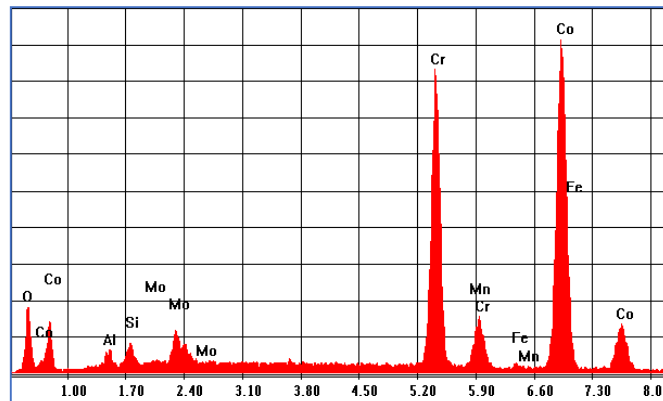


Figure 14. EDAX analysis of Co-Cr alloy powder



Figure 15. Analogue dental implants manufactured by DMLS



Figure 16. The platen of sintering machine

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In figure 15 are presented analogue dental implants manufactured by DMLS using Co-Cr alloy powders and a Phenix Systems machine. The Phenix System machine has a rectangle platen used in the sintering process, as in figure 16.

The material used for the platters is martensitic stainless-steel Fe-15%Cr, with magnetic properties. It has excellent mechanical properties (strength, hardness), corrosion resistance and heat resistance. The spark type is fragmented, straight, white characteristic of martensitic stainless steels. Platens made of martensitic stainless-steel Fe-15%Cr allow to be reused, by carrying out milling and rectification operations, necessarily requiring a hardening treatment to increase the hardness of the superficial layer on the surface of the platen. In figure 17 is presented the SEM analysis of Co-Cr alloy chips and stainless-steel martensitic Fe-15%Cr of the platen of the machine. [1-86]

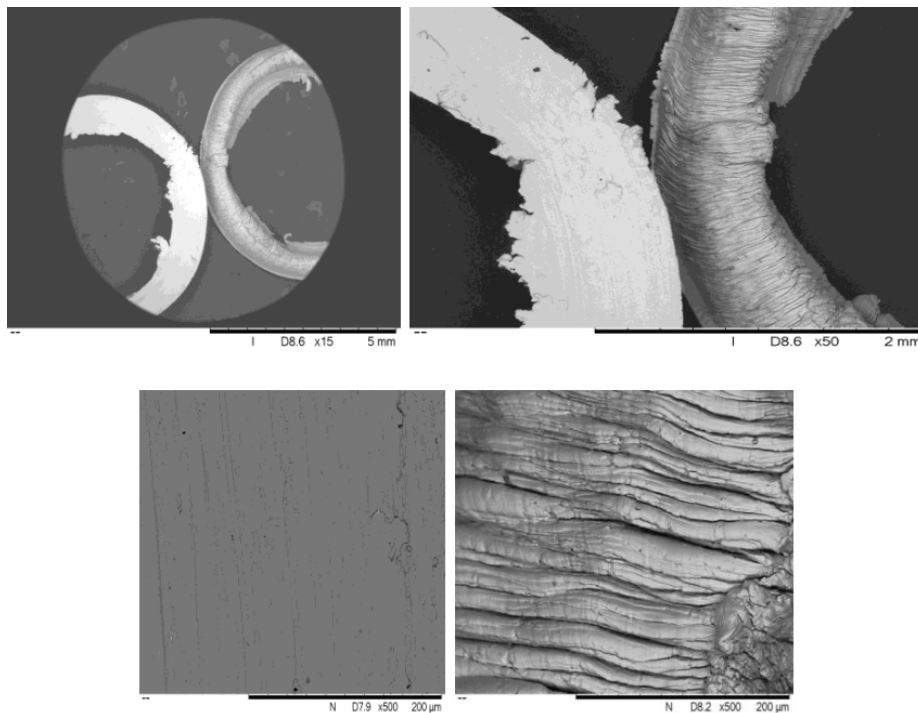


Figure 17. SEM analysis of Co-Cr alloy chips and stainless-steel martensitic Fe-15%Cr of the platen of the machine

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To determine the tensile and compressive strength (Fig. 18) was used an INSTRON 8810 machine, having the speed of 0.5 mm/min. The curves obtained at traction and compression show excellent mechanical resistance, maximum tensile that the samples withstand is 1200 MPa, being a superior mechanical resistance that is required in medical applications (dental crowns or analogue dental implants), as in the figure 18. [1-86]

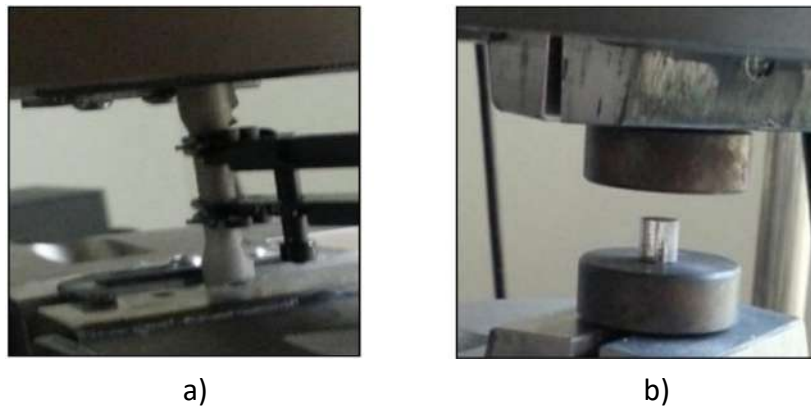


Figure 18. a) Traction and b) Compression tests of Co-Cr alloy manufacturing by DMLS, using INSTRON 8810 machine

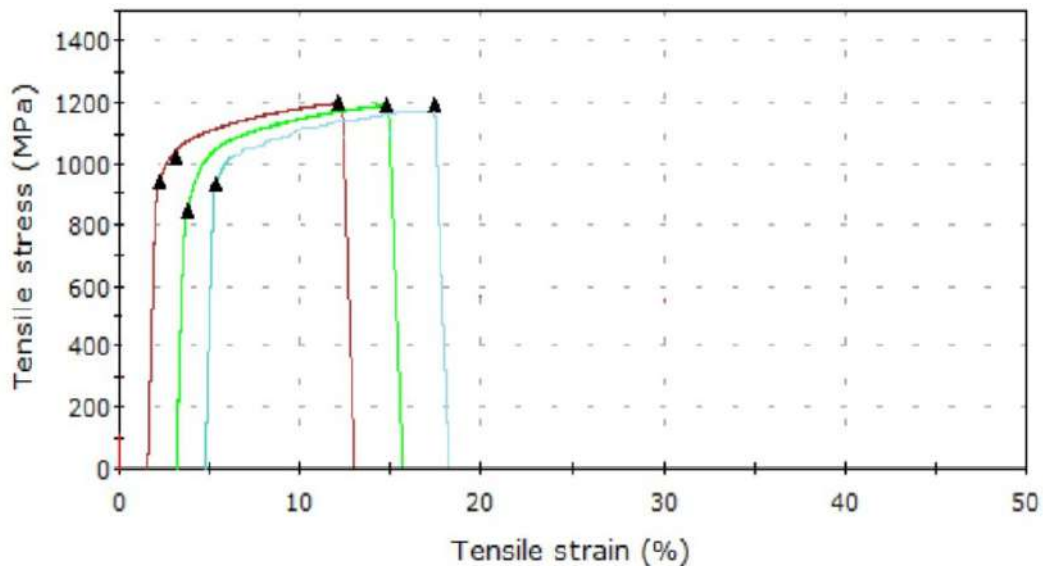


Figure 19. Traction curves obtained for the Co-Cr alloy manufactured by DMLS

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It is noted in the case of tensile tests that the samples break suddenly perpendicular to axis of the specimens, around the stress of 1200 MPa and we can notice the behavior mechanically strong brittle (Fig.19), specific to sintered metallic powder through SLS and DMLS technologies. [1-86]

The morphological structure of the alloy powder tensile specimen of Co-Cr sintered by DMLS technology is shown in figure 20 and can observe the deformation of the material, the structure with deformed pores and the appearance of cracks in the material and regular layers.

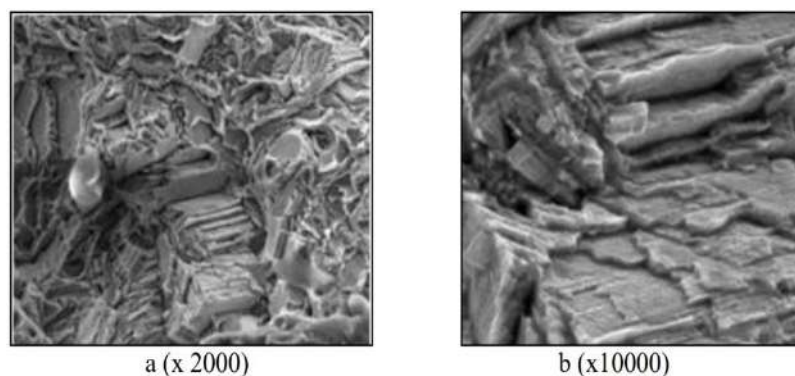


Figure 20. SEM analysis of the samples of Co-Cr superalloy after the traction tests

In the case of compression tests, the behavior is also noted mechanically strong brittle, specific to sintered materials from metallic powders, as in fig. 21.

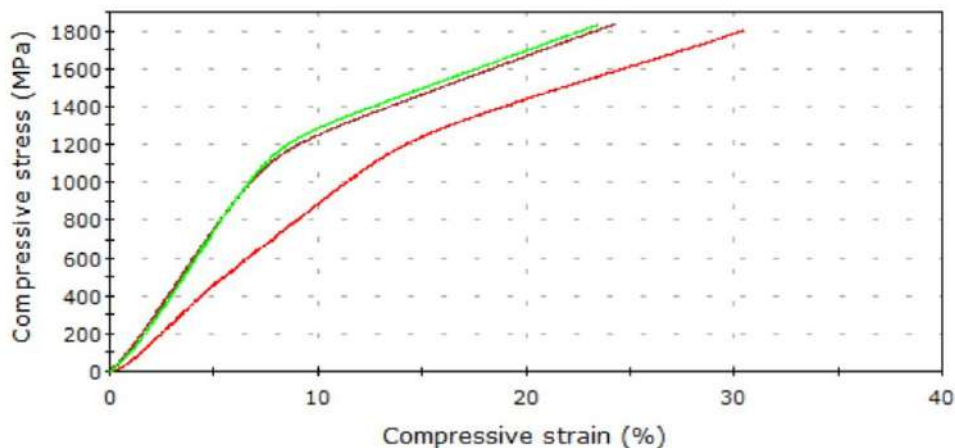


Figure 21. Compression curves obtained for the Co-Cr alloy manufactured by DMLS

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Also, the mechanical strength is up to around 1200MPa. The specimens became barrel-shaped, the deformation is accentuated with deformed pores, regular layers are also noticeable, as in Fig. 22.

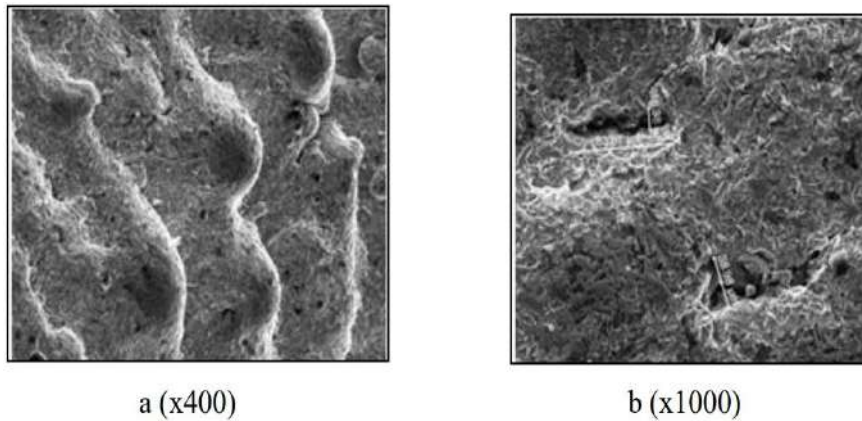


Figure 22. SEM analysis of the samples of Co-Cr superalloy after the compression tests

Following tensile and compression tests it was noted that the samples sintered from Co-Cr alloy powder and obtained by DMLS technology, present excellent resistance up to around 1200 MPa, this resistance is a lot superior to that required in medical applications. [1-86] The ICP-MS analysis (Inductively Coupled Plasma – Mass Spectrometry) was used for determining the amount of metal ions dissolved by mass absorption from SBF in which 6 Co-Cr samples sintered DMLS, were subsequently immersed in SBF – Simulated Biological Fluid (3 samples supported a post sintering treatment in the furnace, at 800°C, during for 30 minutes). The instrument used was an ICP-OES spectrometer 725.

Table 8. ICP-MS analysis

Samples	pH
S1 thermal post-treatment	7,77
S2 thermal post-treatment	7,76
S3 thermal post-treatment	7,74
S4 without treatment	7,74
S5 without treatment	7,73
S6 without treatment	7,77

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In table 8 are presented the ICP-MS analysis, the determination of the metal ions of Co, Cr, Mo, W was carried out with ICP-OES device model 725, from Agilent Scientific.

For all samples the amounts of Co, Cr, Mo, W were < 0.0001 g/l, the amounts of metals were below the detection limit, so this superalloy can be used safely for temporary dental implants and dental crowns manufacturing.

4.1. Laser types used in Additive Manufacturing

Fiber lasers are up to 100 times more powerful than CO₂ lasers and are also used for sintering metal powders. The diode has a long life.

Fiber lasers are the most reliable and most used in industry.

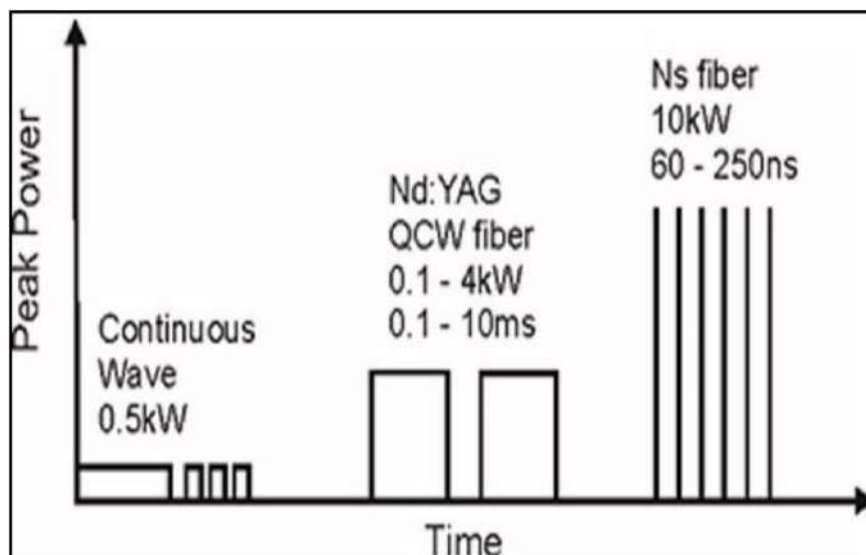


Figure 23. Differences between YAG and fibers lasers

Crystal YAG lasers belong to semiconductor lasers and are suitable for processing metal powders, having the same wavelength as 1,064 micrometer fiber lasers. But they have a short life and are very expensive. [1-86]

The difference between YAG and fiber lasers is the difference in values laser power, as in figure 26. Metals like Al, Ag, Au which are very heat-conducting and highly reflective, present a high thermally gradient and during the manufacture of the powder can appear the agglomeration,

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a powder conglomerate around of the sintered part, a phenomenon noted in the case of aluminum. So, the pieces will not be well delimited. In figure24 are presented different laser modes.

