Iceland Liechtenstein Norway grants

Working together for a green, competitive and inclusive Europe

EMERALD

The Education, Scholarships, Apprenticeships and Youth Entrepreneurship

EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC MECHATRONIC SYSTEMS

INTELLECTUAL OUTPUT O3 - EMERALD

Project Title	**European network for 3D printing of biomimetic mechatronic systems 21-COP-0019**
Output	**O3 - EMERALD e-learning VR / AR platform for programming and using biomimetic mechatronic systems**
Date of Delivery	**2023**
Authors	**All partners**

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

TECHNICAL UNIVERSITY OF CLUJ-NAPOCA ROMANIA

POLITEHNICA UNIVERSITY OF BUCHAREST 1818

POLITECHNIKA POZNAŃSKA POZNAN UNIVERSITY OF TECHNOLOGY

UiA University of Agder

bizzcom

Content

1. Introduction, objectives and tasks of O3 6

2. EMERALD e-learning VR / AR platform 8

2.1.3D scanning laboratory room (PUT) 8

2.1.1. Accessing of 3D scanning laboratory virtual laboratory room 8

2.1.2. 3D scanning teaching resources overview 10

2.1.3. Step 1 - 3D scanning course presentation and technology review 11

2.1.4. Step 2 – 3D scanning tutorial video 18

2.1.5. Step 3 – software for 3D scanning data processing 21

2.1.6. Step 4 – laboratory work on 3D scan data processing 22

2.1.7. Additional 3D scanning materials 24

2.1.8. Conclusions about 3D scanning teaching resources of the e-learning platform 26

2.2. CAD / CAE laboratory (TUCN) 27

2.2.1. Accessing of the CAD / CAE laboratory virtual laboratory room 27

2.2.2. Structuring of the teaching resources being provided about CAD in the e-learning platform 29

2.2.3. Step 1 - CAD lecture 29

2.2.4. Step 2 - CAD additional lecture presentation 37

2.2.5. Step 3 - CAD additional lecture presentation on Topological and geometrical optimization 39

2.2.6. Step 4 - CAD laboratory work teaching resources 44

2.2.7. Step 5 – CAD laboratory toolkit 46

2.2.8. Step 6 - CAD laboratory additional support 49

2.2.9. Step 7 - CAD good practice examples realized by the students 51

2.2.10. Conclusions about CAD teaching resources of the e-learning platform 52

2.2.11. Structuring of the teaching resources being provided about CAE in the e-learning platform 53

2.2.12. Step 1 - CAE lectures 53

2.2.13. Step 2 - CAE lecture additional presentation 62

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.14. Step 3 - CAE laboratory work teaching resources 65
2.2.15. Step 4 - CAE laboratory toolkit 66
2.2.16. Step 5 - CAE webinar 70
2.2.17. Step 6 – Autodesk CAE tutorial 73
2.2.18. Step 7 - Autodesk CAE video tutorial 75
2.2.19. Step 8 - Additional CAE video tutorial 76
2.2.20. Step 9 - Good practice examples realized by students in CAE 78
2.2.21. Conclusions about CAE teaching resources of the e-learning platform 80
2.3. Testing & Materials virtual laboratory room (UPB) 81
2.3.1. Accessing of the Testing & Materials virtual laboratory room (UPB) 81
2.3.2. Structuring of the teaching resources being provided about Testing and Materials virtual laboratory in the e-learning platform 82
2.3.3. Step 1 - Mechanical testing lecture 84
2.3.4. Step 2 - Mechanical experiments video and laboratory presentation 89
2.3.5. Step 3 - Mechanical testing seminar 90
2.3.6. Step 4 – Aspects regarding the prescribed precision and manufacturing precision of implants, prostheses and orthoses lecture 94
2.3.7. Step 5 - Smart (intelligent) materials lecture 98
2.3.8. Step 6 - Smart (intelligent) materials additional presentation 102
2.3.9. Step 7 – Equipment items presentation and tour of the lab 105
2.3.10. Step 8 – Additional lecture on Smart (intelligent) – polymeric materials 107
2.3.11. Step 9 – Additional lecture on Plastic aesthetics 112
2.3.12. Step 10 - Smart (intelligent) materials laboratory work 115
2.3.13. Conclusions about Testing and Materials teaching resources of the e-learning platform 117
2.4. 3D printing virtual laboratory room (PUT) 118
2.4.1. Accessing of 3D printing laboratory virtual laboratory room 118
2.4.2. 3D printing teaching resources overview 120
2.4.3. Step 1 - 3D printing basics – module and lecture 121
2.4.4. Steps 2-5 - 3D printing tutorial videos 125

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.4.5. Step 6 – laboratory work 132
2.4.6. Additional 3D printing content of the Virtual Lab at PUT 135
2.4.7. Additional resources on 3D printing provided by TUCN 138
2.4.8. Step 7 - Additional presentation on 3D printing provided by TUCN 140
2.4.9. Steps 8 and 9 – Tour the 3D printing laboratories of TUCN 143
2.4.10. Step 10 and 11 –3D printing laboratory tutorials realized by TUCN 144
2.4.11. Step 12 – Good practice examples realized by students using 3D printing resources of EMERALD project 145
2.4.12. Conclusions about 3D printing teaching resources of the e-learning platform 146
2.5. Sensoring, assembly and programming virtual laboratory room (UiA) 146
2.5.1. Accessing of the sensoring, assembly and programming virtual laboratory room 146
2.5.2. Structuring of the teaching resources being provided about sensoring, assembly and programming in the e-learning platform 150
2.5.3. Step 1 - Sensoring course module 150
2.5.4. Step 2 - Sensoring lecture additional presentation 154
2.5.5. Steps 3 & 4 - Sensors in Biomechatronics & Actuators Drives additional presentations 155
2.5.6. Steps 5 & 6 – Additional lectures related to Bio-mechatronic systems and CAD for electronic circuits 165
2.5.7. Step 7- Assembling case study and application 171
2.5.8. Step 8 - Programming course module 173
2.5.9. Step 9 – Brain computer interface additional lecture and presentation 176
2.5.10. Step 10 – Computer programming laboratory instructions 183
2.5.11. Step 11 – Computer programming good practice examples realized by the students 188
2.5.12. Conclusions about sensoring, assembly and programming teaching resources of the e-learning platform 189
2.6. VR / AR laboratory room (BIZZCOM) 190
2.6.1. Accessing of VR /AR laboratory room 190

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.6.2. Structuring of the teaching resources being provided about VR /AR in the e-learning platform 192
2.6.3. Step 1 - VR / AR course module 192
2.6.4. Step 2 - AR programming laboratory module and applications 197
2.6.5. Step 3 - AR programming laboratory module and applications 200
2.6.6. Step 4 – AR library of the models 202
2.6.7. Step 5 - Additional resources related to the creating of Virtual laboratories 203
2.6.8. Step 6 - Introduction to VR applications lecture 205
2.6.9. Step 7 - Application realized for visualizing models in VR using GLTF mode 215
2.6.10. Step 8 - Application realized for virtual reality application using Godot 219
2.6.11. Step 9 – Good practice examples done by students in VR 220
2.6.12. Step 10 – Teleporting to PUT VR laboratory room 221
2.6.13. Accessing of XR virtual laboratory room and e-learning resources at PUT 222
2.6.14. XR at PUT VL - teaching resources overview 223
2.6.15. Step 1 - PUT – XR principles in biomechatronic devices 224
2.6.16. Step 2 – PUT - Augmented Reality application tutorial 231
2.6.17. Step 3 – PUT - Mixed Reality application tutorial 234
2.6.18. Step 4 – PUT - Virtual Reality application tutorial 238
2.6.19. Additional VR materials related to EMERALD project 242
2.6.20. Conclusions about VR / AR teaching resources of the e-learning platform 244
3. Final conclusions 244

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

1. Introduction, objectives and tasks of O3

The e-learning virtual laboratory platform conceived in the frame of O3 has been designed especially for anyone who is eager to gain knowledge & expertise in the conceiving, realizing & testing of bio-mechatronics systems for people with special needs (with amputated arms). The e-learning virtual laboratory platform has been conceived by the EMERALD project consortium in such way to be easy accessed & used online. In the context of the pandemic, when physical access to laboratories was restricted, new teaching methods were foreseen to be implemented. In this context, it was intended that the users can easily access the EMERALD e-learning virtual laboratory platform in such way that they will have the feeling as they are being present in the physical laboratories in the end. The e-learning virtual laboratory platform that has been conceived in the frame of O3 (see Fig.1.1) it is not just a place where users can simply look around, but it is a place of a full learning environment. Every digital laboratory room that can be also visualized in VR mode is focused on the presenting of a particular step in the chain of conceiving, realizing & producing of a bio-mechatronic system for people with amputated arms contains lot of different learning materials, starting with VR/AR reality applications that have been conceived with the purpose of helping the user to comprise all the constructing elements of a bio-mechatronic system, up to practical tools on doing VR/AR programming & continuing with other clear explanations with annotations related to the equipment items that are present in different labs & their characteristics (e.g. 3D printer name, model + link to producer), links to videos related to the operating of specific equipment/software, connected to the above mentioned annotations, links to course modules & toolkit (PDF files, results of O1/O2), links from which there can be downloaded freely available/online software programs for CAD, CAE, 3D printing & others. In order to have a logical manner of understanding & following things, a schematic image & one set of instructions have been provided to the users before they are going to access the virtual laboratories as one may notice on the next following link: https://project-emerald.eu/?page_id=404 Actually the way the online rooms have been set up takes users on a full journey for a better understanding the steps that are necessary to be followed for producing bio-mechatronic systems for people with amputated arms, starting with 3D scanning, then continuing with the CAD design, being followed by CAE validation, in close correlation with testing & selecting of the materials, 3D printing of the physical parts, adding of the necessary sensors, assembling of the system, programming, testing & exploring of the conceived system using VR/AR in the end.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

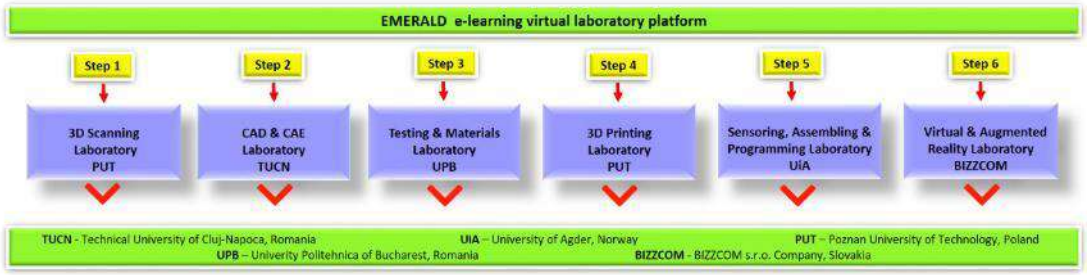


Fig.1.1. Concept of the e-learning virtual laboratory platform

The e-learning virtual laboratory platform has been conceived as one web-based platform that is accessible by WWW browser (see Figure 1.2).

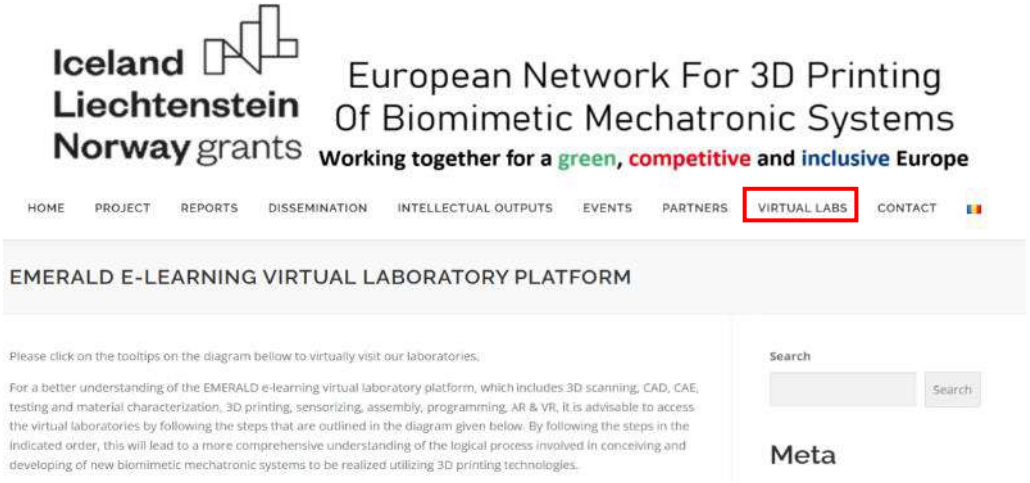


Fig.1.2. Accessing of the e-learning virtual laboratory platform through the www browser

Each institution of the EMERALD consortium has been asked to provide digital image of real laboratory room (possible to be launched also by dedicated external application with the use of VR/AR technology), captured by 360 degree camera, containing basic information about the equipment contained in particular given rooms according to the topic of the room that has been assigned to each institution. Since they had previous experience in building AR applications in particular & in using of Web learning methods, Bizzcom company (Slovakia) has been assigned as leading institution for producing the e-learning virtual laboratory platform.

The distributing of the virtual laboratory rooms for the EMERALD e-learning platform has been realized by taking into consideration the experience of the EMERALD consortium partners &

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

their previous collaborative work done with the other partners in the consortium within the EMERALD project until this phase of the project (see Figure 1.1). In this way, Poznan University of Technology (PUT) has taken the main responsibility in preparing the virtual laboratory room related to the 3D scanning process, while the Technical University of Cluj-Napoca has been assigned to take care about the next following steps (laboratory of CAD/CAE), dealing with both design & engineering aspects. University Politehnica Bucharest (UPB) was given the main role of testing & assigning of the materials, while PUT (which have more than 40 3D printers in their laboratory) have been assigned to take the responsibility of realizing the 3D printing laboratory room. Taking into consideration the experience that the University of Agder (UiA) has concerning the sensorizing, assembly & programming domain (as well as in bio-mechatronics), they have been assigned with the main role of organizing of specific educational tools & methods that are related to this domain in their virtual laboratory. Last, but not least BIZZCOM, which have high experience with the immersive technologies, have taken the responsibility of preparing the AR/VR virtual laboratory room (in cooperation with PUT). In order to provide clarity concerning the challenging developing process of bio-mechatronic systems for people with amputated arms, on the EMERALD official website that is hosting the e-learning virtual laboratory platform it has been featured a well-organized schematic & guide (with specific laboratories assigned to each partner of the EMERALD consortium), in order to lead users to follow the virtual laboratories in a logical way, by accessing step-by-step each laboratory (as well as all facilities that are being offered in each laboratory) so as they can comprise easier all steps that the conceiving, developing, producing & testing of bio-mechatronic systems for people with amputated arms are assuming to.