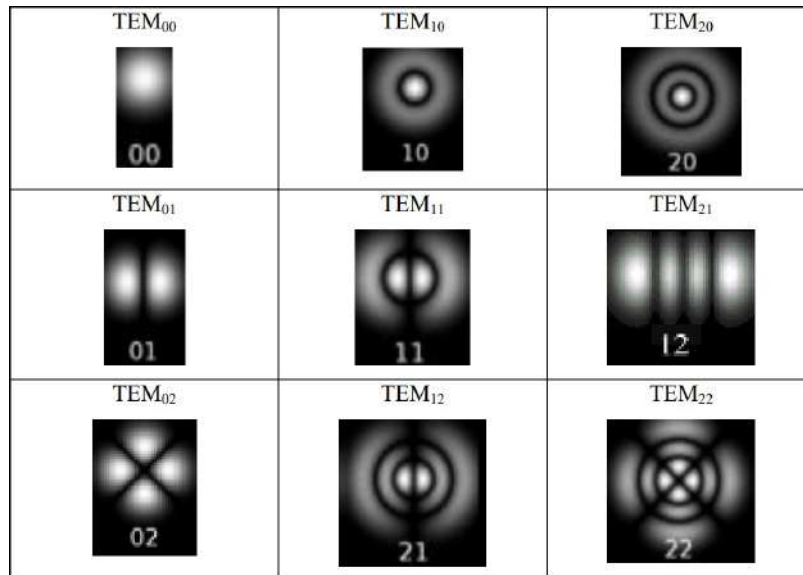


Figure 24. Different laser modes

Fiber lasers can be:

- monomodal, the diameter of the core is very small of $9\ \mu\text{m}$, the outer diameter is of $125\ \mu\text{m}$ and presents a single mode of light propagation ($9/125$) – fig.25;
- multimodal, because light propagates in several ways, so it can follow several trajectories inside the core and are of the type ($50/125$ or $62.5/125$ in μm) – fig.26.

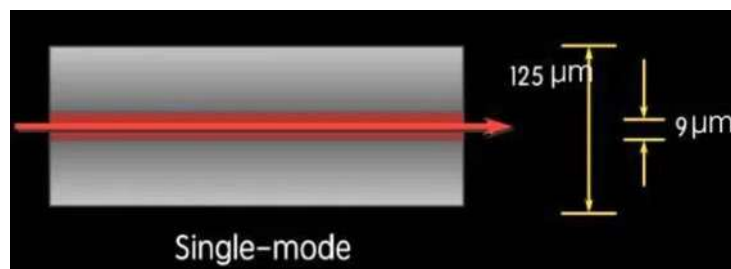


Figure 25. Monomodal laser fibers

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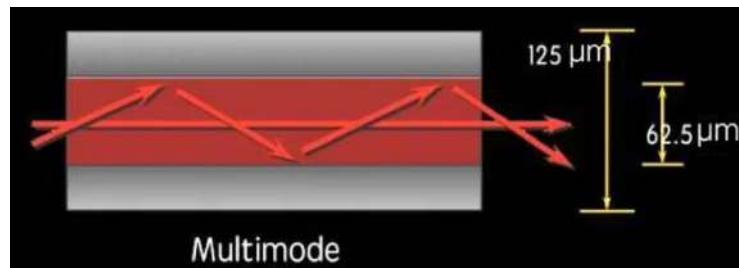


Figure 26. Multimodal laser fibers

For example, the PM100 manufacturing equipment from Phenix Systems (fig.27) uses a powder with a very fine particle size of $10\ \mu\text{m}$, a laser Nd:YAG power of 200W, the laser beam is of monomodal type TEM₀₀ showing a Gaussian-like power density profile.

The LF 250 manufacturing equipment from TrumaForm (fig.28) uses a powder with a grain size greater than $30\ \mu\text{m}$, the laser beam is of the type multimode TEM₁₀ showing a Flat-Top power density profile.



Figure 27. Phenix Systems – PM100 system Figure 28. TrumaForm LF250 system

In the case of SLM manufacturing systems, they can be equipped with a laser source, with two laser sources (Twin laser sources), respectively four laser sources (Quad) working independently, to increase productivity and reduce manufacturing time.

Figure 29 shows the Nd:YAG laser beam profiles: Gaussian laser beam, multimodal laser beam, top-hat laser beam. The most widely used in laser additive manufacturing is the "top-hat" Nd:YAG laser beam.[1-86]

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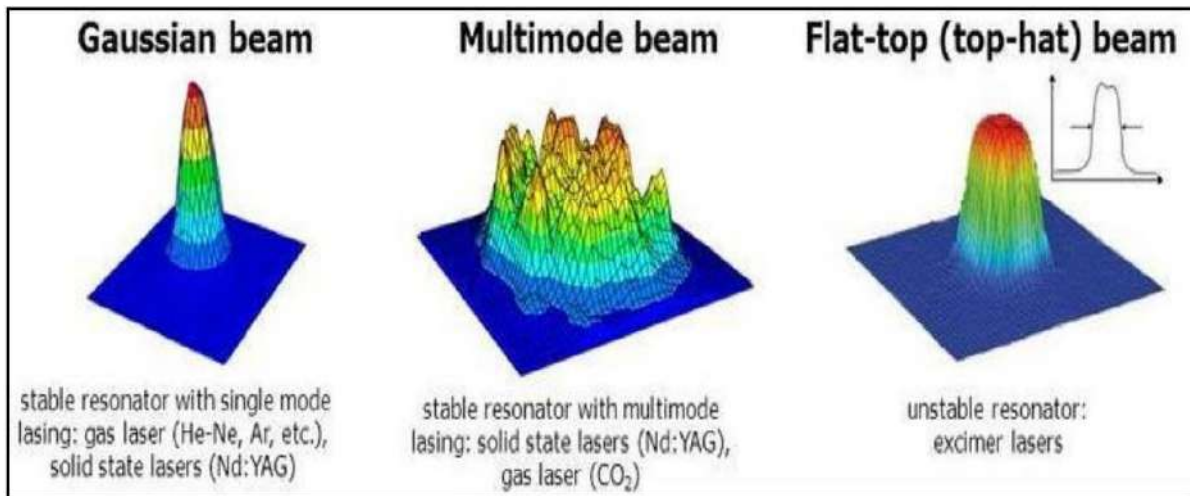


Figure 29. Laser beam profiles Nd:YAG: a) Gaussian beam; b) Multimode beam; c) flat-top (top-hat) beam

Electrons Beam Melting manufacturing is an additive manufacturing process that uses electrons beam for metallic powders melting. This process was researched and developed by Chalmers University in Sweden in the 1990s.



Figure 30. Trabecular Lattice structures for enhanced osseointegration

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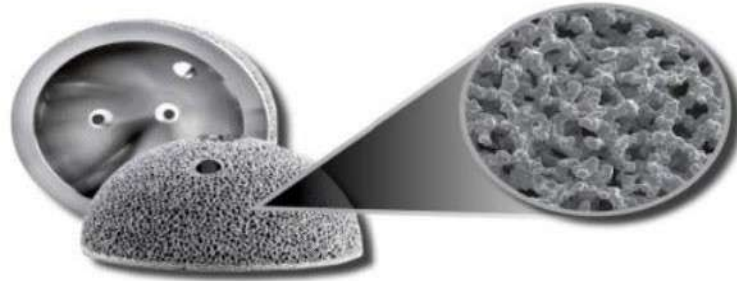


Figure 31. Acetabular cups, manufactured by EBM technology, for hip replacements, with trabecular structure, Courtesy Arcam

The raw material used in this process is metal powder of various qualities, being similar to the selective laser sintering process SLS and selective laser melting SLM. Specific to the EBM process is the fact that the laser is replaced by electrons beam whose power can reach 4kW, as a melting source.

The materials frequently used by this process are pure commercial Ti, Ti-6Al-4V alloy, the Co-Cr alloy, Inconel 718 and Inconel 625. This process allows the development of the manufacturing parameters in order to make parts from alloys of Cu, Nb, Al 2024, stainless steels, titanium aluminide.

The process consists in projecting a beam of electrons that reaches half the speed of light, on the surface of the powder bed, and their kinetic energy is transformed into heat, melting the metal powder.

The structure of the material manufactured by EBM technology is unique, trabecular, i.e. with a very small porosity of the order of microns.

The EBM trabecular structure allows optimization of osseointegration due to pore geometry, pore size, relative density and roughness.

The metal implant with trabecular structure has become the preferable treatment, solving difficult cases and greatly increasing the success rate. The implant has a composition of titanium and tantalum. [1-86]

For these patients, studies highlight different trabecular lattice structures obtained by EBM and that permit the appearance of neof ormation bone in and on the surface of the implant in

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the first 2 weeks after implant insertion, as in figure 30. In figure 31 is presented an acetabular cup, manufactured by EBM technology, for hip replacements, with trabecular structure

4.2. *Metallic powders and filaments used in Laser Metal Deposition and Direct Metal Deposition*

In the field of powder projection for the technology Laser Metal Deposition (LMD), two techniques exist: the powder can be injected laterally (Figure 32(a)) or coaxially to the laser beam (Figure 32(b)). The first technique, very simple to manufacture, involves difficult serving of the position of the injector in relation to the movement of the nozzle to achieve complex shapes.

This explains the use of coaxial nozzles in most cases for multi-directional reloading. This second technique also allows a better homogeneity of the deposit, due to longer irradiation of the filler material and regular. Finally, side spray nozzles are often more cumbersome. Considering their bounding volume when programming trajectories manufacturing is more delicate. [1-86]

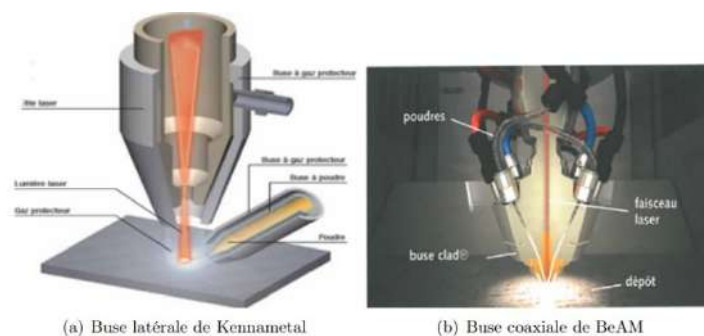


Figure 32. a) Laterally Kennametal buse; b) Coaxially BeAM buse

Several studies have been carried out to compare laser cladding technology and TIG (Tungsten Inert Gas). In most cases, these studies are carried out in order to promote laser reloading, it is thus difficult to find arguments against laser reloading.

The precision of the laser compared to TIG welding makes it possible to produce parts complex, requiring less re-machining as shown in Figure 33.

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Concerning laser cladding, the heating zone being more localized, the heat affected zone (HAZ), which is the site of metallurgical modifications of the metal of base that can induce fragilities, reductions in mechanical resistance, lack of ductility is lower. For the same reasons, the deformations induced in the part by thermal increase are less important.

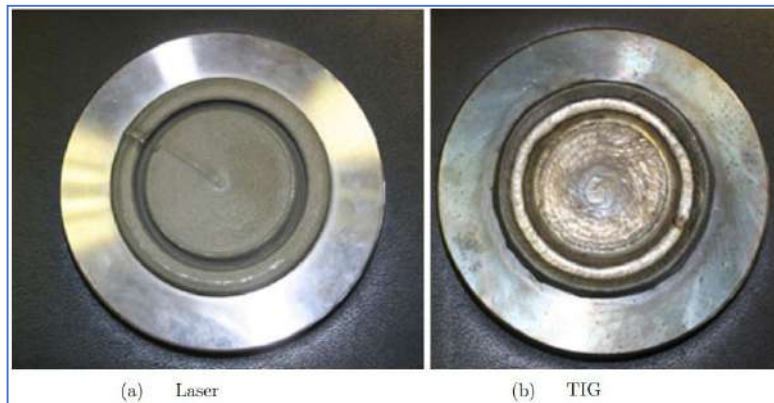


Figure 33. Geometry resulting from LMD process and TIG welding

Another advantage of laser cladding is the lower dilution area compared to in TIG welding, this small dilution zone makes it possible to obtain a homogeneous deposit and having the desired characteristics throughout its thickness, unlike the TIG welding which presents a strong dilution, degrading the quality of reloading and an uneven fusion depth. This feature is illustrated in Figure 34. [1-86]

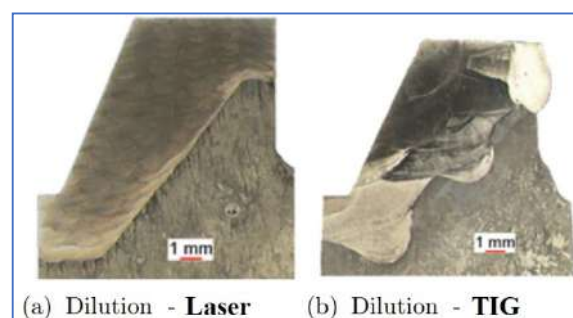


Figure 34. ZAT after: a) LMD process and b) welding TIG

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Microstructure analysis reveals a finer structure in the case of the laser cladding than in the case of TIG welding. The concentration of energy in the case of the laser makes it possible to obtain a higher cooling rate, which reduces the grain size and therefore increases the hardness of the material. In the case of a stellite 6, can notice a hardness of 48-50 HRC against only 40-42 HRC in the case of welding TIG. Figure 35 shows these differences in microstructure. [1-86]

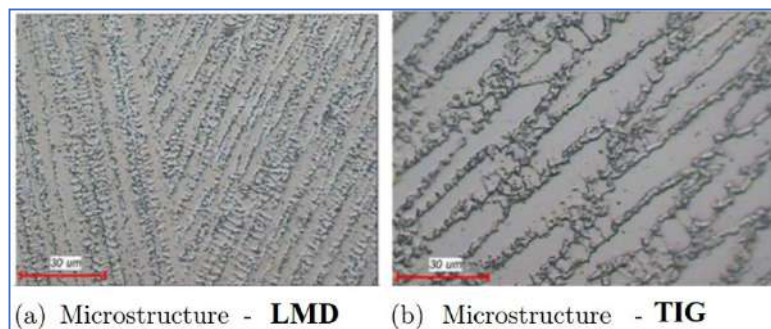


Figure 35. Microstructure after: a) LMD process and b) welding TIG

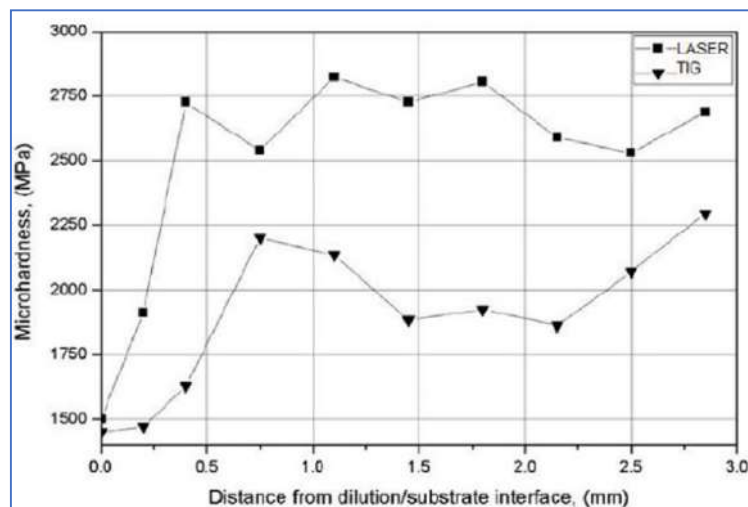


Figure 36. Evolution of the microhardness as a function of the distance to the hardened zone for an Inconel 625 coating added by laser or TIG

The TIG process, like MIG, is characterized by a significant increase in temperature in the room, which leads to recrystallization and weakening of the base alloy in the working area, as can be seen in the graph of Figure 36.

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4.3. Architectural materials manufactured by SLM

In figure 37 are shown simple geometric cells for architectural materials, manufactured by innovative ALM (Additive Laser Manufacturing) technologies.

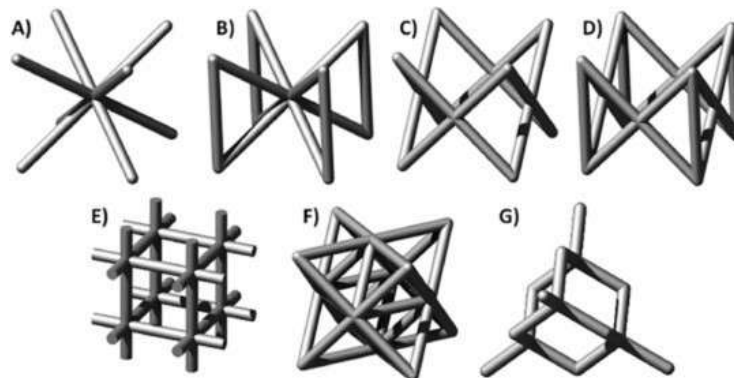


Figure 37. Strut-based lattice structures: BCC (A), BCCZ (B), FCC (C), FCCZ (D), cubic (E), Octet-truss (F), and diamond (G)

The most common strut-based cell topologies that have been investigated are body-centred cubic (BCC) and face-centred-cubic (FCC), or variations of these, such as the inclusion of z-struts (BCCZ and FCCZ) (Fig.39) which are named after analogous crystalline structures. Other strut-based topologies also exist, such as the cubic, octet-truss and diamond.

These topologies are generated using mathematical formulae that define the $U \frac{1}{4} 0$ iso-surface boundary between solid and void sections of the structure (Table 9) [46]. Various parameters such as periodicity and relative density can be altered to tune their mechanical performance. Two industries which have taken particular interest in AM lattice structures are the biomedical and aerospace industries. [1-86]

AM lattice structures are used in the biomedical industry for medical implants, the global market for which is expected to grow to \$116 billion by 2022. The ability to produce high-quality metallic components that conform to complex, patient-specific surfaces makes SLM perfect for the fabrication of medical implants, and the ability to produce metallic components with stiffness closer to that of bone makes AM lattice structures perfect for biomedical applications.

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These structures can be designed to produce optimal osseointegration and have been shown to sustain excellent bone in-growth and achieve high performance in terms of implant fixation. Beyond the manufacture of metallic implants, potential innovative design applications of AM lattice structures have been suggested, such as Burton et al. who have proposed an implant which incorporates a reservoir that locally releases a therapeutic drug to achieve antimicrobial functionality by incorporating a reservoir. [1-86]

The light-weighting potential of AM lattice structures, such as the replacement of internal solid volumes with lattice structures with a similar strength, means AM is of great interest to the aerospace industry. Other properties of AM lattice structures, such as the ability to produce conformal cooling channels also makes them an attractive option for aerospace applications. Zhou et al. have developed a lightweight phase-change thermal controller based on lattice cells [85]. Thermal controllers are an important component to manage the temperature of various electronics in spacecraft, yet traditional designs considerably add to the spacecraft's weight. Using an SLM-fabricated lattice sandwich structure Zhou et al. were able to produce a thermal controller with 50% increased thermal capacity compared to traditional alternatives with similar mass. In the table 9 are presented the SLM processing parameters and in the table 10 are presented the properties of metallic materials used in SLM technology.

Table 9. SLM processing parameters [82]

Machine	Manufacturer	Material	Spot size (µm)	Border power (W) ²	Hatch power (W)	Scan speed (mm/s)	Hatch spacing (mm)	Layer thickness (µm)	Mean powder size (µm)
ProX DMP 300	3D Systems	Ti-6Al-4V	—	—	—	—	—	—	8.64
ProX-300	3D Systems	SS 316L (17-4PH)	70	170	170	1600	0.05	40	—
Concept X-line 1000R	Concept Laser Company	AlSi10Mg	—	—	370	1500	0.19	30	31
M2 Cusing®	Concept Laser Company	Ti-6Al-4V	60	150	150	1750	0.075	20	20-50
EOSINT-M270	EOS	Ti-6Al-4V	100	58.5	117	225	0.18	30	45
M280	EOS	316L SS	100	—	—	—	—	—	20-40
DMLSHSINT-M270	EOS	Ti-6Al-4V	100	170	170	1250	0.06	30	20
M 270	EOS	Ti-6Al-4V	100	170	170	1250	0.1	30	29
M 270	EOS	Ti-6Al-4V	10	117	117	225	0.18	30	—
M280	EOS	AlSi10Mg	—	370	370	1500	0.13	30	30
Realizer II	MCP	316L SS	90	80-160	80-160	—	—	—	16-38
MCP Realizer 2, 250 SLM	MCP	Ti-6Al-4V	54	80	80	—	—	50	45
Realizer SLM Workstation	MCP	316L SS	40	95	95	—	0.075	75	45
AM250	Renishaw	AlSi10Mg	80	200	200	—	0.13	25	—
AM250	Renishaw	Ti-6Al-4V	—	100	200	—	0.065	30	—
AM250	Renishaw	AlSi10Mg	70	—	—	—	—	25	—
SLM 125	SLM Solutions	CP-Ti	—	100	100	385	0.12	—	36.6
SLM250HL	SLM Solutions	Ti-6Al-4V	—	100	100	375	0.12	30	40

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Table 10. Properties of metallic materials used in SLM technology [82]

Material	Property	Value
Inconel 625	Density	8.44 g/cm ³
	Yield strength	460 MPa
	Modulus	205.8 GPa
TiAl6V	Density	4.43 g/cm ³
	Yield strength	880 MPa
	Modulus	193 GPa
Stainless steel	Density	8 g/cm ³
	Yield strength	205 MPa
	Modulus	193 GPa
AlSi10Mg	Density	2.67 g/cm ³
	Yield strength	240 MPa
	Modulus	70 GPa

Table 11. Quasi-static compressive test data for SLM lattice data collected from literature, ordered by unit cell topology [82]

Topology	Material	Relative density (%)	Cell size (mm)	Strut diameter (mm)	Geometry (N = nominal, M = measured)	Compressive strength (MPa)	Modulus (MPa)
BCC	316L SS	3.5–13.8	1.25	0.19–0.22	N	0.38–5.89	17.89–378
BCC	316L SS	2.3–4.3	–	0.162	N	0.2–1	8.68–57.56
BCC, BCCZ	316L SS	5.3–16.6	1.5–2.5	0.25	N	0.92–15	50–2700
BCC, BCCZ	AlSi10Mg	0.7–22.2	10	1	N, M	0.46–4.36	21.71–490.22
BCC, BCCZ, FCC, FCCZ	Inconel 625	2.5–13.8	2–4	0.3	N, M	0.8–10.9	22.1–12.96
BCC, BCCZ, FCC, FCCZ, FBCCZ, FBCCZY	Ti6Al4V, AlSi12Mg	7.5–39.7	2–7.5	0.3–1	N, M	4–124	110–2780
BCC, Octet-truss	SS 630 (17-4PH)	43	–	–	N, M	–	9710–13,960
Diamond	Ti6Al4V	3.6–26.5	–	–	N	8.2–99.64	370–4240
Dodecahedron	Ti6Al4V	15.78–314.55	–	–	N, M	19.4–117.2	550–3490
Gyroid	CP titanium	26.7–31.3	2–3	–	N	44.9–94.5	1465–2676
Gyroid, Schwartz diamond	Ti6Al4V	5–95	3–7	–	N	47–1559	120–17,190
Octet-truss, Rhombicuboctahedron	AlSi10Mg	10.4–14.7	–	–	N, M	4.7–9.1	690–1250
Schwartz primitive, cylinder grid	Ti6Al4V	70–90	1.5	0.37–0.58	N, M	–	920–2420
Simple cubic	Ti6Al4V	19.4–36.2	–	0.54–0.64	N, M	108–170	5360–8730
Truncated cuboctahedron, simple cubic, diamond	Ti6Al4V	20–34	–	–	N, M	31.7–112.6	2180–4578

In Table 11 are presented the quasi-static compressive test data for SLM lattice data collected from literature ordered by unit cell topology.

Other areas of study which would facilitate the greater characterization and commercial adoption of SLM lattice structures include:

- The performance of SLM lattice structures have been characterised in their fabricated state, but knowledge of their performance during operation is still limited. The thermal behaviour of SLM lattice structures during operation, especially the effect of atmospheric phenomena for aerospace applications, and the effect of biodegradation on the fatigue strength of SLM lattice implants for biomedical applications are yet to be characterised. [1-86]

- Most research on SLM lattice structures focuses on either strut-based or TPMS lattice structures discretely. Research on their comparative performance is still needed to identify the appropriateness of these design approaches for different applications and performance requirements.

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-The tensile performance of SLM lattice structures is still not well defined as most research uses compressive experiments for identification of their mechanical properties largely due to the greater difficulty of tensile lattice experimental design.

Knowledge of the behaviour of lattice structures is quite disparate, as researchers have investigated isolated areas of the broad field of lattice structures. Greater homogenisation and standardisation of this field could lead to new insights and enhance the applicability of SLM lattice structures for all applications. SLM allows the fabrication of complex geometries with high resolution, which is perfect for the manufacture of lattice structures. Using this technology, lattice structures with highly tuned geometries and topologies can be fabricated to produce a wide variety of properties unachievable by their bulk materials. This has led to research into these structures, particularly for biomedical, light-weighting and energy-absorption applications. However, there exists no overarching analysis of this data.

In figure 38 are presented the mechanical properties of the principal alloys used in Additive Laser Manufacturing. [1-86]

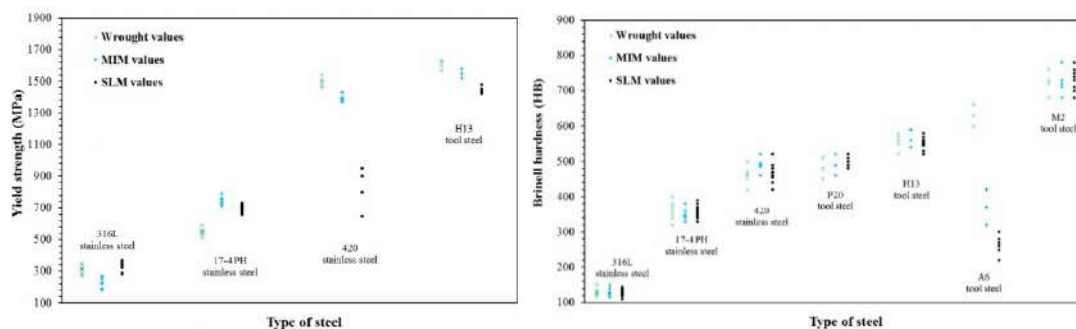


Figure 38. Mechanical properties of the principal's alloys used in Additive Laser Manufacturing

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EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC
MECHATRONIC SYSTEMS

MODULE INTELLIGENT (SMART) MATERIALS POLYMERIC MATERIALS

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1. Introduction

3D printing known as Additive manufacturing is a process where a digital model is converted into a 3D object by adding various materials layer by layer. The digital model is rendered with computer-aided design software (CAD). This virtual model is then sliced into horizontal layers and convert to a STL file which can be loaded into the 3D printer ready to “read” it. This technique is versatile being able to produce complex forms and structures out of different materials for a wide range of applications: construction building, food packaging, aerospace, cosmetic industry, and most of all medical field.

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2. A short history of 3D printing

François Willème who lived between 1830-1905 was a famous French painter, sculptor, and photographer. In 1860 his photosculpture method was able to capture an object in 3 dimensions using cameras surrounding the subject. A subject or object was placed in a circular room and simultaneously photographed by 24 cameras placed equally about the circumference of the room. An artisan then carved a 1/24th cylindrical portion of the figure using a silhouette of each photograph. François Willème was granted U.S. patent 43,822 for *Photographing Sculpture* in 1864, and this is one of the first attempts to obtain 3D printed objects.



Fig.1. François Willème' studio and his photosculptures []

In 1892 J.E. Blather suggested a layered method for making a mold for topographical relief maps for which he was granted the US patent 473,901 []. Later in 1940, Perera invented a method for producing a relief map by cutting contour lines on sheets (cardboard) and then stacking and pasting the sheets to form a three-dimensional map []. Munz developed some techniques in 1951 that resemble the SLA used today. Swainson was also a pioneer in early freeform fabrication by proposing a method to produce plastic models by 3D polymerization of photosensitive polymers at the intersection of two laser beams (1968, Photochemical machining). In this process, the object is obtained by photochemical crosslinking of a polymer at the intersection of laser beams. Next, Ciraud developed a powder process that is like the modern freeform fabrication (1971). The history continues, and Matsubara of Mitsubishi motors developed layered parts out of photo-hardened materials (photopolymers) in 1972.

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The idea of 3D printing could be also related to the science-fiction writer Murray Leinster. He related the 3D printing process in 1945 in his short story “Things Pass By”. The author imagined a machine able to collect his drawings and replicate them with a moving arm, using melted thermoplastic materials to produce 3D objects.

Coming to the early stages of modern 3D printing techniques, the first 3D printing attempts are granted to Dr. Hideo Kodama for his development of a rapid prototyping technique (photopolymerization of polymeric resins in 1980). He created a product that used ultraviolet lights to harden polymers and create solid objects. This is a stepping-stone to stereolithography (SLA). At the same time, but independently Herbert tried the same process at 3M Company. Unfortunately, the patent of Dr. Kodama was abandoned after one year and he did not finance it furthermore.

Jean-Claude André, Olivier de Witte, and Alain le Méhauté were French inventors working at Alcatel and the French National Center for Scientific Research trying to apply the rapid prototyping technique for producing parts. Sadly, their companies were not interested in this topic, and the idea was abandoned.

In 1984 Charles Hull (founder of 3D systems) invented stereolithography (SLA) – which is patented in 1987. The technology allows you to take a 3D model and use a laser to etch it into a special liquid (photopolymer). The object is printed layer by layer, rinsed with a solvent, and hardened with an ultraviolet light. The process uses computer-aided designs (CAD) to create the 3D model.

Hull’s company, 3D Systems Corporation, released the world’s first stereolithographic apparatus (SLA) machine, the SLA-1, in 1988. Hull has more than 60 patents around the technology, becoming the godfather of the rapid prototyping movement and inventing the STL file format that’s still in use today.

Selective laser sintering was invented by university student Carl Deckard somewhere in Texas. His printer was very simple and could only produce basic plastic components. His technology and printer are the basic for the SLS printing used today.

Stratasys and Scott Crump produced the world’s first FDM (fused deposition modelling) machine. This technology uses plastic and an extruder to deposit layers on a print bed. FDM was patented in 1989 by S. Scott Crump just before he launched the Stratasys company with his wife, Lisa Crump.

In 1992 3D systems produce the first commercial SLA 3D Printer machine. In the same year, DTM produced the first SLS (selective laser sintering) machine. This machine is similar to

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SLA technology but uses a powder (and laser) instead of a liquid. SLS uses a laser to fuse the powder together, layer by layer, into more complex shapes than SLA can create.

The term 3 D printing was coined in 1992 by Prof. Emanuel Sachs from MIT replacing somehow the initial term rapid prototyping. He has more than 40 patents from 1988-2002 and is a pioneer in the 3D printing field. Due to the work of Prof. Sachs, 3D printing technology has been used in many applications like metal end-use parts, ceramic parts for electronic applications, ceramic parts for machining, ceramic molds for metal casting, and for medical applications including polymeric materials for tissue engineering and drug delivery systems.

The era for medical applications of 3D printing had started. Scientists managed to grow organs from patient's cells and use a 3D printed scaffold to support them (1999). A 3D printed miniature kidney was manufactured in 2000. Scientists at Wake Forest aimed to produce full-sized, working organs. The first 3D prosthetic leg was produced (2008) without requiring any further assembly after coming off the print bed, and the first 3D printed blood vessel was realized by Organovo (2009). The improvements in medical domains evolved in 2012 with the first printed prosthetic jaw. Unlike the kidney, this part was successfully implanted into a human patient that same year.

A breakthrough was in 2014 when NASA brought a printer in space on the International Space Station. The next breakthrough is related to 2015 when the first commercial bioink for 3D printing of body tissue was on the market. In one year, scientists were able to print human bone and cartilage. Bioprinting is an emerging technology in producing functional tissue scaffolds based on natural/synthetic polymers to replace injured or diseased tissues.