2. EMERALD e-learning VR / AR platform

2.1. 3D scanning laboratory room (PUT)

2.1.1. Accessing of 3D scanning laboratory virtual laboratory room

3D scanning virtual laboratory room which has been assigned to the Poznan University of Technology as one may notice in Figure 2.1.1 can be accessed from the www interface of the EMERALD project (https://project-emerald.eu/?page_id=404) or directly by accessing the next following link: https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-2.95,.1&ss=37

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

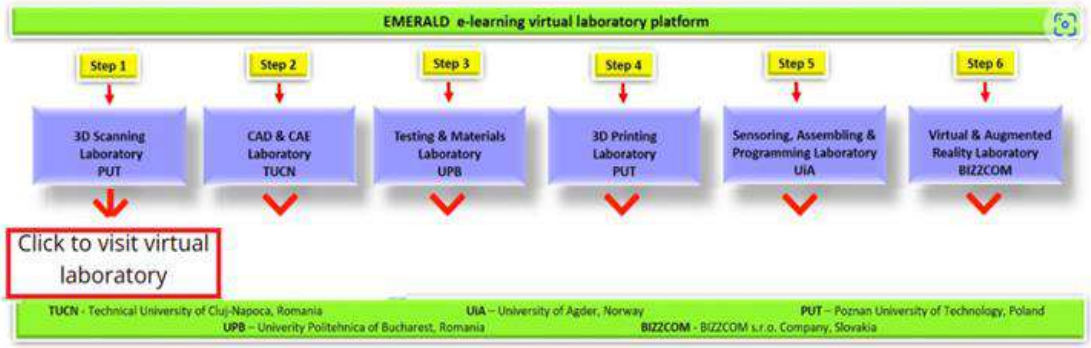


Figure 2.1.1. Accessing of the 3D scanning virtual laboratory room from the e-learning platform

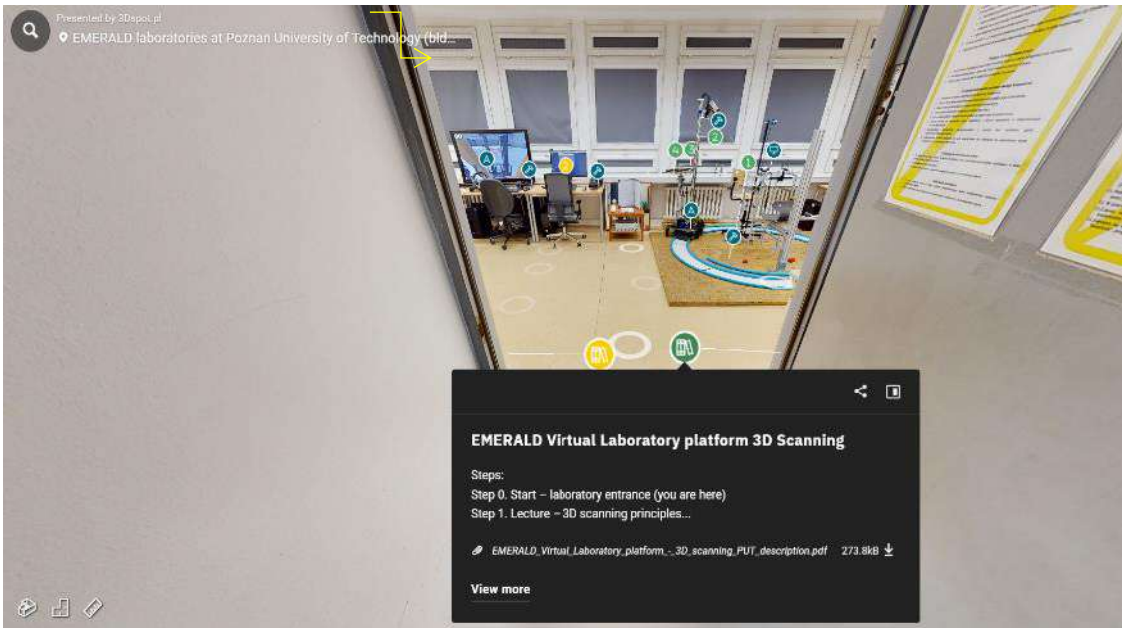


Figure 2.1.2. Main entrance of the 3D scanning laboratory of PUT

The 3D scanning virtual laboratory room at PUT that can be seen in Figure 2.2, has been realized using Matterport Pro camera, the captured images undergoing in further processing using Matterport software, allowing the integration of educational materials related to 3D scanning for the bio-mechatronic components that have been developed within the EMERALD project related to this topic in particular. The laboratory itself is also a XR laboratory (containing various Virtual, Augmented and Mixed Reality devices), and as such is used as a multi-purpose laboratory – it will be referred to in one of the next chapters.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.1.2. 3D scanning teaching resources overview

The e-learning virtual laboratory platform dedicated to the 3D scanning stage in particular offers an enriched educational experience that is tailored to the first step that is necessary to be followed concerning the developing of bio-mechatronic systems destined for people with special needs (with amputated arms) such as orthoses, prostheses or robotic arms. The main aim of the platform in relation to 3D scanning aims to familiarize the users and facilitate their comprehensive learning and understanding by providing them a smooth advancement and gradual progression concerning the teaching materials and resources the users are following and are accessing on the e-learning virtual laboratory platform.

In this sense, upon entering the 3D scanning virtual laboratory room, users gain access to a structured curriculum that starts with foundational course materials that cover the basics of 3D scanning methods, then they have access to highly practical laboratory tutorials, completed with toolkits and instructional videos that are providing the users step by step information data on how they have to do the 3D scanning of specific bio-mechatronic components for people with special needs (like orthoses, prostheses and robotic arms,) and finally users have access to 3D scanned library of models, which corresponds to the models that are being presented in the tutorials, toolkits and instructional videos, along with information for accessing of various software programs that the users can download and work with them, to do preparing of files for the CAD step that will be presented that is needed to be performed in relation with practical cases of bio-mechatronic components that the students (users) will be asked to realize them using the EMERALD e-learning virtual laboratory resources.

The course of 3D scanning available in the laboratory has been divided into 4 main steps (Figure 2.3), with some additional information available besides these steps.

Steps:

Step 0. Start – laboratory entrance

Step 1. Lecture – 3D scanning principles

Step 2. 3D scanning of human limb – video

Step 3. Software for scanning data processing

Step 4. Tutorials on limb scan data processing

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

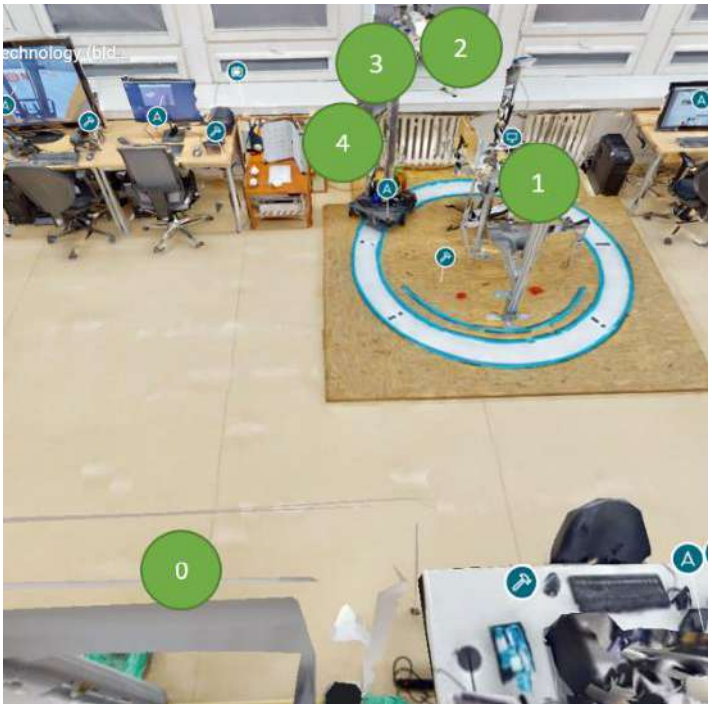


Figure 2.1.3. 3D scanning – steps of the course

Step 0, accessible right after entering the laboratory (green marker), contains overview of all the other steps and a short document with information for the Virtual Laboratory user. Direct link to this starting point is here: https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-.62%2C.96&ss=63&tag=wOmz3i7mWRc&pin-pos=-20.76%2C1%2C2.22

2.1.3. Step 1 - 3D scanning course presentation and technology review

The course module that provide the describing of main methods of 3D scanning are provided and can be accessed like shown in Figure 2.1.4. being possible to be accessed directly on the 3D scanning virtual laboratory of the e-learning platform, using the green marker no. 1 (refer to Fig. 2.1.3 and link below) and the first link contained there.

The presentation offers a comprehensive view of the design process for prosthetics, with a focus on the role of 3D scanning and data processing. It covers a range of techniques, from medical imaging to 3D modeling, and discusses various software tools used in the process.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

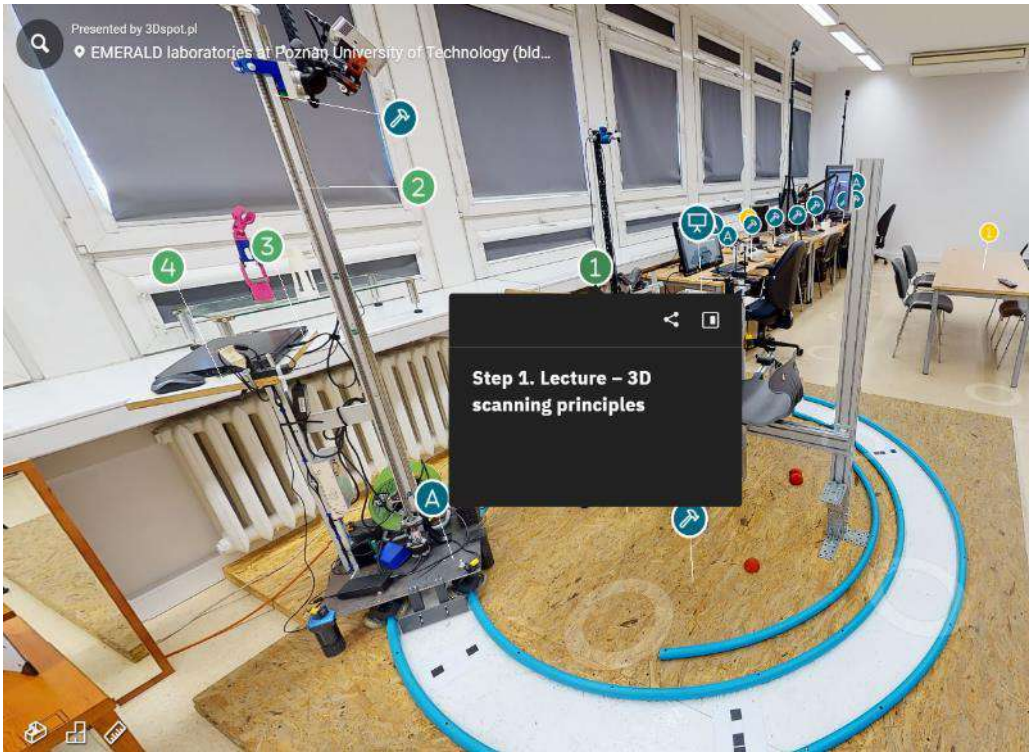


Figure 2.1.4. 3D scanning lecture accessing

For a full understanding, one should consider reviewing the presentation in its entirety.

1. Introduction to Prosthetic Design. Customization and Individualization.

The presentation begins by introducing the basics of engineering design. It emphasizes the creation of new products to meet specific needs, highlighting the significance of individualized design in the context of creating prosthetic devices tailored to individual patients.

Then, distinguishing between customization, individualization, and personalization in product design is made in medical devices, particularly prosthetics, the focus is on anatomical and functional individualization, ensuring that each device is uniquely suited to its user (see Figure 2.1.5). Various medical devices that undergo individualization are mentioned. These include joint replacements, limb prostheses, bone implants, and artificial organs, underlining the broad scope of individualized medical device design.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

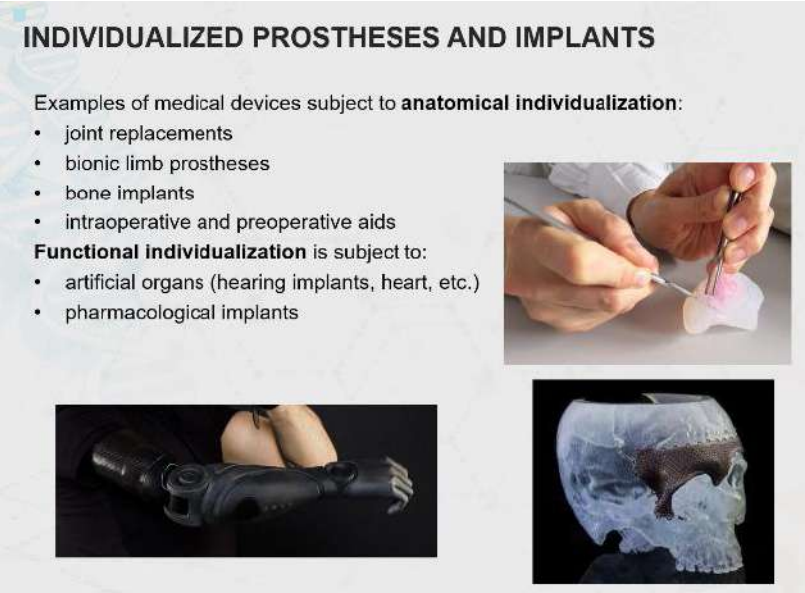


Figure 2.1.5. 3D scanning presentation – individualization aspect

2. 3D Scanning and Medical Imaging in Prosthetics 3D Scanning Techniques

The presentation categorizes 3D measurement techniques into contact and non-contact methods (see Figure 2.1.6). Examples include contact scanners, electromagnetic interaction methods, X-rays, MRI, photogrammetry, and ultrasound scanners. It is emphasized to use using light-based scanners for external anatomy, CT scans for hard tissues, and MRI for soft tissues. These methods are crucial in designing prosthetics.

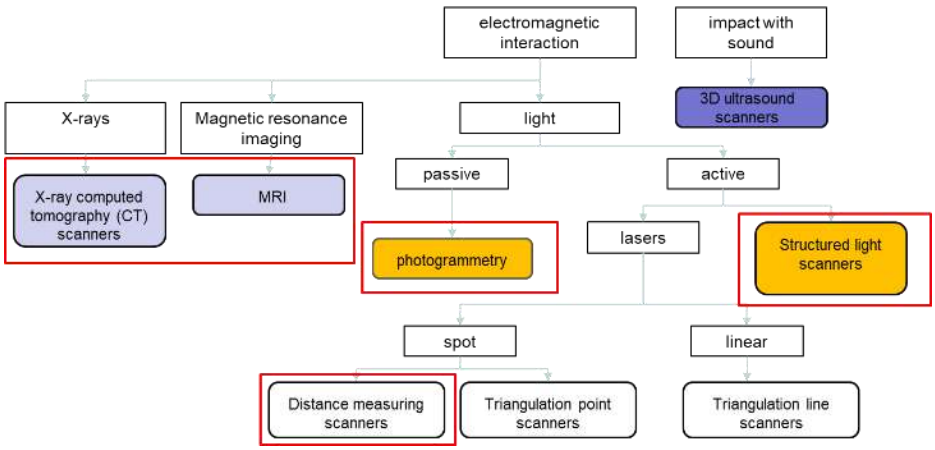


Figure 2.1.6. Overview of methods for 3D scanning of body parts

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The specifics of CT (Computer Tomography) and MRI (Magnetic Resonance Imaging) are discussed in detail. Their applications, benefits, and limitations in medical imaging and prosthetic design are explored. The process of photogrammetry, involving capturing multiple images of an object from different positions to create a 3D model, is explained. The mechanics, applications, and limitations of laser scanning and structured light scanners are discussed in-depth as well.

The full process of 3D scanning is presented, starting from scanner calibration and object preparation. Then the details of catching of the 3D scan are presented, along with recommendations of how patients should be positioned during the scan (see Figure 2.1.7).

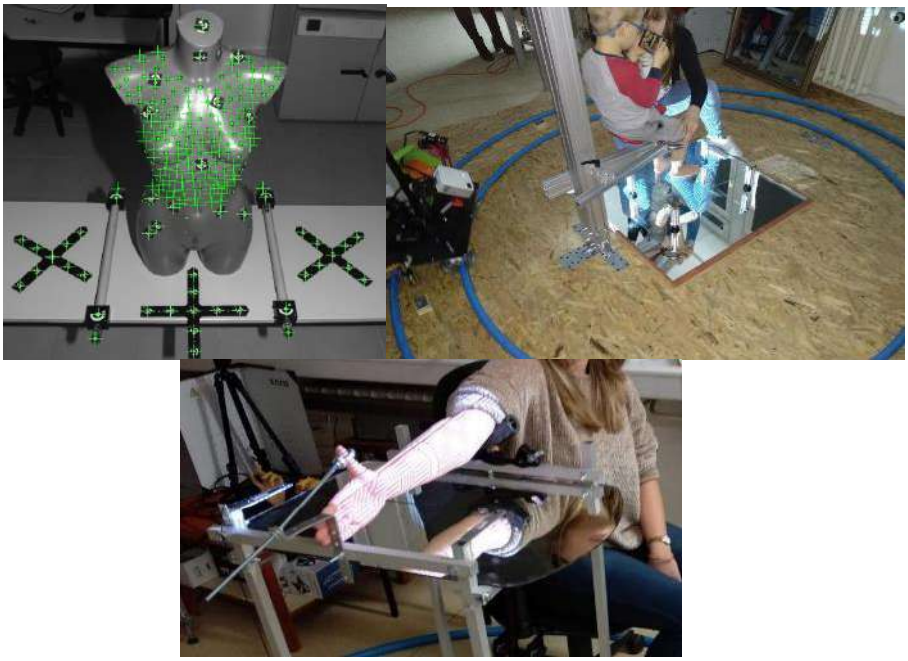


Figure 2.1.7. 3D scanning processes examples detailed in the presentation

3. Data Processing in Prosthetic Design. Data Formats and Processing.

The presentation outlines typical data formats in design, starting with point clouds from 3D scanning and DICOM from medical imaging. The process of segmenting DICOM data and transforming it into 3D models is explained. Additionally, the conversion of point clouds into triangle meshes and subsequent processing is discussed. Characteristics, file structures, and processing methodologies of triangle meshes and point clouds are explored in depth. Steps in mesh processing, such as closing holes, smoothing, removing artifacts, and reducing triangle count, are detailed. Techniques for merging multiple scans and cleaning the resultant data to create a coherent 3D model are covered as one may notice in Figure 2.1.8.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

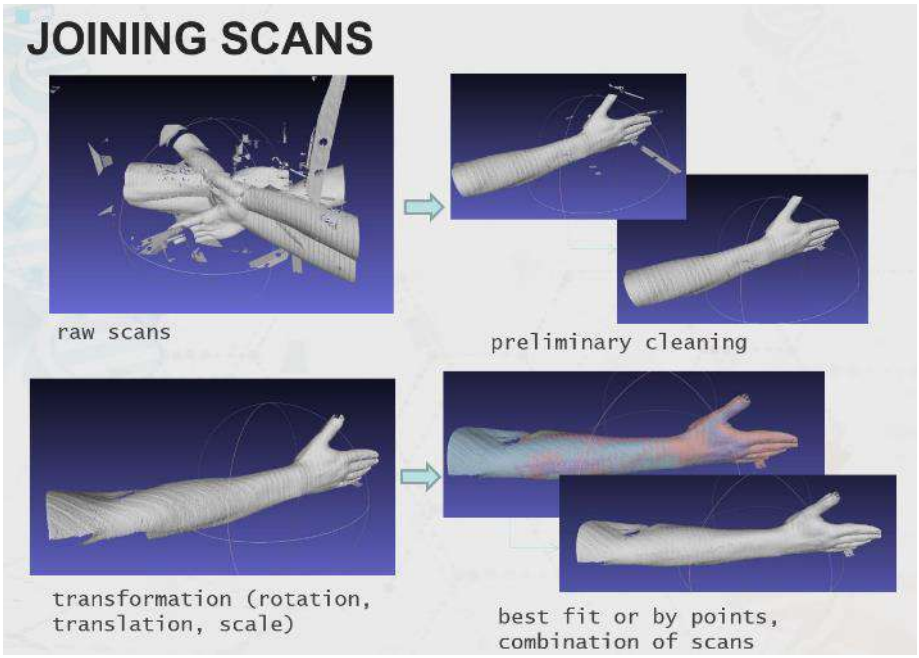


Figure 2.1.8. Data processing – scan joining

In the final part of the lecture, various software tools used in prosthetic design are introduced, including DICOM processing software like Slicer and MIMICS, mesh processing tools like MeshMixer and MeshLab, and CAD systems like Inventor and SolidWorks (see Figures 2.1.9 and 2.1.10). The features, applications, and limitations of each software are discussed, providing insights into their use in prosthetic design.

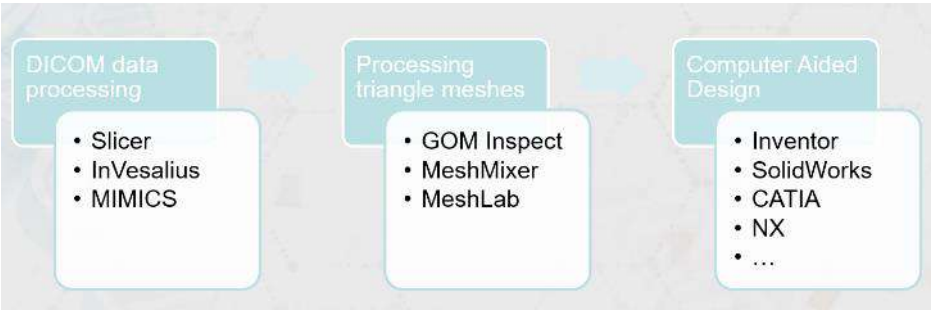


Figure 2.1.9. Data processing software overview

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

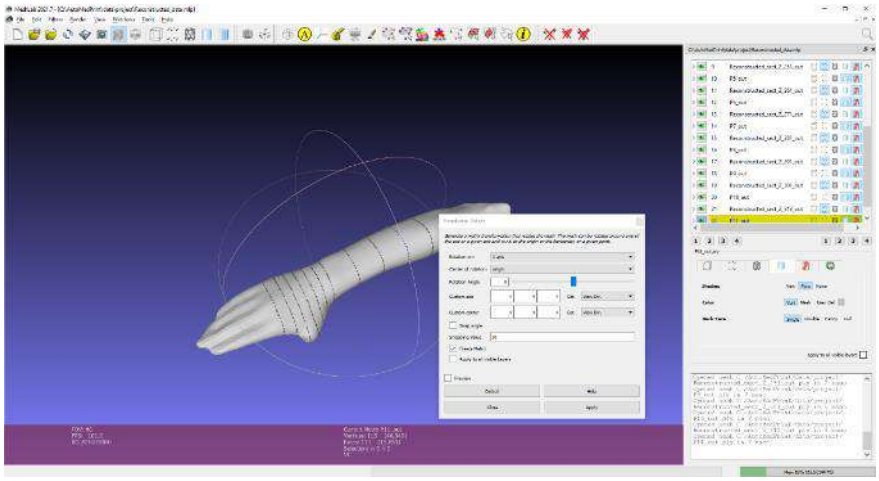


Figure 2.1.10. Example - Meshlab

Additionally, the step 1 of the 3D scanning course available in the virtual laboratory contains a state of the art review of scanners that can be used for 3D scanning of human body parts (second link under green marker no. 1), especially limbs (both healthy, diseased and partially amputated). The document is accessed the same way as the presentation – it's available under the green marker no. 1 in PUT's Virtual Laboratory. The short summary of that review is presented below. The screenshot of the document is presented in Figure 2.1.11.

Figure 2.1.11. The state of 3D scanning technology for human body parts – review document available in Virtual Platform, step 1

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The advancement in non-contact measurement techniques, especially 3D scanners, has revolutionized anthropometric measurements, replacing traditional methods (see Figure 2.1.12). These scanners capture vast data quickly, measuring the entire body or specific parts. They employ passive (photogrammetry) or active methods (laser scanning, structured light, moiré projection).

Photogrammetric systems capture numerous images of an object from various angles, determining spatial coordinates through recognized markers. Laser scanning, on the other hand, uses laser projection or structured light patterns to calculate distances and capture detailed measurements.

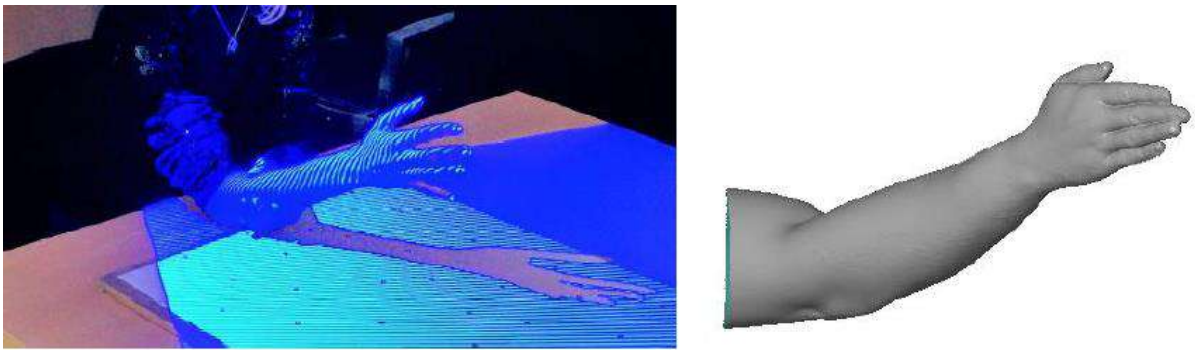


Figure 2.1.12. 3D scanning with optical light – measured person and result of measurement

3D scanners vary in price and capability. Entry-level options (below PLN 10,000) include hobbyist devices like 3D Systems 3D Sense or XYZ Printing 3D Scanner, offering low-accuracy scans (see Figure 2.1.13). Mid-range scanners (PLN 10,000 - PLN 25,000) like HP 3D Structured Light Scanner Pro S3 and RangeVision Smart scanners provide better accuracy and resolution.

The semi-professional range (PLN 25,000 - PLN 100,000) includes devices like Artec's EVA series for industrial applications with higher accuracy. Artec's Space Spider offers enhanced precision. The Artec Leo series provides mobility and convenience.

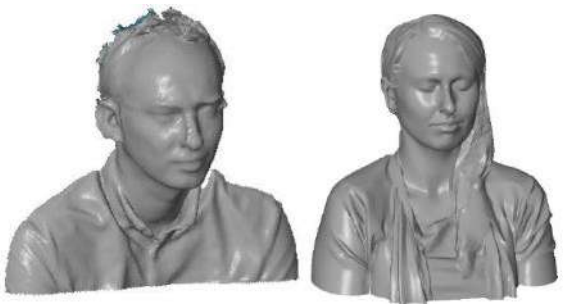


Figure 2.1.13. 3D scanning results with different scanners

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In medical applications, Smarttech's Skan3D Med scanners offer high resolution and quick scans. Professional-grade scanners (above PLN 100,000) from GOM, Hexagon, and Breuckmann are used in aviation and automotive industries due to exceptional accuracy and VDI/VDE 2634 certification.