The last challenge was in 2018 with the development of 3D printed houses. Elize Lutz, 70, and Harrie Dekkers, 67, retired shopkeepers from Amsterdam, received their digital key for a 3D printed house – an application allowing them to open the front door of their two-bedroom bungalow (2021). Virginia family received the keys to their new 3D-printed home for Christmas 2021. The 1,200-square-foot home has three bedrooms, two full baths and was built from concrete. The technology allowed the home to be built in 12 hours, which saves about four weeks of construction time for a typical home.

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3. *Polymeric materials for 3D printing*

The use of polymers for 3D printing led to the development of versatile products for many industries, especially the medical sector. Polymer printing could be performed with extrusion, resin and powder technologies, and many types of polymeric materials are employed: thermoplastic like polylactic acid (PLA), poly(ϵ -caprolactone) (PCL), acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), polyethylene terephthalate (PET), polyethylene terephthalate glycol (PETG), polycarbonate (PC), polyvinyl alcohol (PVA), polyesters/co-polyesters (PES), high impact polystyrene (HIPS), polyamide (NYLON, NOVAMID, etc.), polyether ether ketone (PEEK), polyether ketone ketone (PEKK), poly-aryl ether ketone (PAEK), polypropylene (PP), thermoplastic polyurethane (TPU), thermoplastic elastomer (TPE/TPC) polyetherimide (PEI), polymethyl methacrylate (PMMA), polyvinyl butyral (PVB), polyvinylidene fluoride (PVDF), chlorinated polyethylene (CPE) or other less used types of polymers with thermoplastic behavior [1, 2].

Furthermore, various commercial filaments have been developed starting from composite materials which contain a thermoplastic or thermoplastic-like polymer and a reinforcing agent. Many composite filaments use short carbon fiber as a reinforcing agent, but carbon black, graphite or glass are new choices when aims to develop a top composite filament. They extend the versatility of FDM 3D printing by enhancing the materials mechanical properties. Thus, high-strength parts with desired features (reduced weight, optimized design/geometries, replace metals) are manufactured through the usage of composite filaments. Another important goal of using short carbon fibers/graphite is to produce electroconductive printed materials. These 3D printed materials usually have the capacity to dissipate the anti-static charge, to obtain 3D printed circuits or to display electromagnetic shielding. The achievement of small-scale circuits is challenging due to resistivity values (106 ohm*meter). Considering the desired properties, composite filaments are used use to obtain the products. Thus, if tensile strength, low weight, electroconductivity or stiffness are important, carbon fiber is required. In case of glass fibers, the affordable price,

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durability, flexibility or multiple colors availability are specific. Furthermore, the chemical resistance or UV-light resistance are specific for both type of fibers [3].

Thermo-reactive (resins) polymers are also employed as basic materials for different 3D printing technologies: Stereolithography (SLA), Digital light processing (DLP) or Liquid crystal display (LCD). Therefore, the commercial resins are based on acrylic resins (prototyping acrylate), urethans, water-soluble monomers/oligomers or fluoropolymers from a chemical point of view [1, 2].

Considering the properties of the 3D printed products, the commercial resins can be classified as standard, clear, tough or flexible. The standard resins provide a high detailed surface, are translucent, smooth to the touch, low cost, easy to paint. Most of them requires a post-processing step. The clear resins are a choice to produce transparent 3D products. They are a special category of standard resins where the available colors are clear green, clear red, clear blue or simply clear. Tough resins are used for manufacturing products which can withstand strain or stress. Their properties are close to the thermoplastic ABS materials and because of that they are known as ABS-like materials. The 3D printed products are ideal for machine assembly parts or applications where wear resistance is important. Flexible resins reveal rubber-like properties which depend on the specific Shore Hardness value of the resin. They are very important for applications which requires bending or compressive stress. There is another type of resins which cannot be included in the classification of material properties: water-washable resins are very used because they manifest higher strength with respect to standard resins. Furthermore, they have a lower odour in comparison with other resin types. They may reveal brittleness or gradual water absorption due to more pronounced hydrophilic character. However, they are known as water-washable resins because the post-processing can be carried out with water rather than organic solvents [1-3].

A large variety of resins (thermo-reactive polymers) may provide high-quality, high detailed or smooth surfaces. When consider factors to select the suitable resin for the 3D printing process, it must follow the two main directions: type of materials and applications. As

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in case of thermoplastic filaments, the resulted materials (cured resins) manifest several important properties: elongation, tensile strength, water absorption, surface quality, durability, transparency, cost, etc. These amazing material characteristics led to manufacturing a wide variety of products which cover multiple applications. Thus, resin-based printed products highlight good resolution, and it appears more detailed in comparison with other types of 3D printing materials (including thermoplastic filaments, ceramics, etc.) The 3D printing process can be faster when compare with Fused Deposition Modeling (FDM) while the products are more robust and durable [1-5].

The resin-based technology has also several disadvantages which are coming from the resin itself. The resins are expensive, leading to high production costs in the case of industrial processes. The resins have limited availability and few stores can stock them due to high costs. The resins handling is very complex and may become dangerous when handle without gloves. The 3D printing process requires a work in a well-ventilated room while masks and glasses are necessary to protect all the time. Some resins require a post-processing step by curing in a UV curing chamber. This part is a time-consuming step, and it is difficult to process without a required work experience. Furthermore, large volumes of solvents (alcohols, acetone) are used to wash the remained resin on the product surface. In the case of water-washable resins, the solvent is replaced by water, but the process is still inconvenient [1-6].

The third large 3D printing technology based on polymers is Selective Laser Sintering (SLS). As well as FDM, SLA and DLP, SLS is an additive manufacturing technology which works with a high-power laser to sinter polymer powder into a solid object based on a 3D design. Various applications ranging from custom manufacturing up to rapid prototyping are established by this technology. SLS is an ideal solution due to high productivity, cost-effective per part and a high range of available printable materials. The most used printable material for selective laser sintering is Nylon. This thermoplastic polymer is ideal for both functional components (end-use production) and functional prototyping. Therefore, SLS printed nylon

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components are durable, strong and stiff. This fact makes the complex assemblies to be impact resistant and to endure repeated wear or tear [6].

As a material, Nylon is known being resistant at heat or solvents but revealing some inconveniences for water absorption, UV and light. The adding of additives brings superior resistance for light and UV. Nylon belongs to polyamides family and it is a synthetic thermoplastic polymer. The available SLS nylon-based powders are Nylon 12 (PA 12), Nylon 11 (PA 11), Nylon 6 (PA 6), Nylon 12 GF and Nylon 11 CF. The first three are single-component powders while the next two are composite powders reinforced with glass fibers (GF) and carbon fibers (CF). In the past, the only choice for SLS powders was Nylon 12. Today, the sinterable thermoplastic polymers are showing a wide variety of printable powders from polyamide family or other thermoplastics. The special nylon powders are different from those presented early and they contain additives which make them usable in certain applications. Thus, PA ESD (electrostatic discharging) are powders able to dissipate the electrostatic charges, TPA (thermoplastic amide) reveals elastomeric properties and high energy return while PA FR (flame retardant) powders are able reveal flame retardancy [6-8].

Other types of SLS printable powders contains thermoplastics: polybutylene terephthalate (PBT), polyether ketone ketone (PEKK), polyaryletherketone (PAEK), polypropylene (PP), thermoplastic polyurethane (TPU), thermoplastic copolyester (TPC) or thermoplastic elastomer (TPE). Hence, many SLS printable powders are similar with FDM printable filaments in terms of polymer-type. As in case of FDM, the composite powders reveal higher mechanical properties (high stiffness, high strength, resistance at wear and tear, low elongation at break, etc.) and higher temperature resistance. Many prototyping medical devices such as prosthetics, orthotics (replacement parts ex. Braces), surgical model tools and end-use components are customized from Nylon 12 and Nylon 11 due to mechanical requirements, biocompatibility, or compatibility for sterilization [6-8].

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4. Main applications for 3D printing

The rapid evolution of 3D printing technology qualifies for covering a large number of applications ranging from industry (high-volume production industry, high technology industry, etc.), construction/buildings, recreative activities, education to medicine applications. In the last years, the polymer-based 3D printing technologies (FDM, SLA, DLP, SLS) have started to emerge on the market and overcame many issues which initially limited their large production.

4.1 Industry

The applications across industries vary due to companies which adopt the additive manufacturing technologies. In this regard, the 3D printing was directed to evolve in several different technologies which meet the requirements. Since 2000, the 3D printing technology become relatively affordable and viable for industry. Later, after 2005, the 3D printing become more practical and the sales for printers has grown rapidly.

4.1.1 Aerospace and Defense

The importance of using 3D printing technology within Aerospace and Defence domain is validated by the constant expanding of aerospace applications. The complex and advanced components are most of the time manufactured by conventional subtractive technology like Computerized Numerical Control (CNC) or others. However, conventional subtractive methods produce a high amount of remained materials which is considered a waste. As an additive manufacturing, the 3D printing produces parts layer by layer based on the physical/chemical adhesion between layers. Considering this approach, the printable material is used for most of the time where needed. Thus, 3D printing gain a huge advantage over conventional subtractive methods by revealing less waste. The printable materials selected for this industry are under permanent expanding while raw materials are special developed for this domain. The available materials are not polymers-limited, but it ranges from thermoplastics (specially composites, PEEK, PAEK, reinforced Nylon, carbon fiber filaments, etc.), resins (thermo-reactive) up to metal powders (special alloys, stainless steel, aluminum,

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titanium, etc.). The main reasons for using 3D printing technology for Aerospace and Defense are related with the following benefits:

- *Low volume production*
- *Weight reduction*
- *Material efficiency*
- *Parts consolidation*
- *Maintenance and repair*

The biggest companies in industry, including Boeing, Airbus, GE, Safran or GKN identified the value of using 3D printing in development of functional prototypes, lightweight components, or tooling. Besides functional prototypes, which uses printable materials without any special requirements or properties, 3D printing for aerospace produces real functional components (end-use parts). For example, FDM technology produces wall panels, SLS technology produces air ducts while metal-based technologies produce structural metal components (engine parts, etc.). In the case of Aerospace and Defence industry, one of the most specific aims is to produce highly complex components but in small volumes. This approach is one of the main differences when compare with a high-volume production industry where tens of thousands or even hundreds of thousands of parts are required. Therefore, complex geometries can be developed and produced without high investments in tooling equipment (special molds, press, etc.). This aspect offers a cost-effective way to manufacture small batches of components [9-11].

Weight-effective materials (lightweight) alongside engine performance and aerodynamics are the most important parameters when consider a new aircraft design. The weight reduction can significantly reduce the aircraft carbon dioxide emissions or fuel consumption. Furthermore, the aircraft load may significantly increase. 3D printing is an ideal technology solution for producing lightweight components considering the printable polymer-based materials. In conclusion, the design optimization and the printable materials potential create new possibilities for highly complex components manufacturing.

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4.1.2 Automotive

The use of additive manufacturing in the automotive industry finds some issue statements. Therefore, large challenges appear to stay in the way of changing the paradigm in automotive industry. The problem statements include the high cost of the printable materials in comparison with conventional formative manufacturing (granules for mold injection vs. filaments for 3D printing), and some manufacturing equipment limitations. Other challenges can be related with scaling procedures, lack of expertise in 3D printing design or permanent advances of 3D printing technologies or software. Despite these challenges, the automotive industry has seen the additive manufacturing as a new technology that brings new designs and new types of products (cleaner, lighter, safer) [12, 13].

At the beginning, the suppliers and original equipment manufacturers use 3D printing as a rapid prototyping technology while nowadays the technical trajectory of 3D printing highlights new uses in high-volume production and product innovation. More specifically, 3D printing is able to manufacture parts with fewer design restriction with respect to conventional/traditional manufacturing technologies. This approach is presented as a source of product innovation. In this regard, components with added functionalities (integrated electrical wires) are produced by creating hollow structures. Such structures are often constrained for components manufactured via conventional processing. Complex designs or multi-material components are now possible due to 3D printing. Thus, every material part has specific required properties such as electrical conductivity or a variation of the mechanical properties. Lower weight components are produced due to various lattice structures but with comparable mechanical strength. All these advantages play a vital role for production of efficient vehicles in the future. The 3D printing reduces the overall time for vehicle production. This approach is presented as a supply chain transformation by improvement of market responsiveness. In fact, 3D printing overcomes the need for new tooling and produces direct final components (plus lower handling final costs or lower inventory costs). At this time, a low to medium volume production can be supported and the capacity to manufacture products

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closer to customers can be improved. The literature reveals the production of an electric car based on 3D printing technology. The car components are mainly from composite ABS-carbon fiber and the 3D printing process lasted around 44 hours. The electric components (motors, battery, etc) are manually assembled while the other parts are produced directly assembled. This fact demonstrates that 3D printing has the potential to significantly reduce the time needed for a car manufacture. Furthermore, the workforce required for the components assembling was reduced as well [12-14].

The future potential of 3D printing with automotive industry is managed different depending on the individual companies. Two important conclusions and four tactical paths can arise from usage of 3D printing in automotive. The conclusions present the main advantages of 3D printing. The first conclusion reveals that 3D printing reduces the costs needed to achieve economies of scale. More specifically, 3D printing has the potential to reduce the capital needed to aim minimum efficient scale for production (capital vs scale approach). The second conclusion reveals the increased flexibility and reduced costs needed to achieve the scope. Thus, the flexibility has the potential to increase the variety of products at reduced costs (capital vs scope approach) [14, 15].

4.2 Medicine

The medical field is the main applications domain for 3D printing because of huge development potential. The 3D printing technology is used to produce parts which can replace human organs (transplants) or to bring new approaches related with biomedical procedures. Thus, the surgical procedures can be speed up, low-cost versions of the desired surgical tools can be produced, and the life of many patients can be improved by designing required prosthetic limbs. 3D printing brings many advantages due to ability to produce low volume and various parts on demand based on patient needs [16, 17].

Many surgical grafts are produced by special molds. These mods are made via casting, forging or different machining processes. The final mold is obtained after required surface

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finishing and chemical treatments. All these processes are time-consuming, cost-consuming and can produce large amount of waste. Furthermore, various implants with functional gradation cannot be produced by these methods. 3D printing technology is the alternative to design different functional biomedical devices (orthopedic graft) with complex geometries. The concept of tailored medicine is the main goal that can be reached due to 3D printing. In the past the, the concept had low attention because the lack of tools which can made it possible. Recently, the concept earned much attention and great interest with development of additive manufacturing technologies.

The designers are able to produce on demand products without manufacturing restrains and with structural freedom. However, 3D printing may need for some post-fabrication steps, but they can be kept at a minimum level without any specific tooling. The unit cost for all parts remains constant and the cost evaluation form the main objectives of the 3D printing success within biomedical orthopedic implants.

The five pathways followed by the 3D printing in the medical domain are related with tissue and organs printing, surgical tools, custom-made prosthetics (prototyping), surgical models specific for patients and drug delivery. The first pathway is related with the tissue engineering domain, the next three are related with biomedical devices while the last is related with pharmacology. In this regard, the 3D printing applications in medicine are classified as tissue engineering applications, biomedical device applications and pharmacology applications [16-20].

4.2.1 Tissue engineering application

Despite some remarkable insights over nowadays printable materials, the idea of 3D printing for human tissues or organs continues to pose serious challenges. The bioprinting is one of the many types of 3D printing (extended 3D printing technology) oriented for tissues and organs printing. In comparison with 3D printers using polymers (filaments-FDM; resins-SLA/DLP; powders-SLS) and metals, bioprinters are specialized printers that use computer-guided pipette to print bio-inks layers with or without living cells inside. Bio-inks contains

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natural or synthetic polymers (in solution form) that ensure the viability of cells before, during and after bioprinting step. The bio-ink solutions ensure the required rheological properties to produce layers that encapsulate cells resulting an organized structure similar with extracellular matrices. The final 3D printed products have hydrogel-like structures resulted from polymers crosslinking during or after 3D printing process [21-23].