Specialized scanners, such as Human Solutions' Vitus Smart XXL for anthropometric measurements, boast large chambers and multiple cameras, ensuring comprehensive measurements. These high-end scanners can cost around PLN 250,000 to PLN 450,000, catering to industries with stringent accuracy requirements.

The evolution of 3D scanners, from entry-level hobbyist devices to highly accurate professional tools, has widened their applications across industries, from fashion design to medical imaging, offering varying levels of precision to suit diverse needs and budgets.

2.1.4. Step 2 – 3D scanning tutorial video

The next step are 3D scanning videos, presenting the practices of scanning of various body parts with different scanners. They can be accessed like shown in Figure 2.1.14 being possible to be accessed directly on the 3D scanning virtual laboratory of the e-learning platform, using the green marker no. 2 (refer to Fig. 2.1.3) and the YouTube video contained there.

Figure 2.1.14. 3D scanning – tutorial video accessing

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The video itself is composed of several parts. First main part is presentation of scanning rig and patient preparation, in the AutoMedPrint system, using David SLS-2 scanner as shown in Figure 2.1.15.

Figure 2.1.15. Tutorial video – patient scanning rig

Then, full methodology of scanning is presented, showing the movement of the scanner, data gathering in different positions and also work with the software as one may notice in Figures 2.1.16 and 2.1.17.

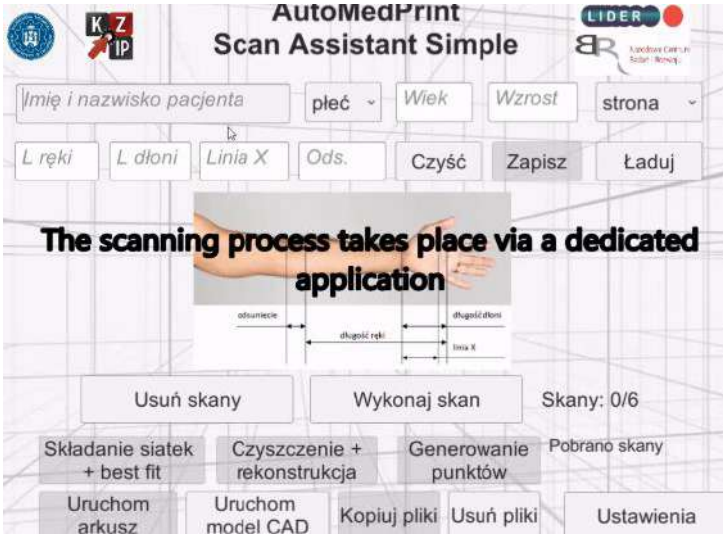


Figure 2.1.16. Tutorial video – AutoMedPrint software

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

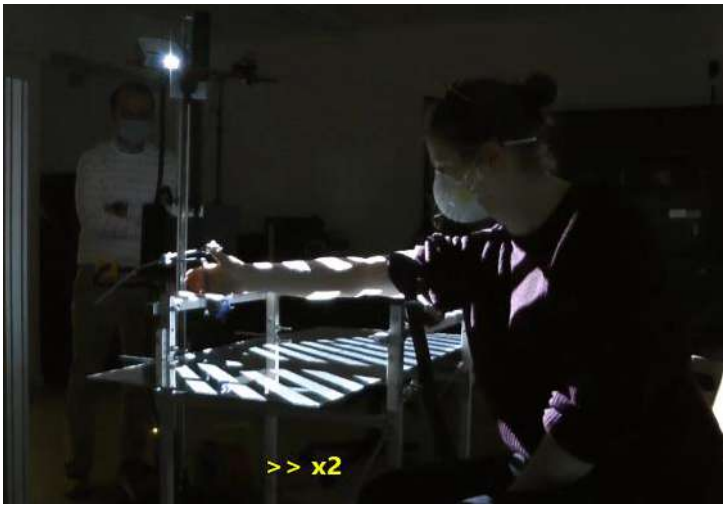


Figure 2.1.17. Tutorial video – scanning with David SLS-3

The second main part of the video presents analogous methodology of 3D scanning using a manual 3D scanner – EinScan Pro (see Figure 2.1.18). The process is covered in great detail, showing both the scanning procedure and the software operation. Then, also an example of hand scanning is shown, in the last part of the video as shown in Figure 2.1.19.

Figure 2.1.18. Tutorial video – EinScan Pro software use

The video contains very detailed descriptions on how the software and hardware for 3D scanning should be used in real life scenarios of scanning of a human limb. The students, if equipped with similar devices, should be able to learn how they should be operated basing solely on the provided videos.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.1.19. Tutorial video – scanning with EinScan Pro

2.1.5. Step 3 – software for 3D scanning data processing

The next step is introduction to the more practical part. The third step contains instruction with links to open source and freeware software that can be used for processing of 3D scanning data. It can be accessed like shown in Figure 2.1.20 being possible to be accessed directly on the 3D scanning virtual laboratory of the e-learning platform, using the green marker no. 3 (refer to Fig. 2.1.3) and the document contained there.

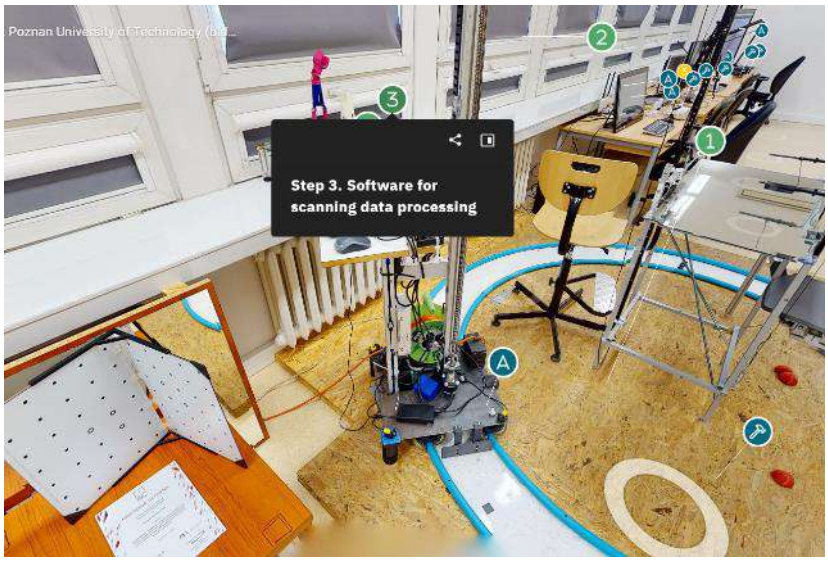


Figure 2.1.20. 3D scanning – software instruction accessing

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

This step contains instruction on how to download and install two popular programs for 3D scanning mesh processing: GOM Inspect and MeshLab. These can be downloaded and used for free and the subsequent laboratory work tutorials are based on them.

2.1.6. Step 4 – laboratory work on 3D scan data processing

The next step is the laboratory work. The step no. 4 contains instruction of tutorials for processing of 3D scanning data. It can be accessed like shown in Figure 2.1.21 being possible to be accessed directly on the 3D scanning virtual laboratory of the e-learning platform, using the green marker no. 4 (refer to Fig. 2.1.3) and the videos and files contained there.

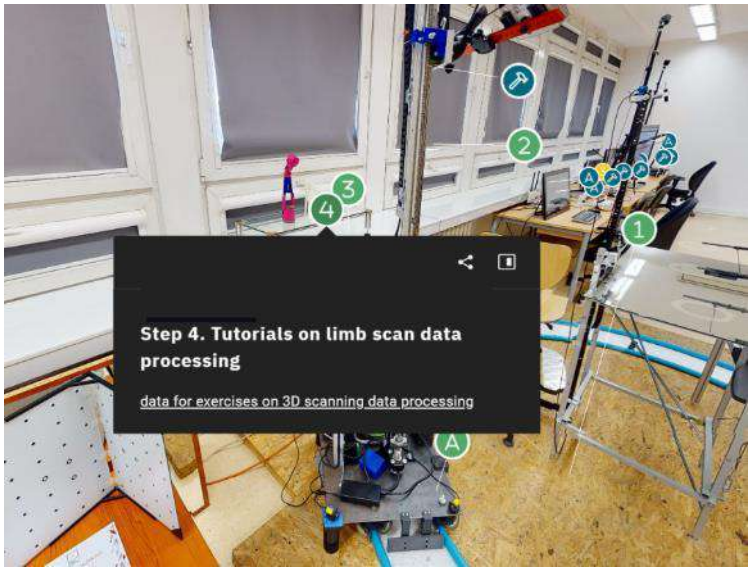


Figure 2.1.21. 3D scanning – software instruction accessing

The instruction video contains two main parts. In the first part, the MeshLab software is shown (see Figure 2.1.22). Upper limb scan is being processed in this part, with data coming from EinScan Pro manual scanner. All the basic operations are shown – selection and cleaning of the data, closing holes, reconstruction and changing the coordinate system. Additionally, it is shown that MeshLab records macros and the user is able to re-use and edit them (see Figure 2.1.23).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

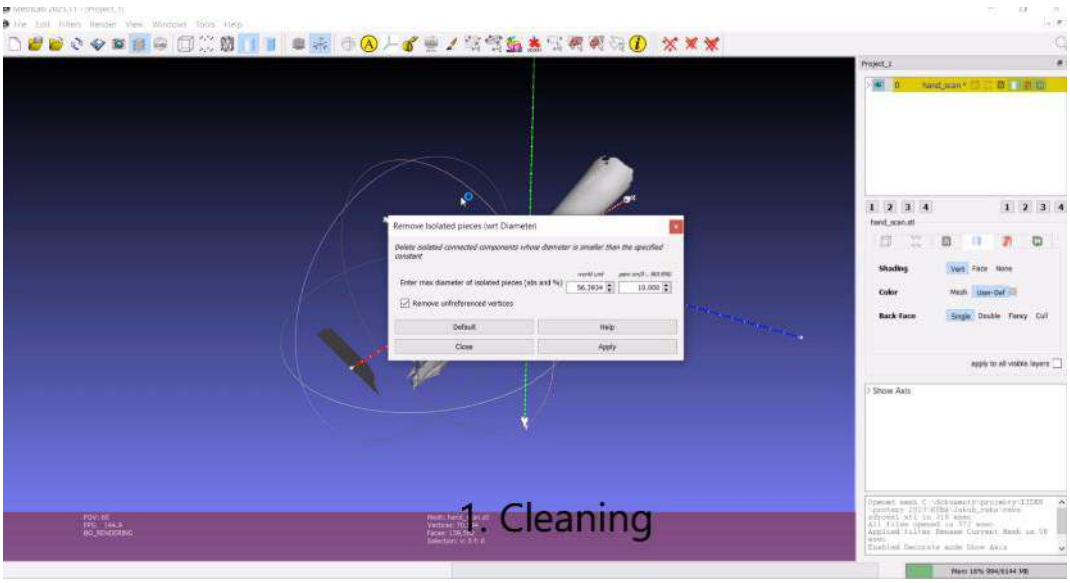


Figure 2.1.22. Data processing tutorial – MeshLab

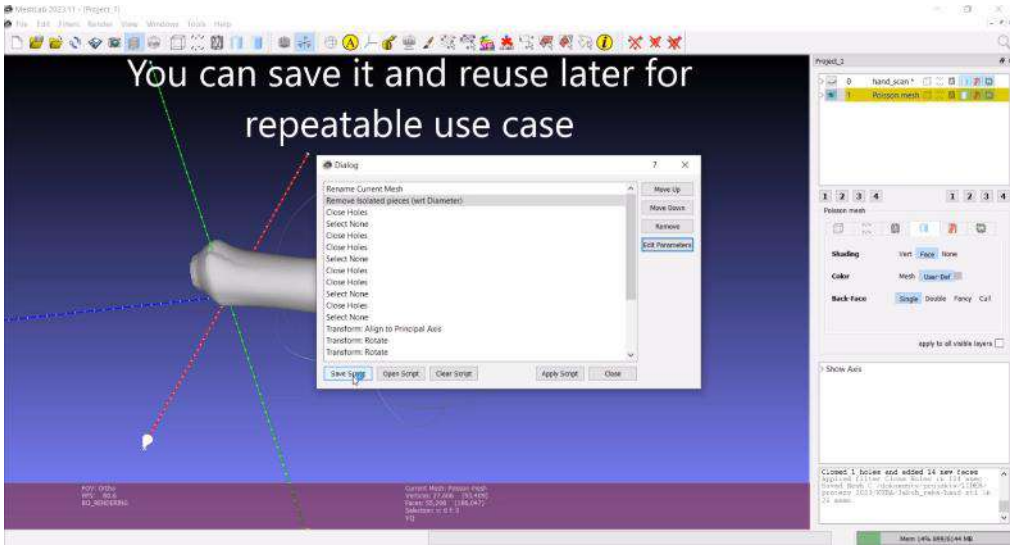


Figure 2.1.23. Data processing tutorial – MeshLab macros

In the second part of the video, GOM Inspect software is used to process the scanning data of the leg as one may notice in Figure 2.1.24. All the basic operations, as the ones presented in the lecture from step 1, are shown – selection, cleaning, closing holes, repairing the mesh and many others.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.1.24. Data processing tutorial – GOM Inspect

Finally, the step no. 3 also contains a library of files with raw 3D scans. The files contain different body parts – legs, hands and also amputated limbs (stumps), of both sides (left and right) as shown in Figure 2.1.25. The files also contain data of different sources – both manual scanning (EinScan Pro) and scanning on AutoMedPrint station are utilized (of David SLS-3) so that the student can exercise and try different data sets. The data shown in the earlier tutorials are also available .