The aim of the bioprinting is to mimic as close as possible the natural architecture of tissues by depositing layers of polymeric materials and cells to restore the normal structure and functionality of various tissues. The bioprinting has been used until now for fabrication of functional tissues or organs like liver, heart, skin, cartilage, bone or microfluidic devices. The main challenges related with tissues fabrication are biocompatibility, biodegradability, vascularization approach, gas or nutrient exchange. The bioprinting relies on multiple derived technologies which are able to ensure precise geometries, meticulous quality-control in order maintain the cell viability during printing process. The main derived bioprinting technologies comprises Inkjet based 3D bioprinting, Extrusion based 3D bioprinting, Laser-assisted 3D bioprinting/Laser-induced forward transfer and Stereolithographic based 3D bioprinting. All these derived technologies offer a huge potential for printing with precise patterning and higher spatial control with respect to manual methods [21-23].

4.2.2 Biomedical device applications

The 3D printers have become more affordable while investments in development of polymeric printable materials have accelerate. Therefore, more and more companies have gained access to 3D printing technology and the bridge from concept to mass production narrowed. There are also companies that offer consulting activities by bridging the medical device developers, manufacturers and hospitals. Through this approach, these companies look for various medical device needs, compare the 3D printing technologies and provide innovative solutions (reduced costs, reduced time, prototyping, etc.) [16-18].

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Surgical models

This approach assumes that surgery preparation can be assisted by the 3D printed models. The conventional methods (moulds and casts) for production of surgical templates using computed tomograph (CT) proved serious limitations. The CAD based 3D printing technologies are vital for fabrication of 3D templates models because it reduces the probability of inaccurate grafts placement or grafts misalignment. These procedures have been used in surgeries from a while and they gained a lot of interest. Therefore, the procedures are becoming a routine practice and various surgeries ranging from face transplant to spinal transplant have been successfully performed. Surgeons can use replicas of patient-specific organs to practice on before performing complex surgeries. There are hospitals that use 3D printing on a large scale, for example, doctors in Dubai have successfully operated a patient (60-year-old woman) who suffered from a cerebral aneurysm in four arteries. They used a state-of-the-art custom 3D printed model of her dilated arteries to make a plan for the complex surgery. More specifically, the doctors map out how to navigate the arteries during surgery [16-20].

Surgical tools 3D printed (surgical instruments and devices)

One of the main advantages of using 3D printing in comparison with conventional manufacturing processes is costs related. Thus, sterile surgical instruments (forceps, clamps, scalpel handles or hemostats) and devices (stethoscope, endoscope, etc.) can be produced at very low costs. Many companies proposed and produced various automated devices with higher complex functions in comparison with simple instruments. Thus, automated 3D printed suturing devices have been developed. The devices are involved in surgical procedures that need suturing (internal or external). 3D printed stethoscopes have been designed and manufactured at very low costs [16-18].

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Prosthetics by 3D printing [24-30]

The 3D printing revolutionizes the field of rehabilitative medicine through the prosthetics application. In the last years, the market for prosthetic limbs has oriented toward systems with higher degrees of actuation. However, there are some concerns of robustness, strength or a wide-user acceptance. Despite these issues, the rapid prototyping is affordable, customizable and can manufacture attractive prosthetics with an easy maintenance and repair. In the world, only 5% of around 40 million patients with amputated limb benefits or have access to assistance or prosthetic devices [24]. In contradictory, even that the percentage is very low, there are many patients with congenital limb loss who do not use prosthetic devices despite having access to assistance [24]. This fact appears because the patient expectations regarding their prosthetic device differ depending on style of the device the patient has. The prosthetics abandonment is a real problem and depends on many reasons and factors. The main factor is comfort related and it is assured by the device performance. The devices with increased hand or leg articulation may change the patient perception. Another important issue is the prosthetic final price because they are expensive when produce through traditional methods. The cost related issues together with the poorly adapted to the patient needs are the main goals for the companies by the help of 3D printing technologies [24-27].

An increased control over device maintains a high level of importance for robust performance. There are three methods of control for modern bionics: body-powered through cable extension and contraction, button press and electromyography []. These methods bring new possibilities that patients may prefer during daily life. These advancements are additional functionalities more important that cosmetic and design in the patient perception. The design using 3D printers allows a high level of individual customization specific to the end-user by volumetric scaling or more precise parametric control. The paradigm is to establish a set of strategies which to integrate the end-user from the start of design process to the finish. The structural and mechatronic parts have to be standardized for the digital designers in order to create the digital 3D representation. Eventually modifications are made from the beginning by some intervention of the artistic design part. The end-user (patient) has access to the artistic

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design through a portal. After the final digital design is achieved, the interdisciplinary work is vital for the prosthetic success while production requires four main steps: 3D printing, surface preparation and priming, automotive finishing and painting [25].

The relative issues related with the prosthetic manufacturing are poor in comparison with the advantages that arise from using the 3D printing technology in this field. Thus, the main driving forces are innovation, customization and cost [24].

4.2.3 Pharmaceutical

The concept of personalized medicine can be extended also for pharmaceutical field, and it is related with the drug delivery approach. The concept promotes that drugs dose combination and drugs activity are tailored for patient specific requirements. Nowadays, conventional pharmaceutical manufacturing technologies are made to allow a high-volume production of unit dosage forms and fixed dose. The main advantage relies from the reduced cost production, but it has serious limitations when discuss about unusual/special dose for some patients [18, 31, 32]. This manufacturing technology was invented more that 200 years ago and its time for crucial changes. In UK, around 70% of patients lack drugs efficiency from conventional mass products, 90% of drugs works only in 30-50% of patients while 7% of hospitals reveal that adverse drug reactions are a serious problem [33, 34].

3D printing is causing a shift in traditional pharmacy practice from mass production towards tailored drugs that can be personalized for each patient. The paradigm shift provides many benefits by enabling the on-demand concept for drug formulations. In this regard, drug formulations become more flexible and more directed towards patient needs (personalized dosage, size, shape, combination of drugs) without being addressed to large-scale public. The 3D printing technologies suitable for pharmaceutical applications are mostly part of 3D bioprinting group. Most of the 3D printed pharmaceutical formulation were manufactured by three derived technologies: Laser-based writing systems, Printing-based inkjet systems and Extrusion-based bioprinting. Besides the three presented bioprinting technologies, FDM and SLS can be used for some specific applications. All 3D technologies work with biocompatible

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polymers. The printed layers have very small thickness due to required high resolution [31, 32].

The 3D printing usage within pharmaceutical domain required clear regulatory guidance for the integration of manufacturing technologies and strategies. They need to ensure the safety and quality of formulations, and further agreements from pharmacists. All these advances produce a new era of pharmaceutical domain, the digital pharmacy era. This concept came with new regulations and steps for the patient treatment management. Basically, there are five main steps when consider the patient treatment: diagnosis and monitoring, electron description, printlet design (formulation design), printlet production (printing of formulation) and personalization. In last years, many companies adopted the concept of Good Manufacturing Practice (GMP). By this approach, companies developed 3D printers that correspond to regulation and can be validated to ensure printed products at a high level of safety and quality. These strategies will be able present a real-time assurance of the 3D printed formulations [31, 32]. Therefore, the future is assured by the integration of the 3D printing within clinical strategies. Until now, FDA approved several grants for clinical study of patients with rheumatoid arthritis using 3D printing as a formulation production strategy [35, 36]. Furthermore, polypills containing multiple drugs for certain disease treatment have been manufactured. The polypills highlighted a discrete dose and release behavior for each drug [37-40].

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EMERALD

**The Education, Scholarships, Apprenticeships and Youth
Entrepreneurship
EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC
MECHATRONIC SYSTEMS**

MODULE

**SOME ASPECTS REGARDING THE
PRESCRIBED PRECISION AND
MANUFACTURING PRECISION OF
IMPLANTS, PROSTHESES AND
ORTHOSES**

Project Title	European network for 3D printing of biomimetic mechatronic systems 21-COP-0019
Output	O1 - EMERALD e-book for developing of biomimetic mechatronic systems
Module	Module - Some Aspects Regarding the Prescribed Precision and Manufacturing Precision of Implants, Prostheses and Orthoses
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Introduction

One of the most important factors that influence the manufacturing cost of a product and, implicitly, its selling price, is the precision, it being known [14, 16, 19, 20] that the higher the precision imposed (tolerances of the characteristics are smaller) the higher the manufacturing cost. Additive technologies are in full development, being applied in many fields, including the medical field, where there is a continuous expansion of these technologies in terms of making implants, prostheses, orthoses, etc.

Under these conditions, the question arises to what extent various additive technologies can provide the processing precision required by the functional role of the product in general and of each individual surface. Both in classical manufacturing based on material remove and in additive manufacturing based on material deposition, the problem of accuracy must be viewed from at least two points of view. On the one hand, greater attention must be paid to the prescribed precision, addressed in the design stage, which is imposed by the functional role of the part and the surfaces. In other words, the prescribed precision is *what we want* from the point of view of the product, parts, and surfaces characteristics. On the other hand, the manufacturing precision is given by the precision of the equipment used in the production of the products, which must ensure the achievement of the prescribed precision. In other words, manufacturing precision represents *what we can* ensure with the means we have at our disposal. Obviously, *what we want* is not always in line with *what we can*, and therefore there is a need for the further improvement of technological means, in particular of 3D printing equipment.

In the case of classic technologies based on material remove, we can use various machines, various tools, and we can vary the parameters of the processing regimes (cutting) within wide limits. On the other hand, with additive technologies we usually use only one machine. Is it possible to vary the working parameters according to the precision required for each surface? Obviously, the answer lies in the performance of the 3D printer used. Also, in the case of classic technologies based on material remove, we can use several positioning/orientations/fixings of the piece established based on a very well-founded theory and widely recognized by specialists. With additive technologies, we use only one position of the part throughout the processing, a position that must be analyzed very carefully. Is this sufficient to ensure the prescribed precision in terms of dimensionality, macrogeometric and microgeometric shape and relative position? The answer to this question requires more detailed studies. Anyway, depending on the answers we will give to the questions above, depending on the prescribed precision and depending on the performance of the 3D printers used, the decision will be made whether processing by removing material is applied after additive processing (usually milling processing), with the tendency to ensure all characteristics only by applying additive technologies.

The present paper aims to address some aspects related to ensuring the precision of processing through additive manufacturing of specific parts for prostheses and orthoses, as part of a larger study on this issue.

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1. General aspects of prescribed and manufacturing precision of implants, prostheses, and orthoses

1.1. Prescribed precision of implants, prostheses and orthoses

Currently, the design and manufacture of implants, prostheses and orthoses is in an accelerated development due to cutting-edge technological developments, one of the most important of which is considered to be the exponential increase in the performance of additive technologies.

A very large number of works deal with the precision of implants, prostheses, and orthoses. In this sense, the most important research directions can be mentioned: precision of dental implants [1, 3, 4, 12], precision of articular surface of ankle joint [2], tolerance measurements of various implant components [5], implant displacements [6], comparative analysis of different additive manufacturing technologies [7, 8], difference between the CAD model and the 3D-printed parts [10], etc.

Synthesizing many works, a series of data can be structured, according to those presented in table 1.1. The functional role of these products requires the establishment, during the design stage, of specific characteristics regarding dimensional accuracy (DP), macrogeometric (PMaF) and microgeometric shape accuracy (PMiF), relative surface position accuracy (RPP), etc. In establishing these characteristics, the functional role of the surfaces must be taken into account, i.e. the fact that some surfaces are in contact with mucosae or external tissues (skin), others are assembly surfaces and other surfaces are external surfaces that must have dimensions and anatomical shapes and a corresponding appearance as close as possible to the natural human one.

Table 1.1. Specific characteristics of implants, prostheses, and orthotics

Product	Precision	Surfaces in contact with mucous membranes	Surfaces in contact with external tissues (skin)	Assembly surfaces	Exterior surfaces
Implants	DP	10 ⁻³ , anatomical	is not applicable	Precision fits, ball joints	is not applicable
	PMaF	Anatomical, Classes V-IX		Circularity and cylindricity are especially important, Classes V-IX	

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	PMiF (R)	As small as possible in the contact area; porosity; coatings (metallic and non-metallic), impregnations		Small roughness	
	RPP	Anatomical, Classes V-IX		Classes V-IX	
Prostheses	DP	General tolerance f, m; individual tolerance IT9-12	Anatomical, general tolerances, f, m	Precision fits, ball joints	General tolerance f, m
	PMaF	Anatomical, Classes V-IX	Anatomical, general tolerances, H, K	Circularity and cylindricity are especially important, Classes V-IX	General tolerance H, K
	PMiF (R)	As small as possible in the contact area; porosity; coatings (metallic and non-metallic), impregnations	As small as possible; coatings, impregnation; lining, rubber	Small roughness	Reduced roughness, aesthetic appearance, coatings, gripping surfaces – functional roughness-adhesion
	RPP	Anatomical, Classes V-IX	Anatomical, general tolerances H, H	Classes V-IX	General tolerance H, K
Orthotics	DP	is not applicable	Anatomical, general tolerances, f, m	Precision fits, ball joints	General tolerances, f, m
	PMaF		Anatomical, general tolerances, H, K	Circularity and cylindricity are especially important, Classes V-IX	General tolerance H, K
	PMiF (R)		As small as possible; coatings, impregnation; lining, rubber	Small roughness	Reduced roughness, aesthetic appearance, coatings
	RPP		Anatomical, general tolerances H, H	Classes V-IX	General tolerance H, K

Legend: DP – Dimensional precision; PMaF - Precision of macrogeometric form; PMiF(R) - Precision of microgeometric form (roughness); RPP - Relative position precision

The work deals with some aspects regarding the prescribed precision and manufacturing precision of prostheses, with an example of a prosthesis made in a frame of the Emerald project. The applications will be in direct connection with the example in figures 1.1 and 1.2.

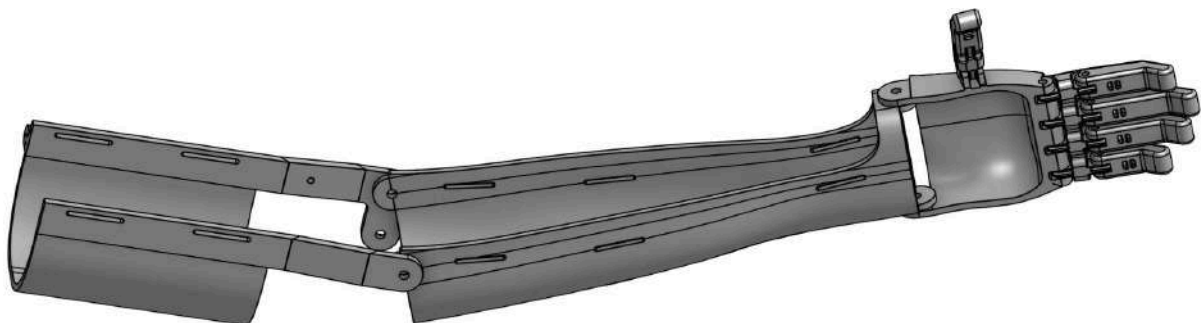


Figure 1.1. General assembly of prosthesis

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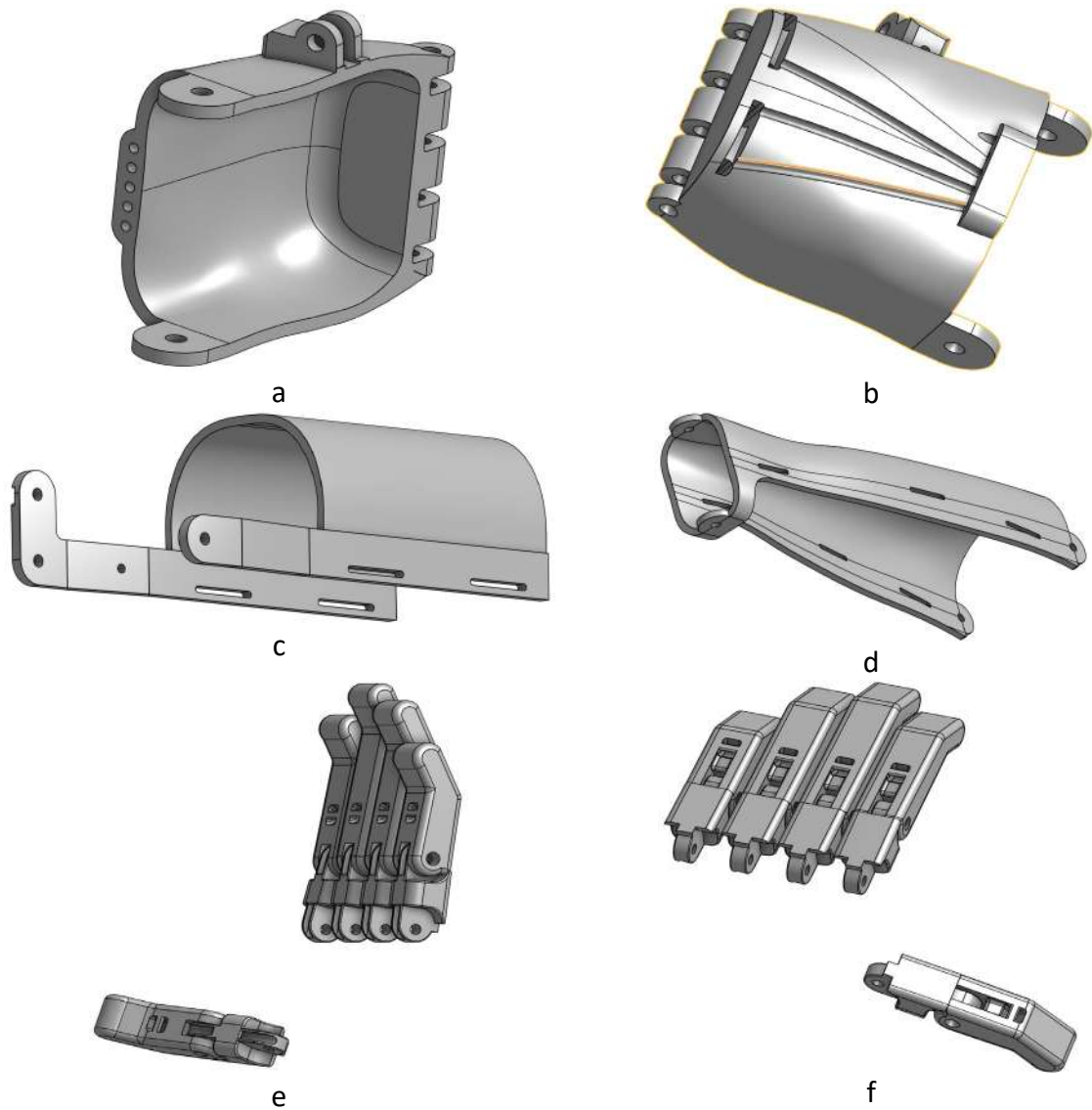


Figure 1.2. The component parts of the prosthesis: a. The back-view of palm; b. The front view of palm; c. Clamping element on the arm; d. Clamping element on the forearm; e. The back-view of fingers f. The front view of fingers;

1.2. Manufacturing precision of implants, prostheses and orthoses

The processing methods and procedures chosen for the manufacture of implants, prostheses and orthoses must ensure the prescribed precision, which requires the satisfaction of the most severe precision conditions imposed on each surface. For these categories of parts, CNC milling, additive manufacturing (AM) or a combination of them can be used [15], with the tendency to generalize the first category with the improvement of AM technologies [9, 11, 13].

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2. Prescribing dimensional and geometric precision of assemblies

2.1. The problem of prescribing the precision of fits

The *fit* is defined as “relationship – prior to the assemblage – between an external feature of size and an internal feature of size (the hole and shaft of the same type) which are to be assembled” and that “have the same nominal size” [16].

In general, in the design activity, in the case of prescribing some fits, the influence of the precision of the macrogeometric form such as straightness, roundness or cylindricity is not considered. ISO standards are designed on the principle of independence between dimensional and form precision. Thus, if we consider, for example, a shaft with a diameter of $\varnothing 20_{-0,013}^0$, the maximum material size ($\varnothing 20.000$) does not cover the deviation from straightness, unless otherwise specified. Accuracy from straightness must be entered separately. In contrast, ASME standards are designed on the principle of envelope [17], meaning that the maximum material size also includes deviations from shape, including straightness, unless otherwise specified.

Thus, in the case of a fit, for example $\varnothing 20 H7_{(0}^{+0,021})/h6_{(-0,013)}^0$, the minimum clearance should theoretically be zero (figure 2.1). If we analyze it based on ISO standards [18], for the case of the minimum clearance (the shaft has the maximum diameter $d_{\max} = 20.000$ and the hole has the minimum diameter $D_{\min} = 20.000$), we can have problems during assembly since the straightness tolerance not being mentioned, means that it is considered according to the general tolerances, that is, we can have large deviations from straightness. If we analyze it based on the ASME standards [17], according to the “size controls the form” principle, it turns out that at the maximum material ($d_{\max} = D_{\min} = 20.000$), the dimensions also include the deviations of the form and there will be no problems during assembly.

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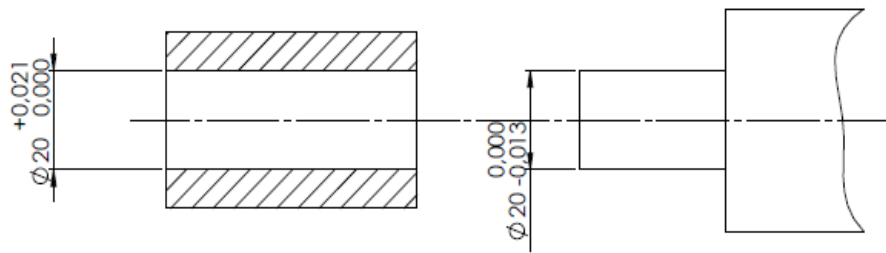


Figure 2.1. Example of clearance fit

2.2. Prescribing the accuracy of fits based on the principle of maximum material and envelope condition

In the case of using ISO standards [18], the straightness precision prescription with or without the application of the maximum material principle may be unsatisfactory in the extreme case of zero minimum clearance. The prescription shown in figure 2.2 implies that the hole must circumscribe the ideal cylinder with a diameter of $\varnothing 19.990 = 20.000 - 0.010$ and the shaft must be able to be inscribed in the ideal cylinder with a diameter of $20.010 = 20.00 + 0.010$ (fig. 2.3). This situation does not ensure zero minimum clearance [21].

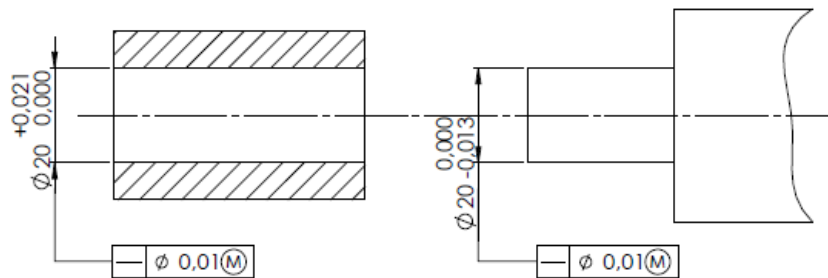


Figure 2.2. Application of the maximum material principle in the case of a fit

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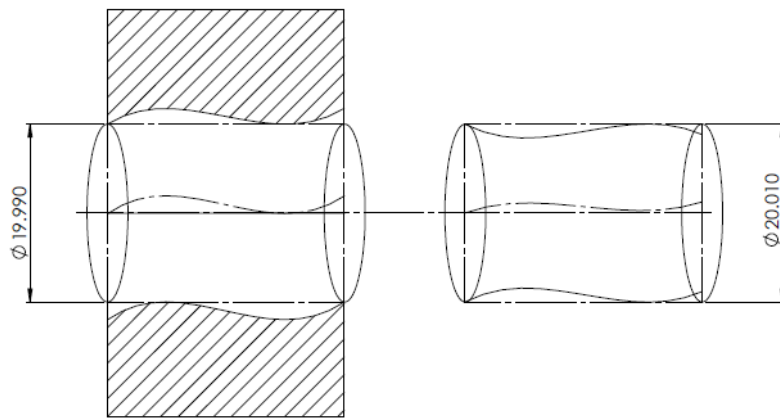


Figure 2.3. Interpretation of the prescription based on the maximum material principle

In the case of the shaft (fig. 2.4), the straightness tolerance varies between the one inscribed ($\varnothing 0.010$) when the shaft is at the maximum material ($\varnothing 20.000$) and $\varnothing 0.023 = 0.010 + 0.013$ when the shaft is at the minimum material ($\varnothing 19.987$). For the hole (fig. 2.4) the straightness tolerance varies between the one inscribed ($\varnothing 0.010$) when the hole is at the maximum material ($\varnothing 20.000$) and $\varnothing 0.031 = 0.010 + 0.021$ when the hole is at the minimum material ($\varnothing 20.021$).

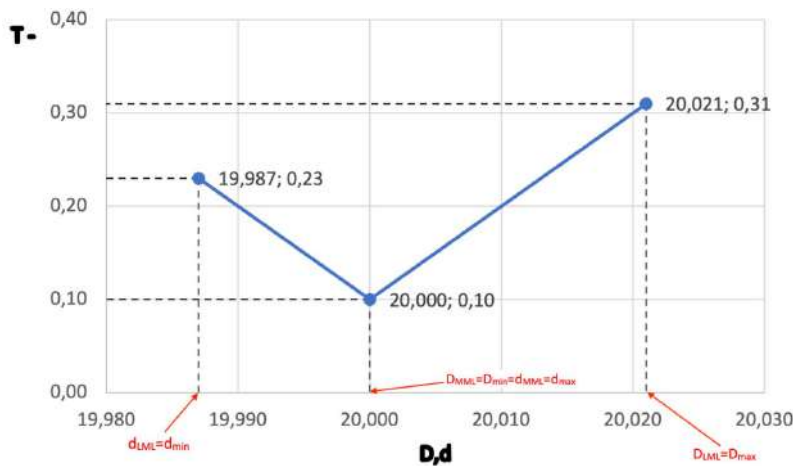


Figure 2.4. The variation of straightness tolerance when applying the maximum material principle

The most favorable situation is when using the envelope condition (fig. 2.5) according to ISO [18], equivalent to the one $\varnothing 0 \text{ (M)}$ prescribed according to ASME [17] (fig. 2.6).

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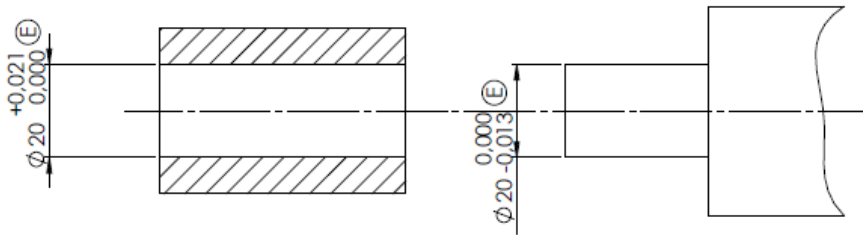


Figure 2.5. Application of the envelope condition in the case of a fit

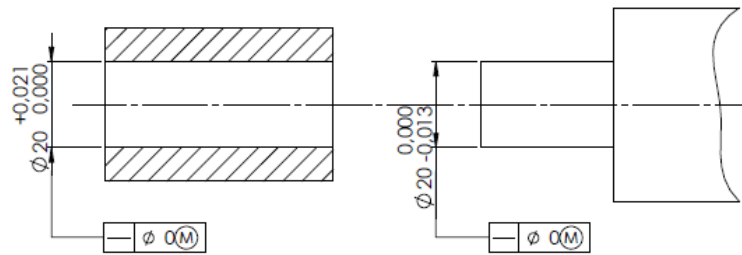


Figure 2.6. Applying the zero tolerance condition to the maximum material (ASME)

Indeed, in this case the inner cylindrical surface must circumscribe an ideal cylinder with a diameter of $\phi 20.000$ and the outer cylindrical surface must be inscribed in a cylinder with a diameter of $\phi 20.000$ and, thus (fig. 2.7), minimum zero is guaranteed.

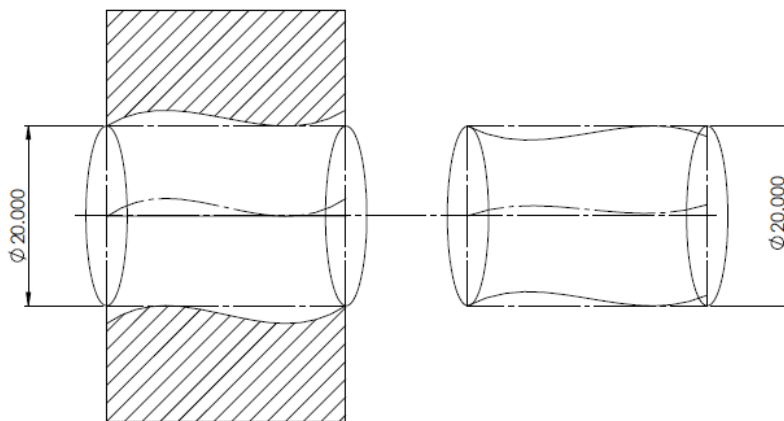


Figure 2.7. Interpretation of the prescription based on envelope condition

In the case of the shaft (fig. 2.8), the straightness tolerance varies between zero when the shaft is at maximum material ($\phi 20.000$) and $\phi 0.013 = 0 + 0.013$ when the shaft is at minimum material ($\phi 19.987$) and for the hole (fig. 2.8) straightness tolerance varies between zero when

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the hole is at maximum material ($\varnothing 20.000$) and $\varnothing 0.021 = 0 + 0.021$ when the hole is at minimum material ($\varnothing 20.021$).

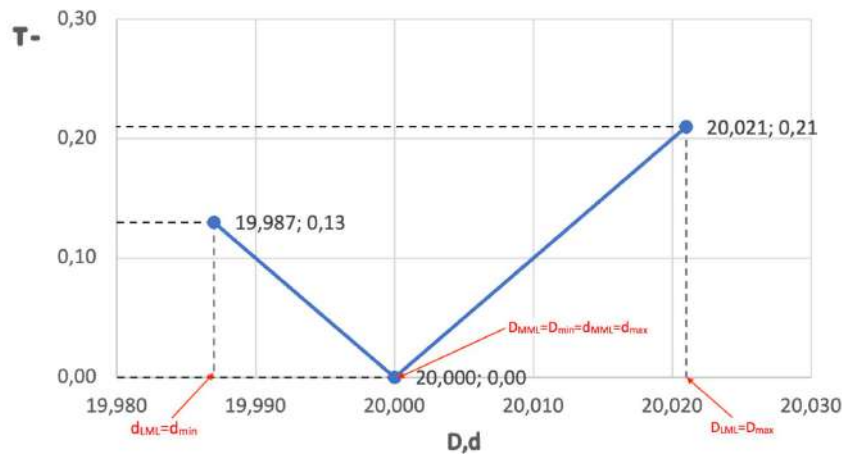


Figure 2.8. The variation of straightness tolerance when applying the envelope condition

This case corresponds to a simple prescription simple $\varnothing 20 H7(0^{+0,021})/h6(0_{-0,013})$, without other conditions, based on ASME standards when the envelope condition is implicitly applied, i.e. "size controls the form".

2.3. Labview modeling of straightness accuracy prescription based on size dependent tolerances

The prescription of macrogeometric shape precision based on the size-dependent tolerances detailed in subchapter 2.2 (maximum material principle \textcircled{M} , envelope condition \textcircled{E} , minimum material principle \textcircled{L} , etc.) according to ISO standards, can raise problems for design engineers, technologists and product (prostheses) precision inspection [19, 20, 21].

In some situations, design engineers and technologies do not know the interpretation and how to prescribe precision based on size-dependent tolerances, they prescribe intuitively or based on experience (without taking into account the evolution of standards) and in the case of complex parts (prostheses, for example) made by combined processes of additive manufacturing and cutting, wrong or incomplete prescriptions may appear.

Starting from these shortcomings, in the Manufacturing Engineering Department of the POLITEHNICA University of Bucharest, applications were developed in LabView to help the

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design engineer and the technologist to use the size-dependent tolerance prescriptions [19, 20, 21]. Given that they offer tight tolerances, depending on the size, these prescription rules lead to a reduction in manufacturing costs, as it is known that costs increase exponentially with increasing precision (reducing the value of tolerances).