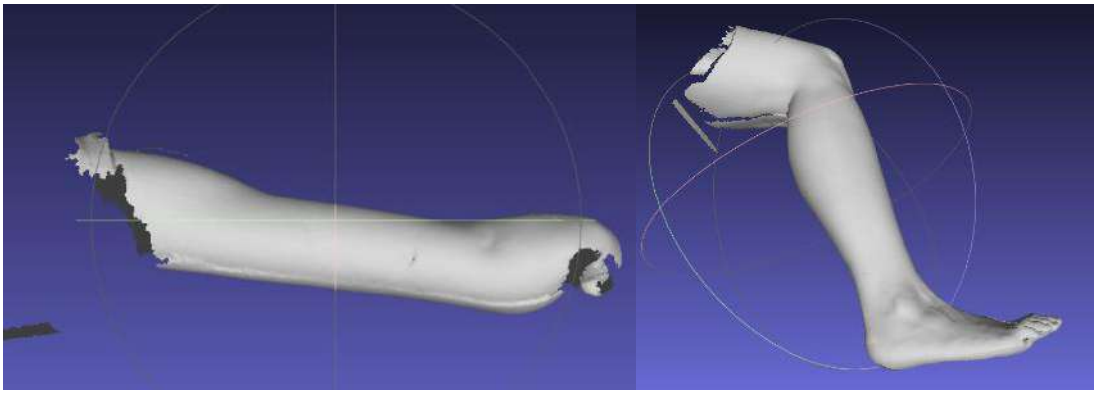


Figure 2.1.25. Examples of 3D scans contained in the exercise library at the platform

2.1.7. Additional 3D scanning materials

The 3D scanning laboratory also contains additional materials, for the students. These include the following:

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

- Virtual Reality executable application (see Figure 2.1.26) – interactive tutorial on how to realize work with AutoMedPrint system in the aspect of 3D scanning, design and 3D printing – the students may learn the whole scanning procedure on their own from the video.

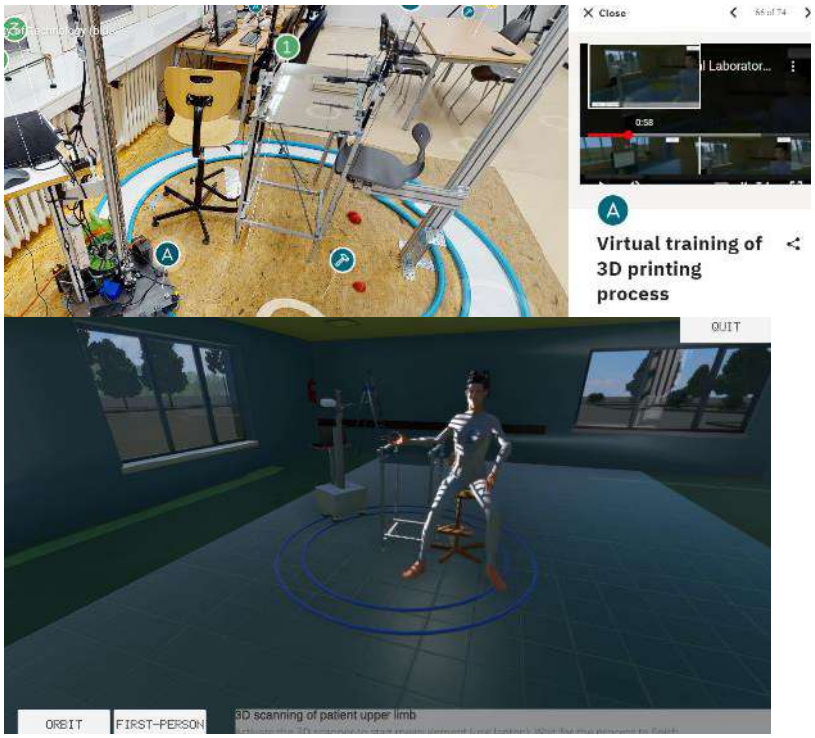


Figure 2.1.26. Interactive Virtual Reality tutorial application – to be downloaded from the platform

- best practices presentation example – made by a student at PUT, realizing one of case studies and scanning leg of a patient (see Figure 2.1.27)

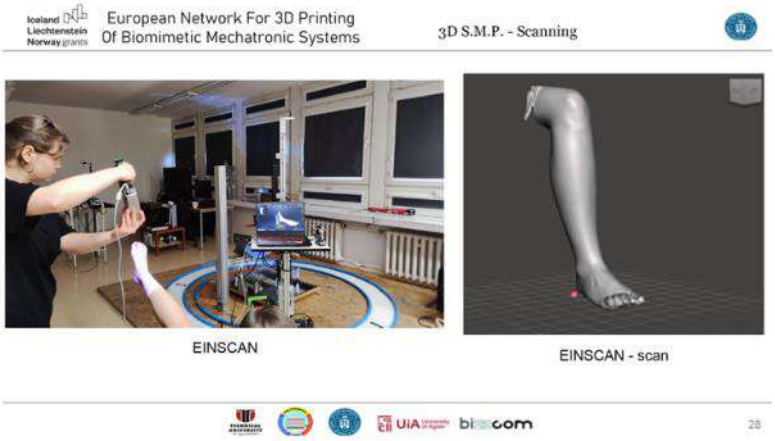


Figure 2.1.27. 3D Scanning best practices presentation (student work)

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

- description of work and operation of a 3D scanner – David SLS-3 (see Figure 2.1.28)

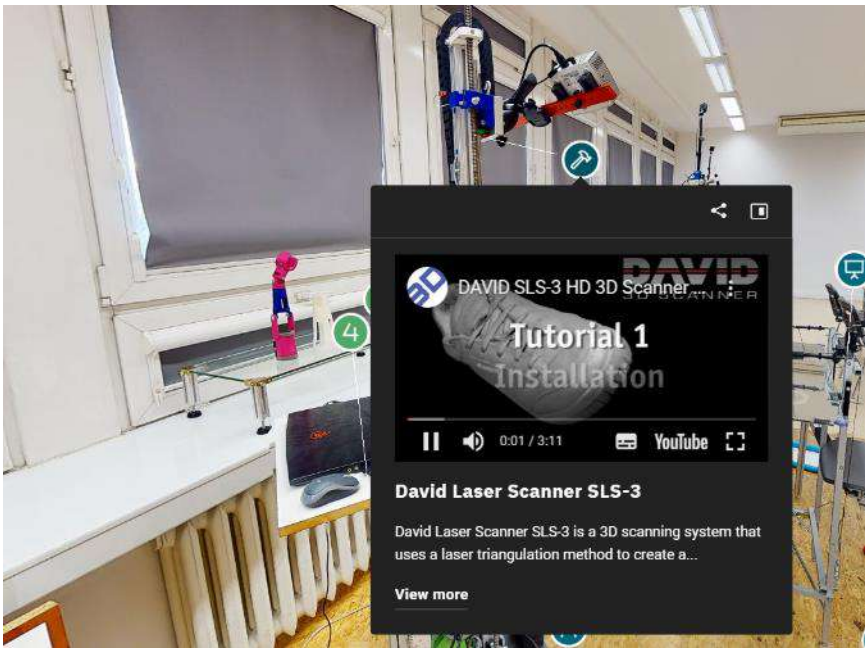


Figure 2.1.28. Examples of 3D scans contained in the exercise library at the platform

These materials are complementary towards the main path of the course, however they provide interesting insights on how to work with the 3D scanners for the need of scanning of limbs for people with needs for customized biomechatronic devices, such as prostheses.

2.1.8. Conclusions about 3D scanning teaching resources of the e-learning platform

The materials contained in the Virtual Platform regarding 3D scanning present a unique opportunity for any student to get familiarized with the newest possibilities in 3D scanning of human limbs and methods of processing of such scans. The comprehensive, detailed presentations and analyses presented allow the students to get a grip on the technology, its foundations, requirements and use. Great expertise of authors of the materials (coming from Poznan University of Technology, related to multi-award project AutoMedPrint) brings possibilities to learn a great deal about the 3D scanning, both by watching very detailed videos on how to realize the process and by doing work themselves, on a presented set of data of real patients, captured in real working conditions. Such a course is unprecedented and unavailable at any other e-learning platform.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2. CAD / CAE laboratory (TUCN)

2.2.1. Accessing of the CAD / CAE laboratory virtual laboratory room

Computer Aided Design / Computer Aided Engineering (CAD / CAE) virtual laboratory room which has been assigned to the Technical University of Cluj-Napoca, as one may notice in Figure 2.2.1 can be accessed from the www interface of the EMERALD project (https://project-emerald.eu/?page_id=404) or directly by accessing the next following link: https://bizzcom.viewin360.co/share/collection/7J4Qk?logo=0&info=0&fs=1&vr=1&sd=1&initload=0&thumbs=1

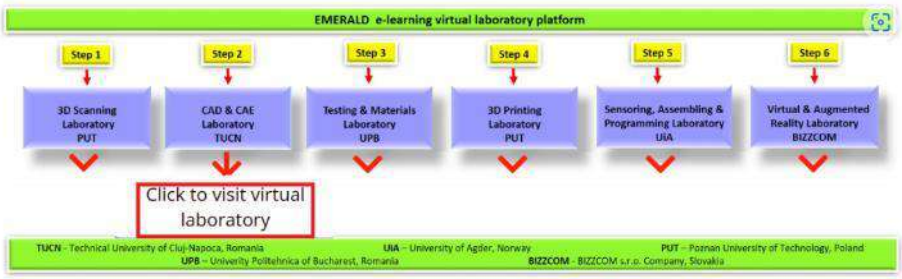


Figure 2.2.1. Accessing of the CAD/CAE virtual laboratory room from the e-learning platform

The Virtual Laboratory tour begins at the entrance of the TUCN main building, as shown in Figure 2.2.2. Upon entering the building through the main corridor, one may access the CAD/CAE virtual laboratory of TUCN, as shown in Figure 2.2.3.

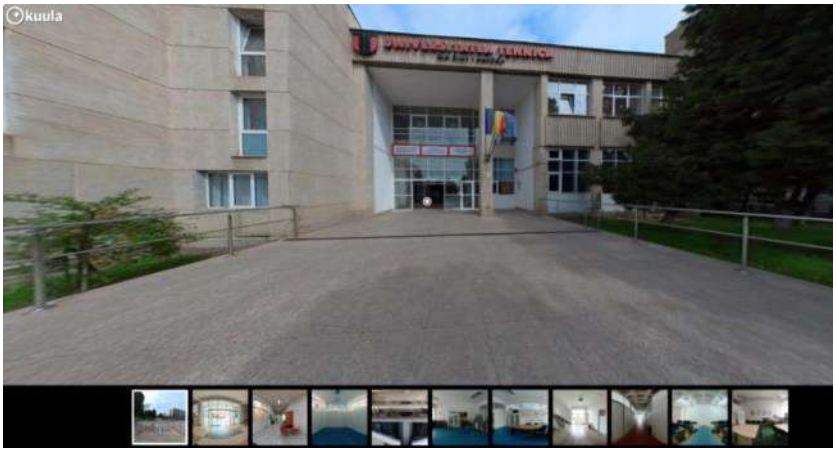


Fig.2.2.2. Entrance of the TUCN main building

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

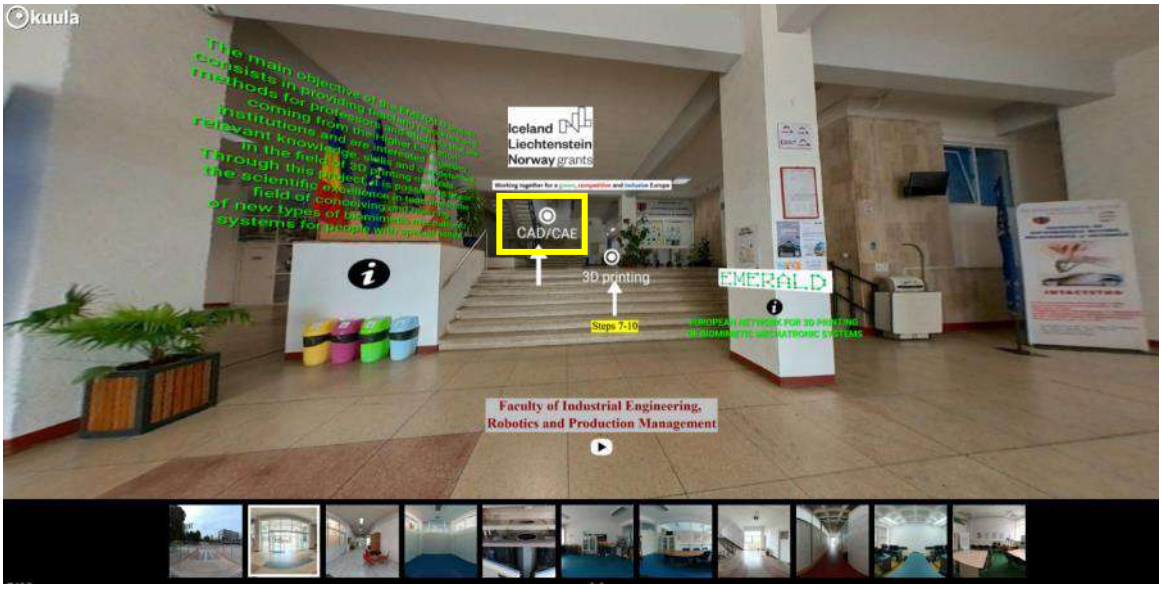


Fig.2.2.3. Access to the CAD / CAE laboratory (TUCN) from the main corridor

The CAD/ CAE virtual laboratory room at TUCN that can be seen in Figure 2.2.4 has been realized using Insta 360 camera, the captured images undergoing in further processing using Kuula software, allowing the integration of educational materials related to CAD / CAE for the bio-mechatronic components that have been developed within the EMERALD project related to these topics.