A first application developed [20] is that regarding the prescription of straightness accuracy based on the maximum material principle and the envelope condition. Figures 2.9 and 2.10 show the block diagrams for shafts and bores, respectively, made in the LabView programming environment.

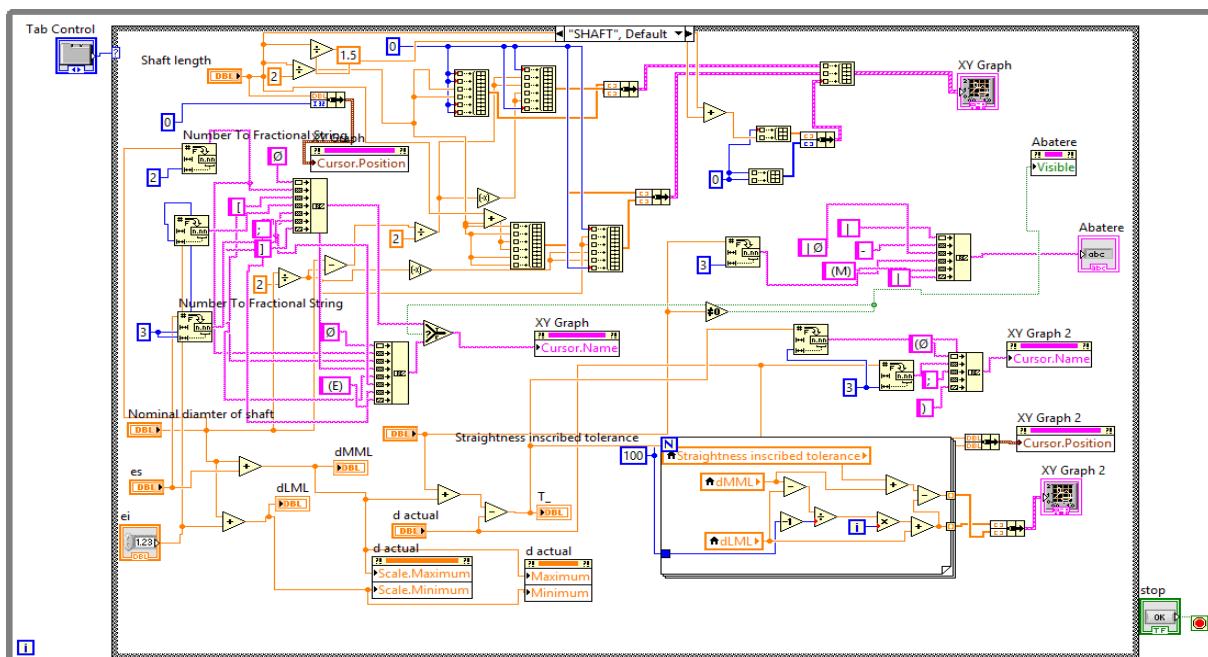


Figure 2.9. Block diagram for shafts [20]

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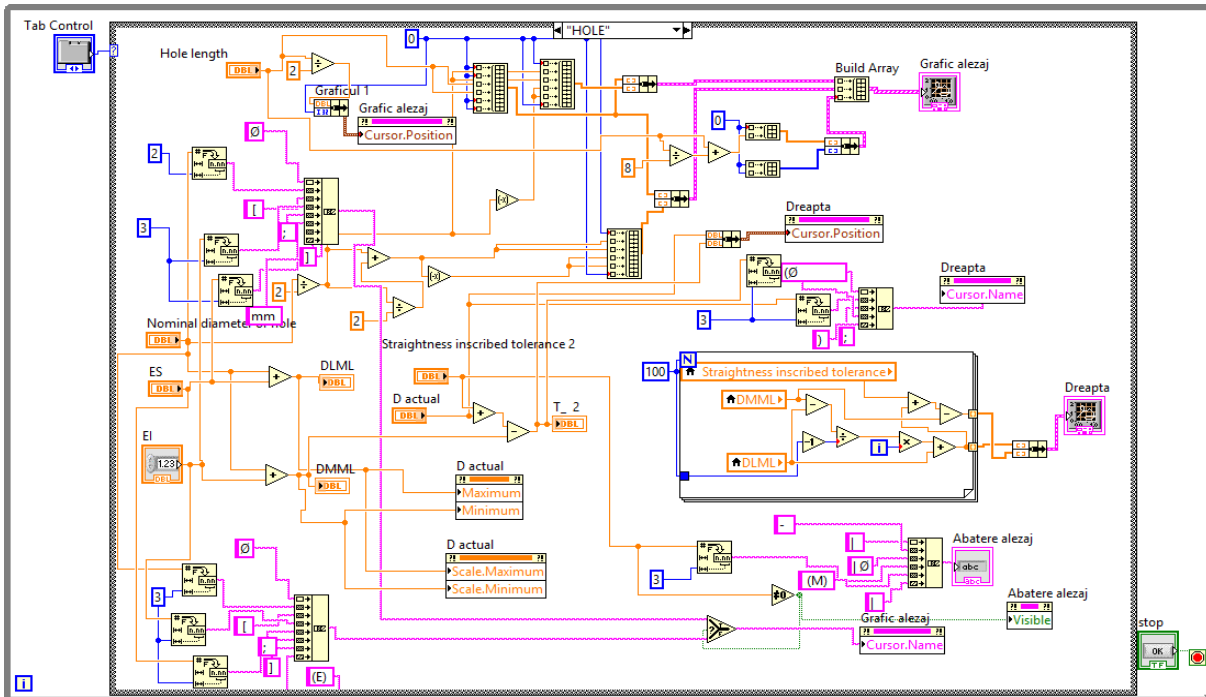


Fig. 2.10. Block diagram for holes [20]

Using the dimensions analyzed in subchapter 2.2, figures 2.11, ..., 2.18 we present several cases: at maximum material, at minimum material and intermediate dimensions.

To obtain the variation of straightness tolerance values, the user enters (fig. 2.11) for the shaft and/or hole the value of the nominal diameter, d_{nom}/D_{nom} , the effective diameter d_{ac}/D_{ac} , the upper deviation es/ES and the lower deviation ei/EI . After running the program, the program displays the straightness tolerance and its dependence on the effective diameter (Fig. 2.11, ..., 2.18).

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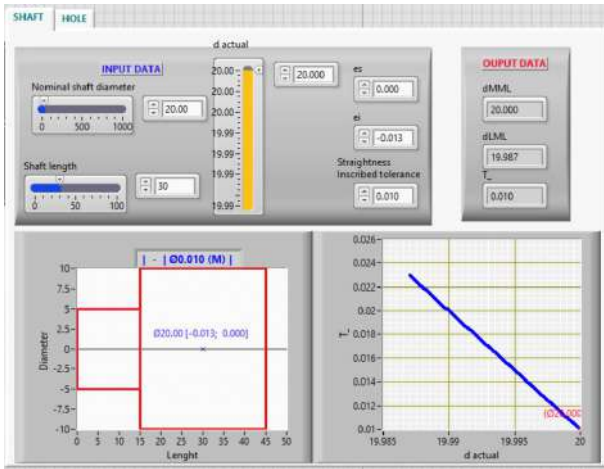


Figure 2.11. Example for $d = d_{MML} = 20.000$ and (M)

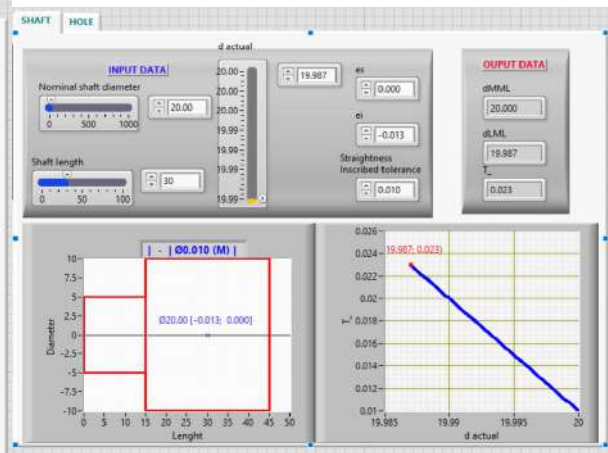


Figure 2.12. Example for $d = d_{LML} = 19.987$ and (M)

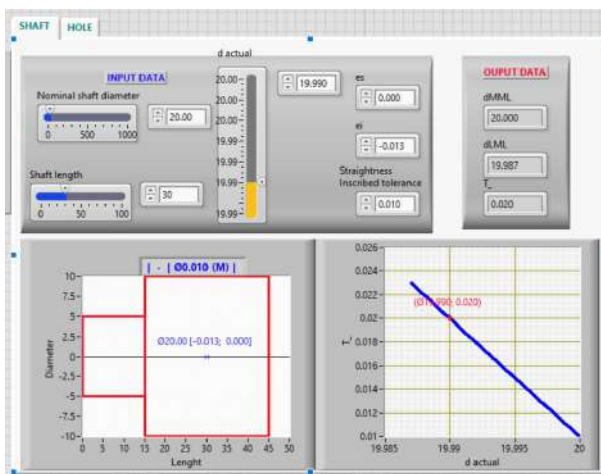


Figure 2.13. Example for $d = 19.990$ and (M)

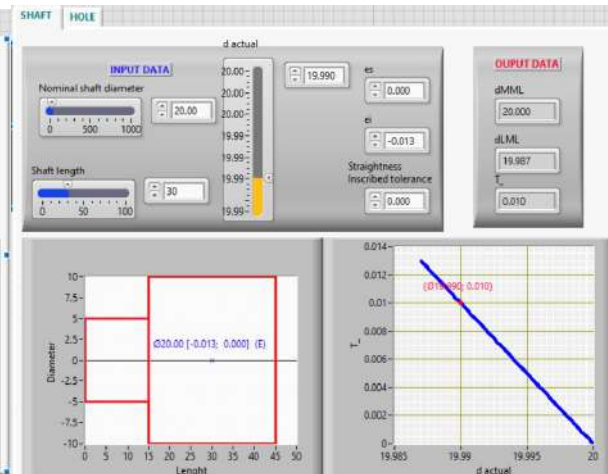


Figure 2.14. Example for $d = 19.990$ and (E)

As mentioned in subchapter 2.2, the case where precision is prescribed based on the winding condition is a particular case where the straightness tolerance at the maximum material is zero, being identical to the prescription $\text{---} \varnothing 0 \text{---} (M)$ based on ASME [17].

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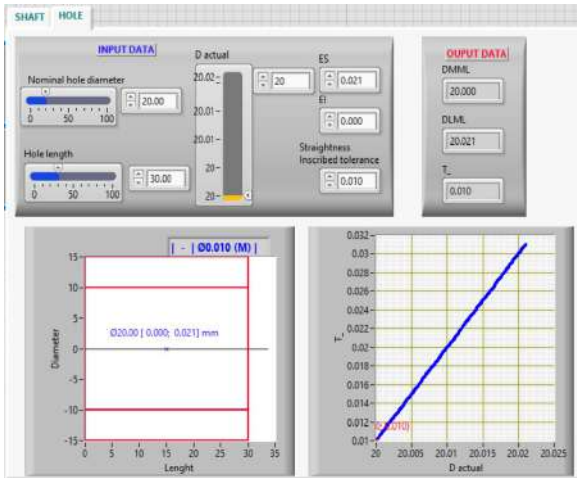


Figure 15. Example for $D = D_{MML} = 20.000$ and (M)

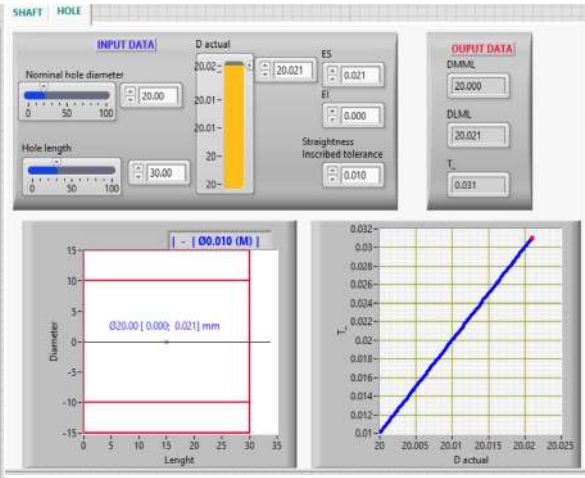


Figure 2.16. Example for $D = D_{LML} = 20.021$ and (M)

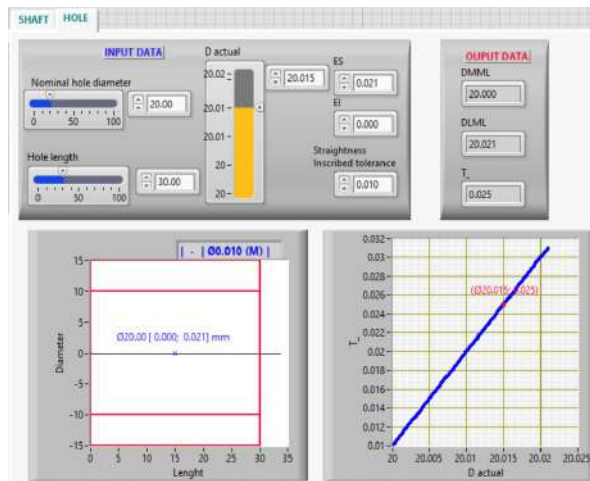


Figure 2.17. Example for $D = 20.015$ and (M)

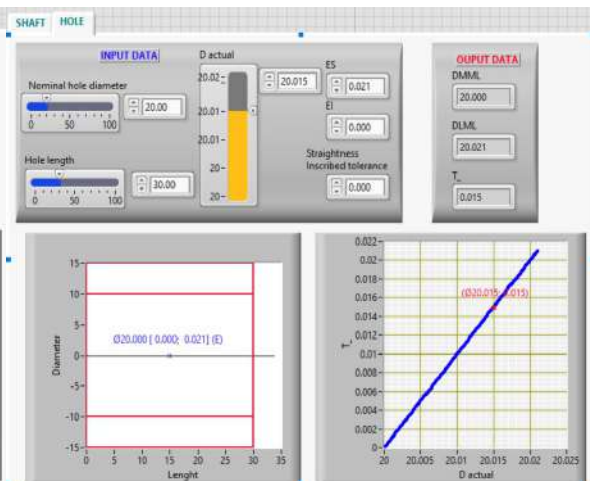


Figure 2.18. Example for $D = 20.015$ and (E)

The application presented above can be used in the design and additive manufacturing of prostheses.

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3. Prescribing the minimum thickness of some walls

3.1. Prescribing nominal position precision based on size-dependent geometric tolerances

The nominal position is one of the most frequently used position tolerances in design, especially after in 2018, according to the latest version of the American standard ASME Y 14.5 [17], the coaxiality-concentricity and symmetry tolerances were repealed. Considering that in the homologous standard ISO 1101 these tolerances were maintained, it is interesting to analyze the way of prescribing the precision of specific features of prostheses, based on both standards.

It is known [17, 18] that one of the cases where precision is prescribed at the nominal position is when we want to position one or more holes to each other and/or to certain datums. In this case, the dimensions that determine the position of the axis of the hole relative to the bases become "theoretically exact dimensions" and the tolerance zone is a cylinder with the axis in this theoretically exact position (Fig. 3.1).

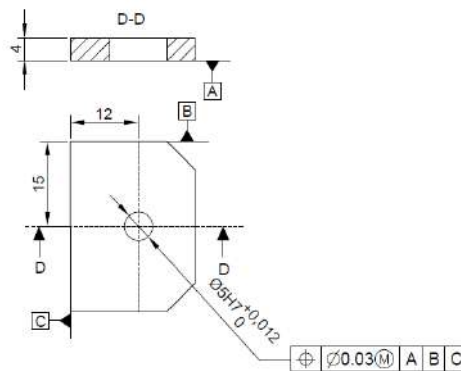


Figure 3.1. Example of prescribing nominal position precision

For functional and economic reasons, the nominal position is prescribed in most cases based on the maximum material principle. In the example presented in figure 3.1, a case that can be encountered in the prescription of the precision of prostheses and orthoses, the tolerance to the nominal position can vary between the value entered (0.030), when the effective diameter of the hole is at the maximum of the material (i.e. the minimum diameter

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of 5.000) and $0.042 = 0.030 + 0.012$, when the effective hole diameter was at the material minimum (i.e. the maximum diameter of 5.012). The concepts of maximum material size and minimum material size are very important in product design.