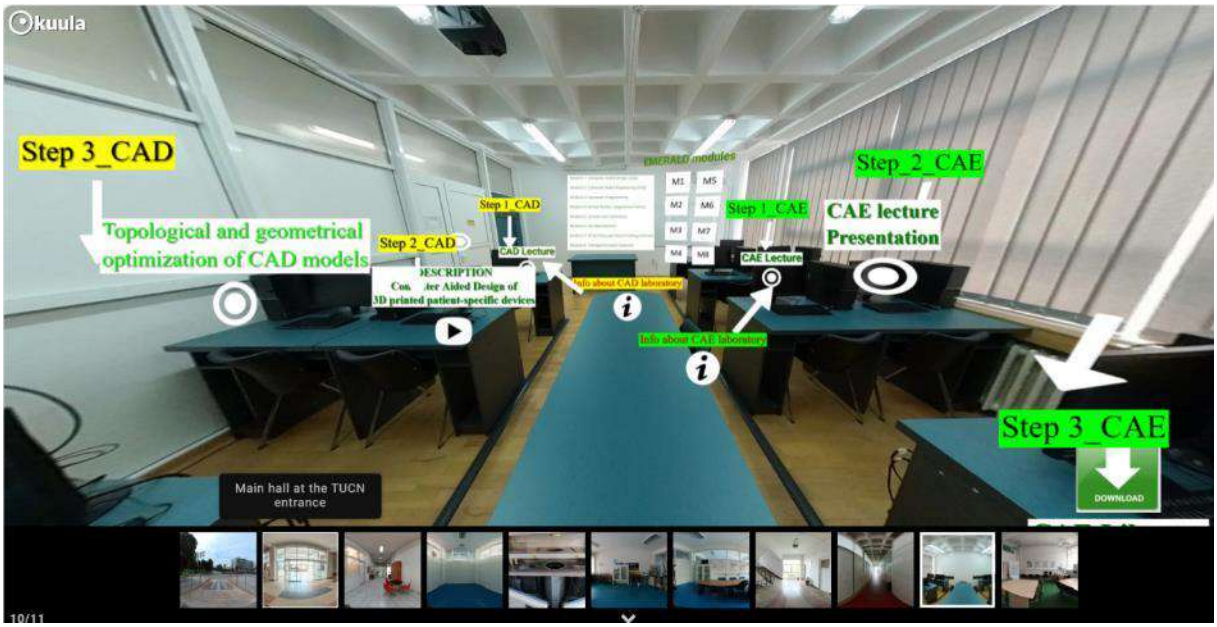


Figure 2.2.4. CAD / CAE laboratory of TUCN

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.2. Structuring of the teaching resources being provided about CAD in the e-learning platform

The e-learning virtual laboratory platform dedicated to the Computer Aided Design (CAD) stage in particular offers an enriched educational experience that is tailored to the design of bio-mechatronic systems destined for people with special needs (with amputated arms) such as robotic arms, orthoses and prostheses, focusing on the necessary steps that are particularly necessary to be followed after the initial 3D scanning process of patients. The main aim of the platform in relation to CAD aims to familiarize the users and facilitate their comprehensive learning by providing them a smooth advancement and gradual progression concerning the teaching materials and resources the users are following and are accessing on the e-learning virtual laboratory platform. In this sense, upon entering the CAD virtual laboratory room, users gain access to a structured curriculum that starts with foundational course materials that cover the basics of CAD, then they have access to highly practical laboratory tutorials, completed with toolkits and instructional videos that are providing the users step by step information data on how they have to do the designing of specific bio-mechatronic components for people with amputated arms (like robotic arms, orthoses, prostheses) and finally users have access to CAD library of models, which corresponds to the models that are being presented in the tutorials, toolkits and instructional videos, along with information for accessing of various CAD software programs that the users can download, replicate the CAD steps they are seeing being made in the instructional materials or modify them in a very stimulative, creative or innovative way, by working further on their own case studies they have been generated in this way by using the EMERALD e-learning virtual laboratory resources.

2.2.3. Step 1 - CAD lecture

Going in much details on this process in order to comprise better the CAD stage related in the conceiving of the bio-mechatronic systems for people with special needs (amputated arms) first step that has to be followed is related to the foundational course materials that cover the basics of CAD, as it is shown in Figure 2.2.5.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

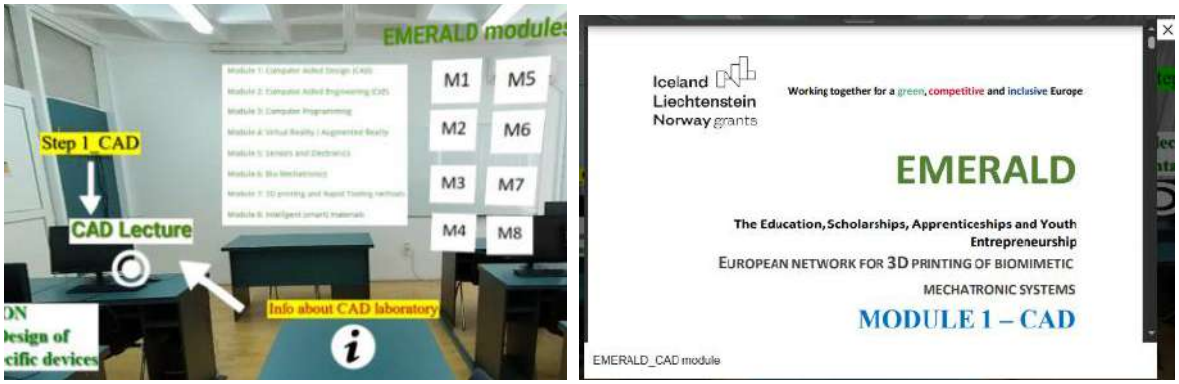


Figure 2.2.5. Step 1 related to CAD stage suggested to be accessed by the users

The CAD lecture resources being provided in the EMERALD e-learning virtual laboratory platform is leading first to the CAD course module that has been produced by the EMERALD consortium in the frame of O1 (by PUT partner), course that can be accessed through the platform, can be visualized or can be downloaded as one may notice in Figure 2.2.5 – see: https://project-emerald.eu/wp-content/uploads/2023/02/EMERALD_IO1_module_1_CAD.pdf.

In order to comprise how bio-mechatronics systems can be designed, it is important first to get familiarized through this teaching resource (course module and lectures) with the basics of CAD and of 3D modelling in general for the beginning as well as with the particularity that biomimetic / bio-mechatronic systems for people with amputated arms (like the ones shown in figure 2.2.6) are assuming to.

Fig. 2.2.6. Examples of biomimetic products

In this context, from the theoretical point of view it is important for anyone to comprise that Computer Aided Design, also known as 3D modeling encompasses various methods, each one being tailored to specific purposes, complexity of the realized models, suitability for certain applications, and the way the objects are being represented in 3D.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

It is highly important to understand all the existing methods, differences in between them, limitations and advantages in order to select the proper one when designing of a bio-mechatronic component (robotic arm, orthosis, prosthesis) for people with special needs is being requested.

First method (and most basic CAD method) that can be used is **Solid Modeling.** Solid modeling is a mathematical approach that is used to represent solid objects in a precise and geometrically accurate manner, ensuring that all surfaces of the object meet correctly, making it an ideal choice for applications such as 3D printing, where geometric accuracy is essential. Solid modeling is relatively user-friendly, allowing users to create 3D objects by combining basic shapes like boxes, cones, cylinders, and spheres. These shapes can be modified, joined, subtracted, or intersected to create more complex solids. Additionally, solid models can be constructed by sweeping a 2D object, typically a closed curve, along a path or revolving it around an axis. This method forms the foundation of modern CAD systems for parametric 3D solid modeling.

Surface modeling, which is an alternative method of working with **Solid Modeling** is a technique that represents objects by defining their outer surfaces. While it is more complex than wireframe modeling, it's not as sophisticated as solid modeling. Surface modeling is commonly employed in CAD systems for purposes like creating illustrations and architectural renderings. Unlike solid modeling, surface models lack the ability to be sliced open and they may not always adhere to strict geometric correctness. To create surfaces, two fundamental methods are typically used: constructing surfaces from curves like splines or directly manipulating surface poles or control points. This method allows for flexibility in shaping the object's outer surface, making it suitable for various visualization purposes.

Hybrid modeling (third possible method to be use) combines wireframe, surface and solid modeling within a single model. This approach offers flexibility, allowing different parts of a model to be represented in different ways based on the specific requirements of the component. It is often used in reverse engineering and medical applications where measured points and surfaces are imported to build a solid model. For example, a surface representing a patient's limb can be used to develop a solid 3D model for a prosthesis or orthosis.

Wireframe modeling (forth method) represents a 3D object as a skeletal structure composed of points, lines, and curves. Unlike solid or surface modeling, wireframe models lack surfaces. This method is often used in combination with other modeling techniques.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Creating a wireframe model involves creating points, lines, curves, and planes and applying transformations such as mirroring, translation, and rotation. While it may be time-consuming due to the need to independently draw and position each object that makes up the wireframe, it serves as a complementary technique for particular applications.

Mesh modeling (fifth method) shown in Figure 2.2.7. deals with point cloud or triangular mesh data. It's not exclusive to CAD systems and is found in various software packages. This method is commonly used in reverse engineering and cleaning up 3D scan data. Mesh processing involves manually or semi-automatically manipulating triangles, filling holes, smoothing surfaces, repairing defects, and removing unwanted

artifacts. Additionally, basic shaping tools are available to make specific manipulations and create new geometries.

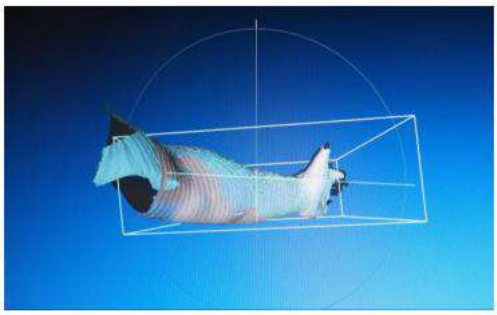


Fig.2.2.7. Mesh modeling

Assembly (6th method) is a process in which complex models of devices are created by assembling models of their individual components or parts. To create an assembly, at least two parts are inserted and linked together using geometric and dimensional constraints. Constraints include line/ plane contact, offset/ distance, angle, concentricity, and symmetry. Assemblies are typically fully parameterized, allowing for control over part arrangement. Parts within an assembly can be edited on the spot, adding new features to the part itself or features specific to the assembly, such as holes through multiple parts or welds between them.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In continuing it is essential to comprise the main software programs that are being used for 3D modeling / CAD (Computer-Aided Design), as well as for mesh modeling, in order to comprise their unique features and capabilities tailored to different applications, complexity of designed models and user preferences. In this context, **CAD Inventor** by Autodesk program is provided as specialized software in mechanical design this program being one of the most popular programs that are being used in education and SMEs due to its affordability and student-friendly versions. Inventor's interface includes a ribbon structure with numerous features and tutorial resources. It supports STL file import for 3D printing and offers automation tools for mechanical and electrical assemblies that are important especially in case of robotic systems or sensorized prostheses.

SolidWorks CAD program (see figure 2.2.8), which is recognized for its user-friendly interface, excels in 3D modeling, technical documentation, FEM simulation, and kinematic analysis that it can provide. SolidWorks CAD program is widely adopted in various industries for its intuitive tab-based interface and knowledge base. However, it demands substantial computing power and may not be ideal for complex surface modeling, especially in the case when irregular or freeform shapes with high precision have to be materialized.

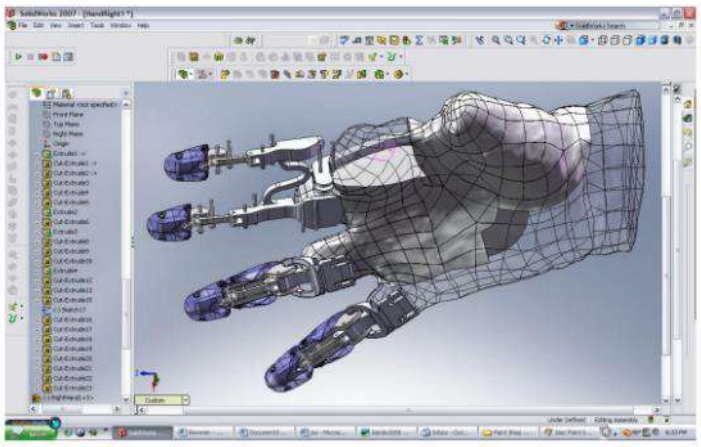


Figure 2.2.8. Example of 3D model realized in SolidWorks

A cloud-based collaborative tool from Autodesk, **Fusion 360** covers the entire product development lifecycle, including CAD modeling, CAM programming, FEM simulation, generative design and 3D printing. Its user-friendly interface supports multiple design methodologies and real-time collaboration. Fusion 360 is free for educational use and startups with limited revenue, being possible to be used for designing of prosthesis like the one shown in Figure 2.2.9.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.2.9. Prosthesis design realized in Fusion 360 software

One most common used open-source software that is dedicated to mesh modeling / processing of 3D triangular meshes, point clouds, and raster objects is **MeshLab** software, which comprises a wide range of tools for editing, cleaning, healing, rendering, and converting meshes of complex components. Meshlab is particularly valuable for aligning 3D scanned data, mesh reconstruction and preparing models for 3D printing. While its interface may be less intuitive for beginners, the extensive documentation and tutorials available make it a powerful tool for advanced mesh processing (see Figure 2.2.10).

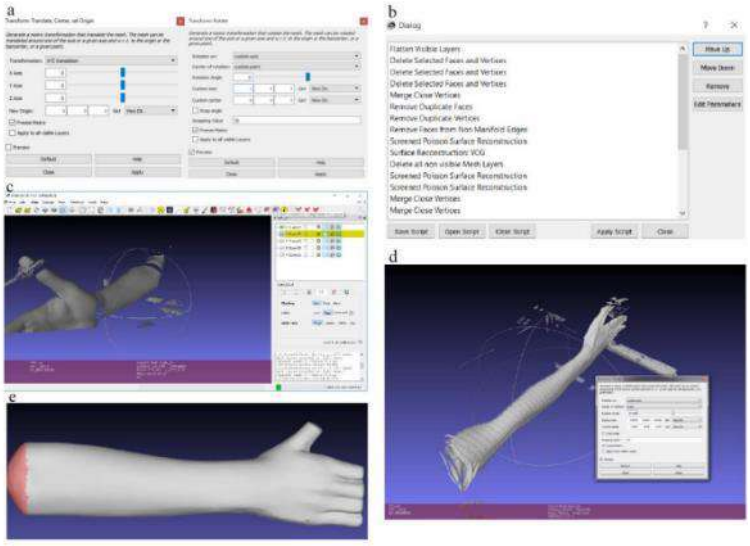


Figure 2.2.10. Processing of a scanned part using Meshlab software

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Last, but not least, primarily being used for 3D data analysis, **GOM Inspect** mesh modeling software is proficient in processing point clouds and geometric meshes. It features a user-friendly interface with tools for hole filling, mesh smoothing, and precise selection, exceling in aligning geometries, generating measurement reports and creating color deviation maps. However, it is important to mention that scripting and automation are only available in the professional version.

In continuing, there are provided few practical examples on the methodology of CAD design of 3D printed biomimetic mechatronic systems and main steps that are needed to be followed in this context, starting with medical diagnosis / consultation: Initial medical consultation that is being performed to comprise better the patient's needs, prescribing of medical products such as orthoses, prostheses, or implants, reverse engineering and measurements using 3D scanning or medical imaging to obtain a basic dataset for design engineering, continuing with designing steps (CAD systems that are used to create a 3D model of the desired biomimetic device, employing various modeling techniques, such as the “shell” approach or the “spline” approach shown in Figure 2.2.11.

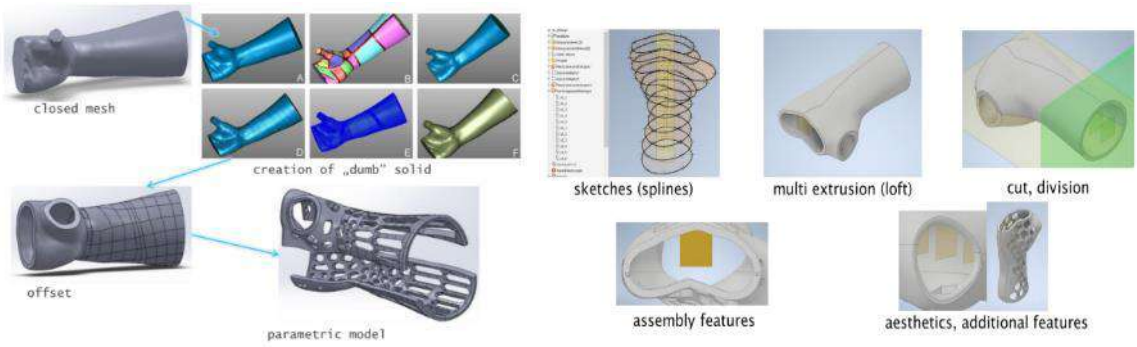


Figure 2.2.11. „Shell” and “spline” approach of the orthoses

The "shell" approach involves directly converting a 3D scan into a solid model, subsequent steps including manually performed operations like offsets, extrusions, cutouts, fillets, and adding holes to shape the solid, essentially "carving" it to match the required anatomical features, while, in contrast, the "spline" approach begins by creating splines or curves based on specific points extracted from a mesh model representing anatomical features, these splines being therefore used to generate a multi-extrusion forming a 3D structure. The resulting basic solid can then be refined by cutting, dividing and adding features using various modeling techniques. The "spline" approach offers more parametric flexibility and customization, making it suitable for accommodating different patient-specific needs.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In continuing the advantages of using automation of medical product design methods, as exemplified by the AutoMedPrint system developed by Poznan University of Technology (PUT) is presented and is well exemplified in how it was used for automatically creating prostheses and limb orthoses for real patients with special needs (amputated arms) – see figure 2.2.12. The AutoMedPrint innovative system developed by PUT leverages 3D printing technology and automation for the designing and production process of which pediatric patients could take real benefit of. By utilizing a 3D scanner, AutoMedPrint streamlines the entire workflow, significantly reducing costs and waiting times for functional prostheses and orthoses. Unlike traditional approaches, this system offers rapid design and production, often delivering the needed devices within days of initial measurements. This breakthrough addresses key challenges in the field, making prosthetic and orthotic solutions more accessible, affordable, and user-friendly for patients, especially children, who often face long wait times and high costs associated with conventional methods.

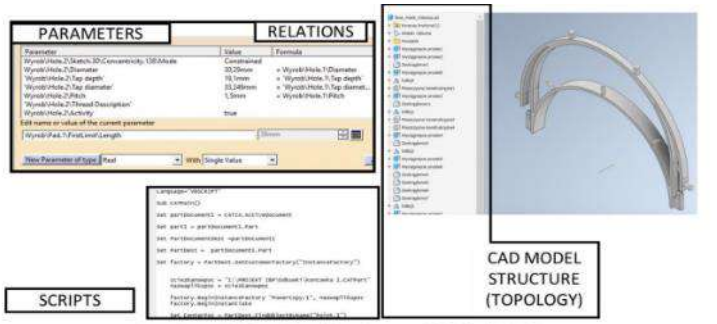


Figure 3.5 Basic ideas of intelligent CAD models [Górski 2021]

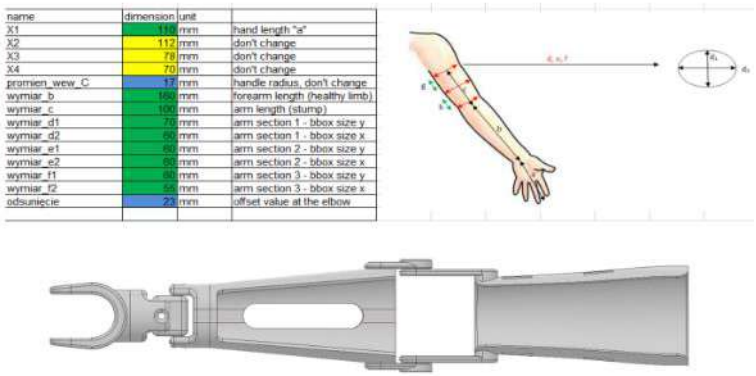


Figure 2.2.12. AutoMedPrint system used for designing of the orthoses and prostheses

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.4. Step 2 - CAD additional lecture presentation

For a better comprising of the AutoMedPrint innovative system developed by PUT and particularities of CAD design for various case studies of different patients with amputated arms, a Powerpoint presentation has been created in the frame of O3 by the EMERALD consortium (PUT partner in particular), this presentation comprising valuable information being integrated within the CAD virtual laboratory room of the e-learning platform, as one may notice in Figure 2.2.13. Presentation can be accessed through the e-learning laboratory platform or can be visualized by accessing the following link: https://drive.google.com/file/d/1z3P4YVdmXNSB09M9rSVa2vNhyC7CzMi_/view

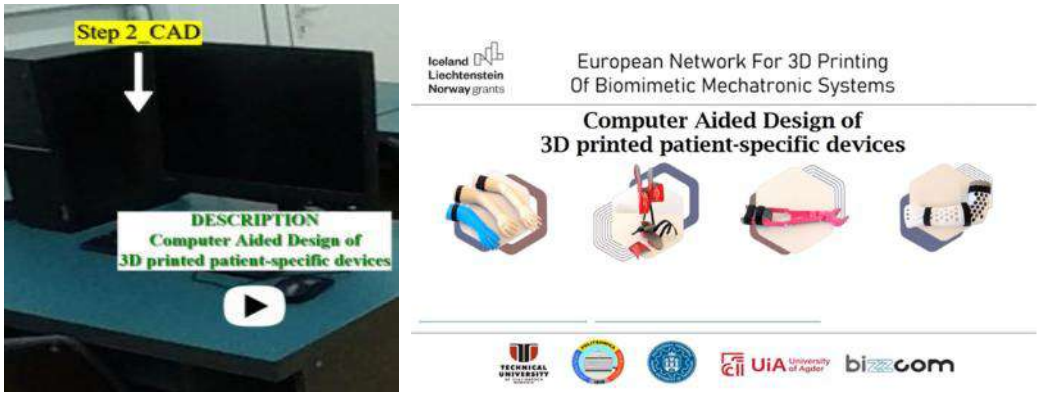


Figure 2.2.13. YouTube presentation realized in completion to CAD course module in the frame of O3

Besides the basic concepts in terms of Design that are presented in the course module, in this video presentation there are emphasized few additional basic concepts of the design, referring to designing engineering in general, engineering to order and individualized design concepts. (see Figure 2.2.14).

Figure 2.2.14. Basic concepts of design. Cleaning and reconstruction methods.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

As one may notice in Figure 2.2.14, Design engineering is referring to activities conducted by engineers to create a new product that addresses a specific need, Engineering-To-Order involves creating of a product directly and specifically for the needs of a given client or a group of clients, while Individualized design pertains to creating a new variant of an existing product that is tailored to meet the requirements of a particular client in the end. Especially in the last case, there are needed lot of processing data and corrections to be realized in the CAD stage, after the 3D scanning process. Some practical solutions that are easy to be understood from visualized images (e.g. deleting of surfaces using a plane", "closing holes with specific surfaces that are generated for this purpose", "mesh repairing using patch surfaces" are provided in the presentation.

Being an innovative method that is used for Automated Design of different types of bio-mechatronic components particularized in concordance with patient needs, in the presentation are provided additional highly useful information about the AutoMedPrint system that has been conceived at Poznan University of Technology, along with important design parametric settings that the students will need further on to use on laboratory work when they will be realizing step by step CAD design of the presented components (bicycle prosthesis, hand prosthesis or orthosis) (see Figure 2.2.15).

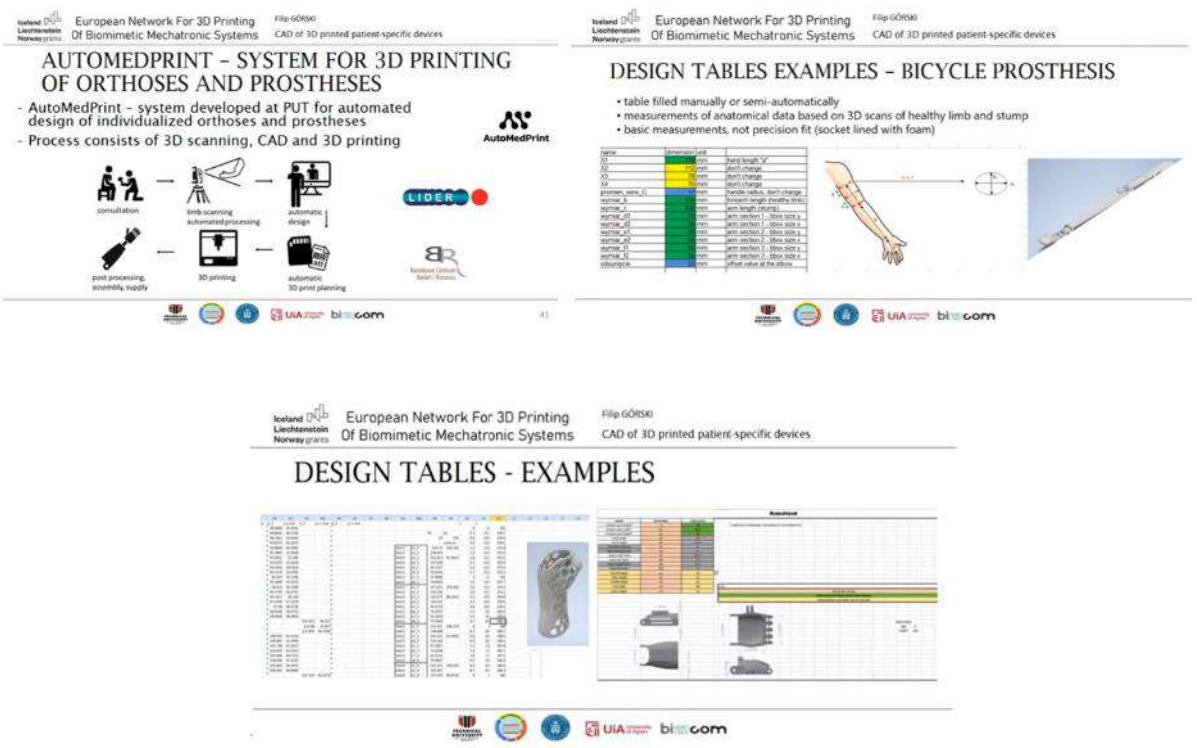


Figure 2.2.15. AutoMedPrint system and CAD settings of bio-mechatronic components

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The AutoMedPrint system realized by PUT is a solution that contains many scripts and programs. Various techniques and languages for programming were employed while building it. The most important are detailed below.

1. Windows application programming, using Visual Basic – in that way, software handling the 3D scanning rig and track was prepared.
2. MeshLab macro programming – XML scripts were used, based on MeshLab original format of writing macros.
3. Excel macro programming – Visual Basic for Applications was used in that context, to create intelligent design tables, extracting data from the scans, automatically processed by MeshLab.
4. Unity visual programming – visual programming methods were employed while creating the GUI part of the AutoMedPrint system, for which Unity engine was used (in 2D mode).
5. Unity C# programming – for 3D applications (product configurators, limb plane selectors, Virtual Reality tutorials etc.), C# programming was extensively used in creating custom scripts.
6. Batch file programming – Windows own language for creating batch files was used in preparing them, for various courses of work (e.g. opening MeshLab and then Excel in a succession, to automatically prepare data for an orthosis).

2.2.5. Step 3 - CAD additional lecture presentation on Topological and geometrical optimization

In completion to the existing CAD lecture module and the supplementary realized presentation, in the frame of O3 an additional course module about Topological and geometrical optimization has been realized by TUCN (see Figure 2.2.16), being recommended to be followed by the users in step 3 – see: https://drive.google.com/file/d/1b0Qc2NgnIQyr6F4CBXBo7D37S-Ala6Nt/view

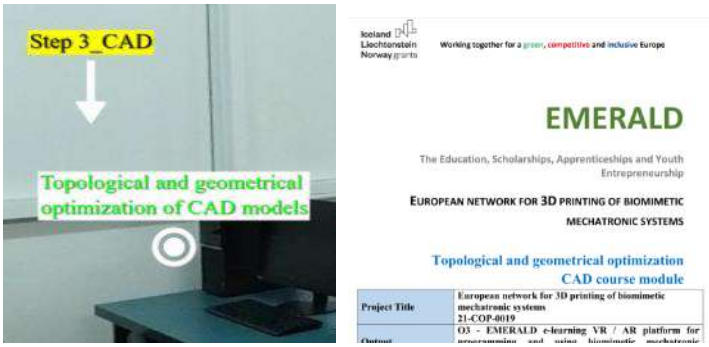


Figure 2.2.16. Course module on Topological and geometrical optimization

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In completion to the Computer Aided Design (CAD), but inter-correlated to this topic it is important to comprise that through the Topological optimization, a topic that it is in trend nowadays, there are some benefits in relation to the designing of bio-mechatronic systems (like robotic arms, orthoses, prostheses, etc.). **Topology optimization** is a structural optimization technique that it is utilized in various medical applications, particularly in the domain of bio-mechatronic systems. It involves optimizing the distribution of material within a product to meet specific performance requirements, ensuring that it efficiently withstands loads and deformations under defined boundary conditions. CAD (Computer-Aided Design) is employed to create an initial product model, while the primary objective of topology optimization is to eliminate material in areas of the product that do not significantly bear loads or deformations, optimizing its functionality. Different optimization algorithms are applied based on design goals and constraints, which can vary from maximizing stiffness to limiting allowable deformation. The result is a complex, naturally-shaped design that removes material in line with the set goals and constraints. This design is further refined in CAD software to create a smooth final product shape. Topology optimization plays a crucial role in enhancing the structural efficiency and performance of bio-mechatronic systems in the field of medicine. Beside the already mentioned advantages, topological optimization offers several additional advantages when it is applied to bio-mechatronic systems such as robotic arms, orthoses, and prostheses for real patients with amputated arms: it enhances structural efficiency by removing unnecessary material while maintaining integrity, resulting in lighter and more agile devices that reduce strain and improve mobility. Customization is facilitated, accommodating unique anatomical variations and patient-specific needs. Material efficiency and sustainability are promoted, contributing to cost-effective solutions. Lattice structures integrated into these systems enhance performance, offering strength, flexibility, and shock absorption.