As can be seen from the detailed interpretation in figures 3.2 and 3.3, the effective axis of the tolerated cylindrical surface must be able to be included in a cylinder, the diameter of which varies between 0.030 and 0.042, having the axis placed at the theoretically exact distance of 15 mm from the plane adjacent to the reference surface B and at the theoretically exact distance 12 mm from the plane adjacent to the reference surface C. The reference base A imposes the additional condition that the axis of this tolerance zone is perpendicular to the plane adjacent to the reference surface A, according to ISO 1101 [18].

Two other very important concepts when prescribing accuracy at the nominal position based on the maximum material principle, based on both ISO 1101 and ASME Y 14.5, are the Virtual Condition Boundary (VCB) and the Resultant Condition Boundary (RCB) which form as the geometric locus of the points closest and farthest from the theoretically exact position when the effective axis floats inside the tolerance zone (fig. 3.2 and 3.3). It is important that the VCB diameter remains the same (4.970 in the case of the considered example) regardless of the actual diameter of the hole (MML, LML or an intermediate position), thus ensuring a maximum mounting diameter of the shaft ("which must not be violated" according to ISO&ASME [17, 18]).

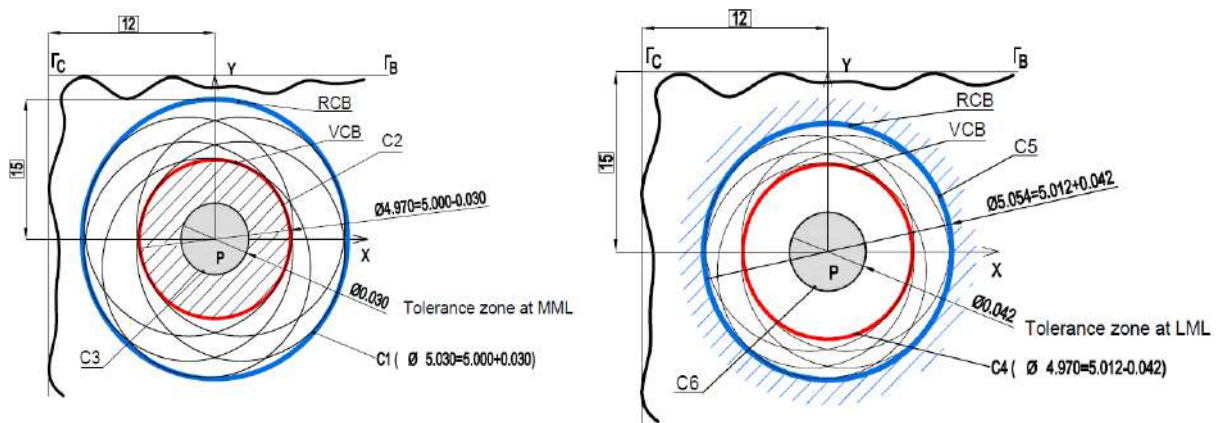


Figure 3.2. Interpretation of nominal position at maximum material

Figure 3.3. Interpretation of nominal position at minimum material

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3.2. Modeling in LabView the prescription of nominal position accuracy based on size-dependent geometric tolerances

In order to create a LabView application to help the designer and the technologist in the interpretation of the previously presented prescription, the general case presented in figure 3.4 was considered [19] and the mathematical equations of the cylinders highlighted in figures 3.2 and 3.3 were written.

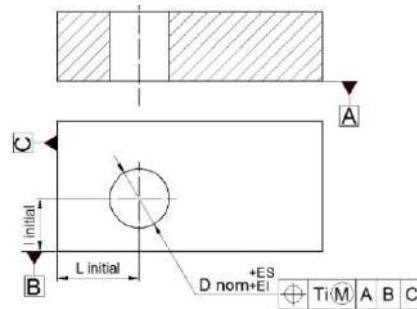


Figure 3.4. The general case of prescribing nominal position accuracy for a hole [19]

Figure 3.5 shows the front panel where the input data is entered (nominal size, upper deviation, lower deviation, tolerance to the minimum position and in fig. 3.6 the block diagram of the application is presented.

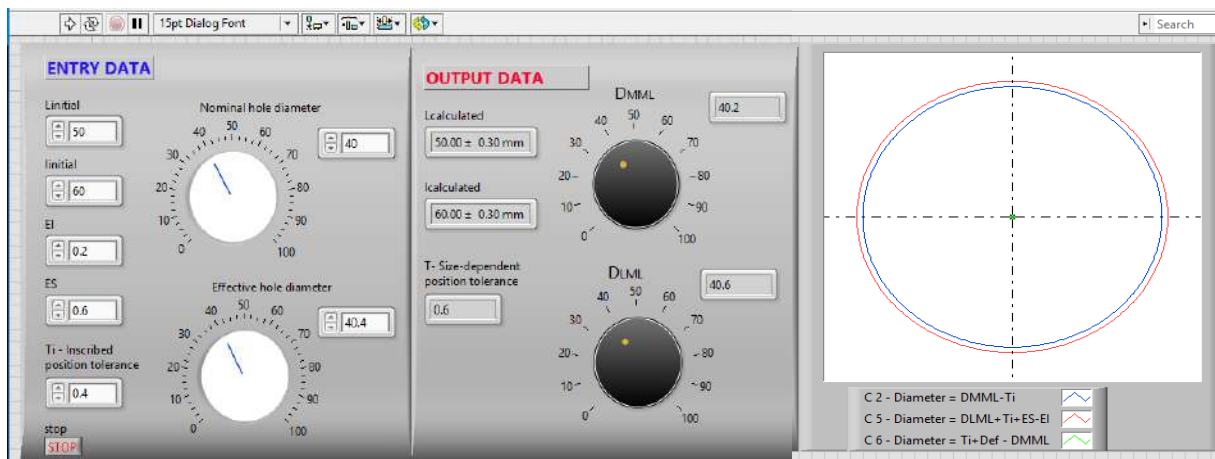


Figure 3.5. Front panel of the virtual instrument [19]

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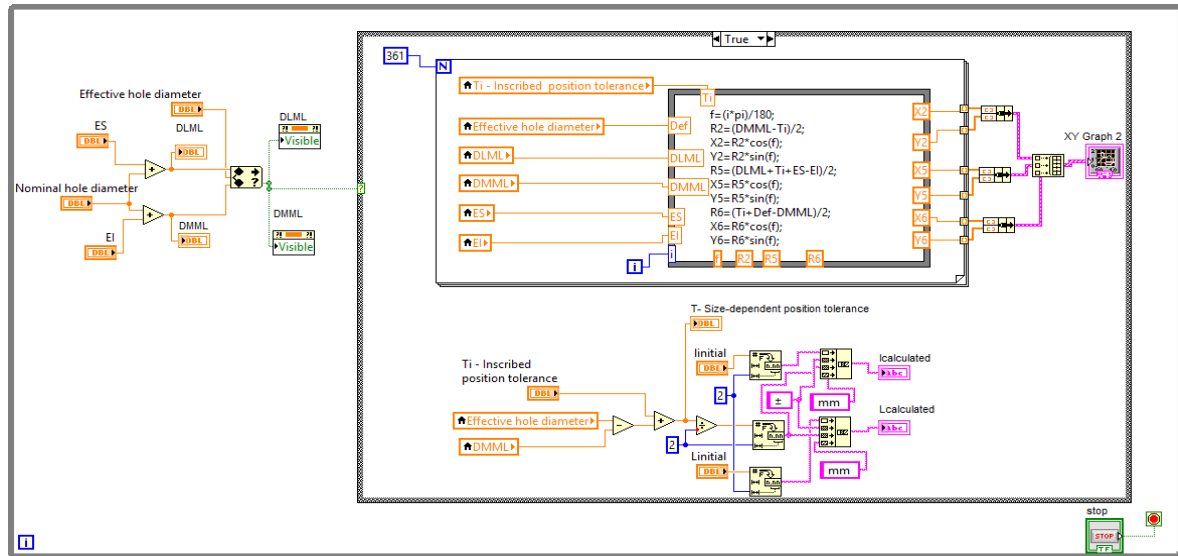


Figure 3.6. Application Block Diagram for nominal position [19]

A similar application can be made for external surfaces, with the mention that in this case the maximum material diameter is $D_{MML} = d_{max}$ and the minimum material diameter is d_{min} D_{LML} .

Also, similar applications are in progress for the prescription of the precision at the nominal position based on the minimum material principle \textcircled{L} , in which case the listed tolerance is valid at $d_{LML} = d_{min}$ for shafts and $D_{LML} = D_{max}$ for holes and the difference between the effective diameter and the diameter at minimum material is added to the nominal position tolerance.

These applications assist design engineers and technologists in interpreting position accuracy prescriptions based on individual size-dependent tolerances, such as those related to nominal position, being very useful for example in ensuring the minimum thickness of some walls, as will be presented in chapter 3.3.

3.3. The thickness of a wall between a cylindrical surface and a flat surface

In the design activity, in general, and design of prostheses, in particular, there may be situations where, for technological and/or functional reasons, a minimum thickness must be ensured between a cylindrical surface and one or two flat surfaces. In the example in figure 3.7, it is easy to see that the thickness of the wall between the inner cylindrical surface of the hole with a diameter of $\varnothing 5$ mm and the outer flat surface and, respectively, the thickness of

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the wall between the surface of this hole and the inner flat surface have minimum values when the dimension $d_1 = 25$ mm is maximum (25.08 mm) and the dimension $d_2=35$ mm is the minimum (34.92 mm).

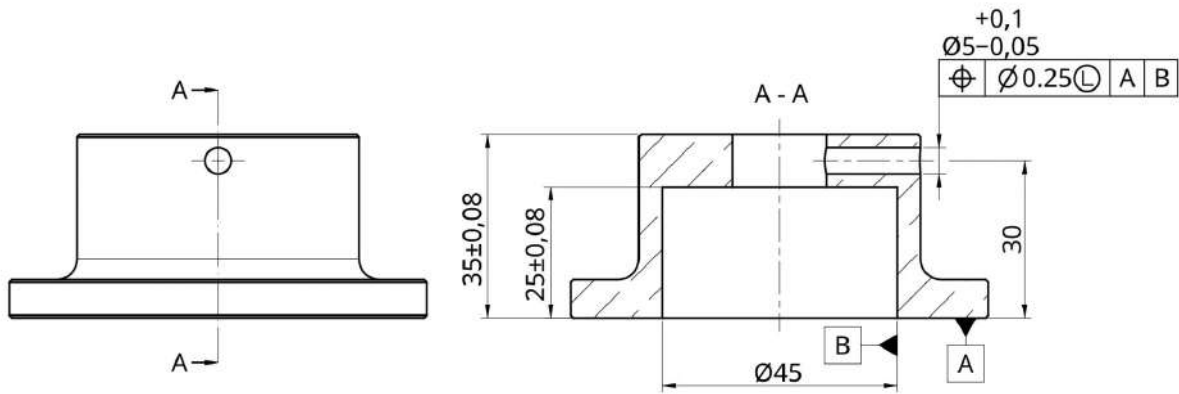


Figure 3.7. Example of prescription of nominal position precision based on the minimum material principle

But the problem is not so simple because the two wall thicknesses also depend on the nominal position of the axis of the cylindrical surface. A way to solve this problem, which we find both in the ISO standards and in the ASME standards, is based on prescribing the precision at the nominal position of the hole based on the principle of minimum material, as shown in figure 3.7. Thus, the tolerance at the nominal position varies between $\varnothing 0.25$ mm at the minimum of the material (hole diameter $\varnothing 5.100$ mm) and $\varnothing 0.25 + 0.15 = 0.40$ at the maximum of the material (hole diameter $\varnothing 4.950$ mm), according to the dependence represented in the figure 3.8.

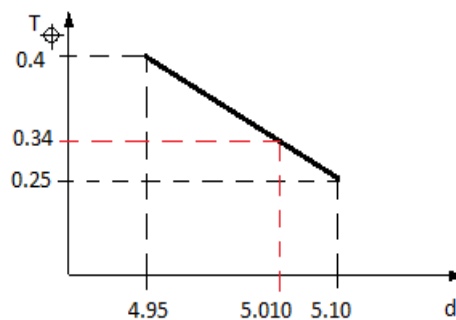


Figure 3.8. Tolerance variation for nominal position

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4. Conclusions

In this paper is presented the importance of correlating the function of a medical product, with its' design and manufacture stages within the global product design and development process. Together with the function of the product, custom requirements usually dictate the dimensional accuracy, macro-geometric and micro-geometric shape accuracy, relative surface position accuracy and other prescribed characteristics of medical products. AM products are designed with more demanding functional requirements; thus their accuracy tolerances are prescribed similarly as those of conventional manufacturing processes. Stability of overall dimensions over a period of time is also important in obtaining an adequate bespoke part in the medical industry, compared with repeatability of the results, as products are often customised on patient anatomical data. When prescribing nominal position precision based on size-dependent geometric tolerances, Boundary and Virtual Condition Boundary have been graphically identified for both maximum and minimum material principles in a cylindrical surface. A software application has been used to validate the selected case study and demonstrate the proposed principles of minimum and maximum of material for prescribing the nominal position precision based on size-dependent geometric tolerances for an upper limb prosthesis. The software applications assist design engineers and technologists in interpreting position accuracy prescriptions based on individual size-dependent tolerances, such as those related to nominal position, being very useful for example in ensuring the minimum thickness of some walls. A similar application can be adapted for external surfaces, with the mention that in this case the maximum material diameter is $D_{MML} = d_{max}$ and the minimum material diameter is $d_{min} = D_{LML}$. Also, similar applications are in progress for the prescription of the precision at the nominal position based on the minimum material principle, in which case the listed tolerance is valid at $d_{LML} = d_{min}$ for shafts and $D_{LML} = D_{max}$ for holes and the difference between the effective diameter and the diameter at minimum material is added to the nominal position tolerance.

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CONCLUSIONS

As one may notice while going through the e-book that has been realized by the EMERALD project consortium in the frame of the EMERALD 21-COP-0019 project, the realized e-book is a key resource, filled with knowledge and basic information data that are needed for conceiving, developing, realizing and testing of biomimetic mechatronic systems that are aimed to support real patients with amputated arms, covering in this context highly important topics such as Computer Aided Design, Computer Aided Engineering, Computer Programming, Virtual and Augmented Reality, Sensors and Electronics, Bio-Mechatronics, 3D Printing, Intelligent Materials and Prescribed / Manufacturing Precision methods. These topics are essential for the conceiving, developing and testing of biomimetic mechatronic systems like sensorized orthoses, prostheses and robotic arms that are needed to be realized to support real patients with amputated arms by taking into consideration the needs of these patients in a customized way. The e-book that has been realized with the significant contribution of each partner of the EMERALD project consortium is highly diverse and full of practical examples in this context.

The e-book that has been realized is not intended just to be used as an educational tool and resource for providing necessary knowledge and skills in the field of biomimetic mechatronic systems to anyone who is interested in conceiving, producing and testing of biomimetic mechatronics systems using 3D printing technologies to support real patients with amputated arms, but it is also aimed to be used as one tool in sharing and transferring the knowledge, experience and expertise to the important stakeholders (like private companies, medical institutes, etc.) who are interested in producing such biomimetic mechatronic systems to support people with special needs (patients with amputated arms) on a larger scale in the future.

The potential collaboration between higher educational institutions, medical institutes and private companies in the future is aimed to be focused on more than just teaching. By commonly sharing new ideas and knowledge in between all institutions that are interested on using all their resources in producing biomimetic mechatronic systems on a larger scale this could bring a highly practical support for the end-users (real patients with amputated arms) in the end in the future.

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