Reduced production costs, faster prototyping and patient-centered designs further enhance the quality and accessibility of bio-mechatronic devices, ultimately improving the lives of patients. In terms of software programs used specifically for the topological optimization there are few of the most used programs that can be mentioned, such as: nTopology (see Figure 2.2.17): Next-generation Design & Engineering Software (https://ntopology.com/topology-optimization-software/), Altair OptiStruct™ (https://www.altair.com/optistruct/), etc.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

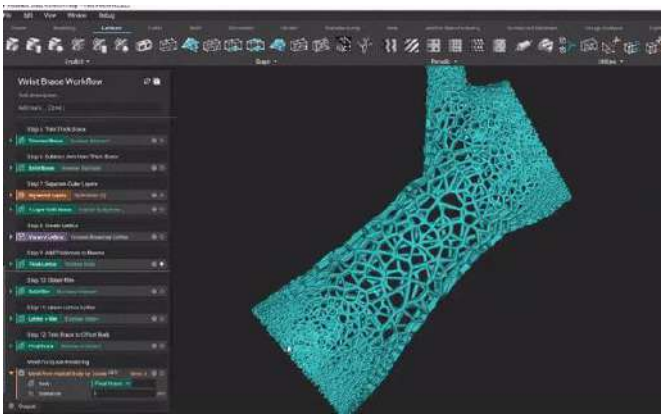


Figure 2.2.17. Lattice structure applied for an orthosis using nTopology software

In case of bio-mechatronic systems, where factors like strength, weight reduction, and biocompatibility are highly important, various types of lattice structures can be considered in close correlation with the type of application to be developed. One choice that it is often used is the Honeycomb lattice structure, favored for its regular geometry, which balances strength and weight efficiency, making it suitable for robotic arms, orthoses, and prostheses. Its hexagonal pattern offers structural integrity, while its inherent lightweight properties help in reducing the overall size and weight of the wearable device. Additionally, there are other types of structures (like Body-Centered Cubic – BCC), known for their optimal material distribution with high mechanical resistance (see Figure 2.2.18).

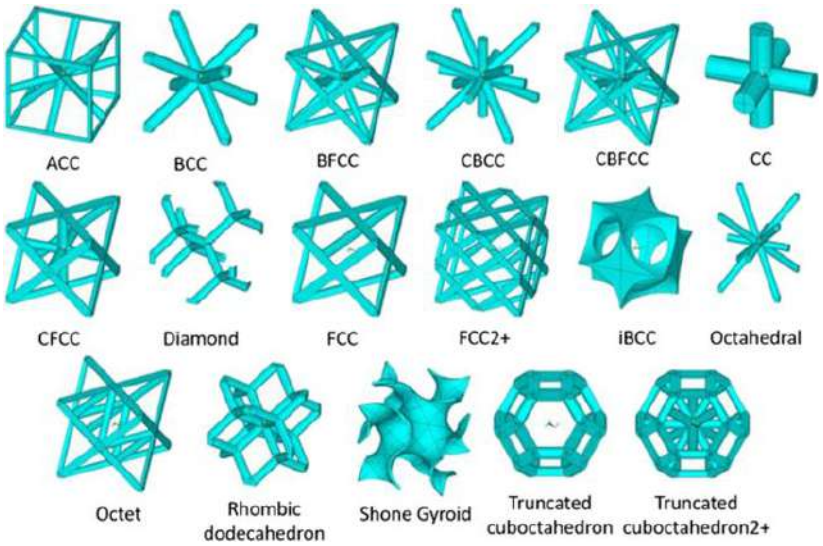


Figure 2.2.18. Types of lattice structures used for topology optimization

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Gyroid lattices, with their intricate patterns provide a blend of strength and lightweight properties, making them valuable for various load-bearing components in bio-mechatronic systems. In contrast, octet lattices excel in energy absorption and impact resistance, rendering them essential for protective gear in bio-mechatronic applications. While the choice of lattice structure depends on specific design requirements, the honeycomb structure stands out as one of the most versatile and used option, offering a quite well balance of structural integrity and weight reduction for bio-mechatronic systems.

In close correlation to the topology optimization, it is highly important to understand the differences between the Curve Based Method (CBM) and Pattern Based Method (PBM) for creating scaffold 3D models in the context of medical applications, including bio-mechatronic systems like robotic arms, orthoses, and prostheses (see figure 2.2.19).

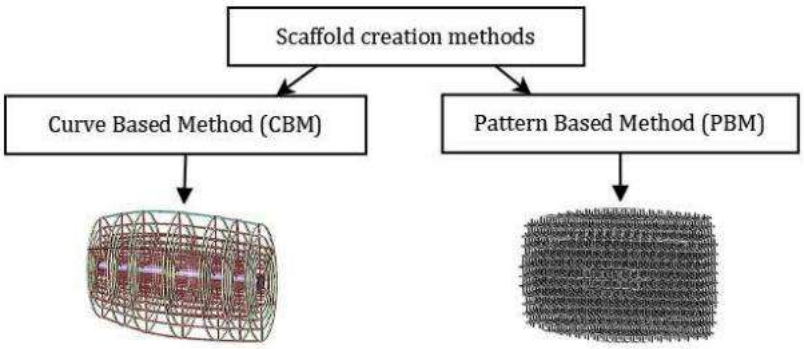


Figure 2.2.19. CBM and PBM methods for designing scaffolds

Actually, in the CBM case, a nucleus parametric model is used as the basic construction element for scaffold architecture, with interpolated splines guiding grid construction. This method involves defining boundary radial splines, creating scaled curves, and using them as support elements for scaffold model construction. In contrast, the PBM method uses a nucleus element to form a basic unit cell, defined as a 3D cross and this unit cell is multiplied throughout the volume model of the part to create a pattern structure. The difference lies in the manner of model construction: CBM uses a nucleus parametric model, while PBM creates a pattern architecture composed of unit cells. Both methods involve three groups of processes: preparation, shared, and method-specific processes. The preparation process defines the initial structure of scaffold components and includes nucleus length and cross-section definition. Shared processes, such as selecting points in the designed area enable

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

the creation of the boundary surface of the missing part of the arm (see Figure 2.2.20). With prosthetics it is very important to create lightweight assisting devices, which have the ability to withstand load, and to adjust to the patient. Topological and shape optimization is very important for prosthetic devices, especially in the case of limb replacements.

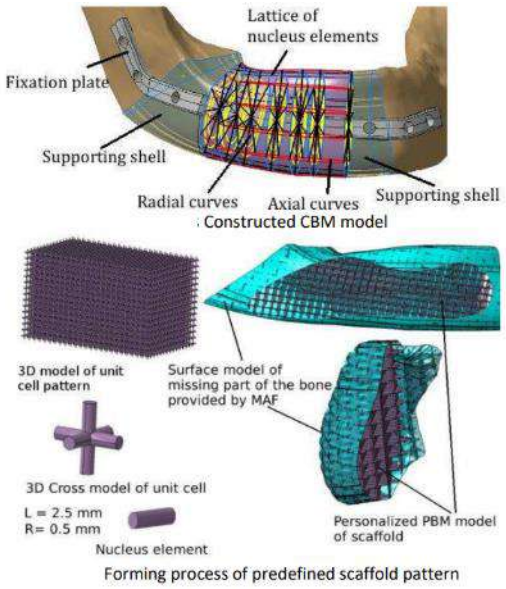


Figure 2.2.20. Creating of bio-mechatronic systems using CBM method

In Figure 2.2.21 is presented a practical case study on which lattice structures have been included and used in case of a real patient that needed a wrist-orthosis, several similar cases being considered also in the case of the EMERALD project in relation to the CAD topic.

Figure 2.2.21. Example of lattice structures integrated into wrist-orthoses

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.6. Step 4 - CAD laboratory work teaching resources

In the next step after the users are getting familiarized with the theoretical aspects related to CAD lectures, they are invited to go through a series of practical teaching resources that are referring to practical laboratory work, in which they are asked to follow step by step teaching materials, to be guided to go through the steps that are necessary for realizing the designing of bio-mechatronic systems (like robotic arms, orthoses, prostheses, etc.) for people with amputated arms (see Figure 2.2.22).

Figure 2.2.22. Set of laboratory educational tools related to the designing of bio-mechatronic systems

For an interactive following of the CAD toolkit laboratory, in the e-learning platform, there have been uploaded CAD models which have been uploaded on a Google drive link that can be accessed through the e-learning platform as one may notice in Figure 2.2.23. - https://drive.google.com/drive/folders/1O3P8_o2D6yNgbTPnTO6setzJYNyzKR47 Accessing the CAD models leads to a description of the model along with one representative image of the model for an easy recognition of the model to be downloaded – all CAD models that were realized in the frame of IO3 for this purpose are provided in step and stl format, being able to be downloaded and further on customized by the users, in order to improve the aesthetics, functionality or simply to improve the design.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

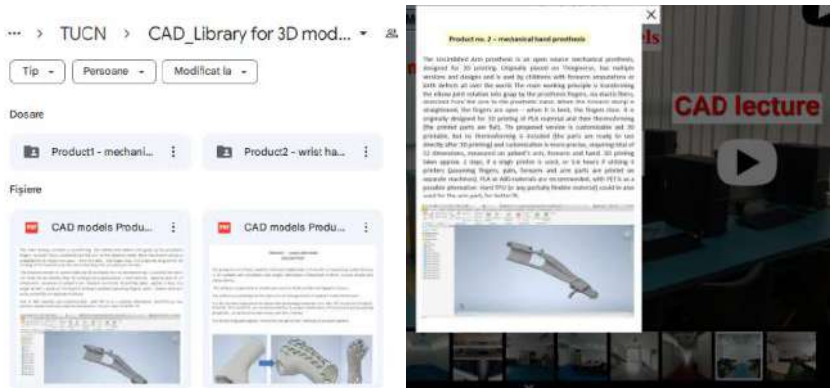


Figure 2.2.23. CAD library of the models and description of CAD models to be downloaded for laboratory practical excercises

One last important thing is necessary for the users before they can proceed with laboratory exercises following the instructions that are being provided in the e-learning platform and this is referring to the CAD software packages that are necessary to be downloaded and installed on the computer / laptop. In terms of CAD software alternatives, links have been incorporated into the e-learning platform (see Figure 2.2.24), providing free licenses or educational licenses for the students: Autodesk Inventor (https://www.autodesk.com/education/students), SolidWorks educational variant (https://www.solidworks.com/product/students) and Mesh Lab (https://www.meshlab.net/), software programs that were used for producing the laboratory educational materials. All these are free resources for the students in particular, they need simply just to register and prove they are students in order to have free access to these software and educational tools.

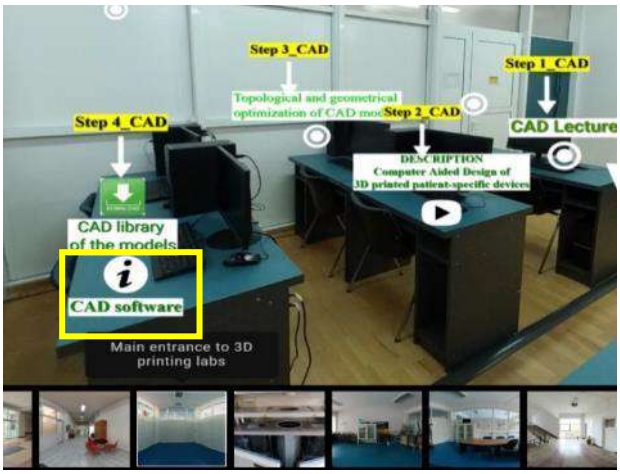


Figure 2.2.24. Software educational licenses for the students to download, install and run with the provided laboratory exercises

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.7. Step 5 – CAD laboratory toolkit

Having these entire aspects well settle, the next necessary thing is to access the resources that are being provided concerning the laboratory work, starting with the toolkit manual (that has been conceived in the frame of O2) and continuing with the additional supportive educational resources that have been provided in the frame of O3 – instructional educational videos, additional YouTube presentations, additional exercises that are being proposed in relation to the CAD models that have been uploaded on the Google drive.

Concerning the CAD toolkit module that has been realized in the frame of O2 provides in high detail all steps that are necessary to be followed in terms of CAD design. The CAD toolkit module can be accessed through the e-learning CAD virtual laboratory room or can be accessed directly on the next following link: https://drive.google.com/file/d/1Z38wpzj5qDYHBoKftHFP6WVeSX9XQxsv/view Accessing of the CAD part of the toolkit module is easier to be made through the e-learning platform since here is presented just the selection that was prepared and was referring strictly to CAD steps that are necessary to be followed in case when a bio-mechatronic system is needed to be prepared. The link related to this part of the toolkit referring to CAD has been uploaded on YouTube channel of EMERALD: https://youtu.be/6D8sj5R5eZ0 (see Figure 2.2.25).

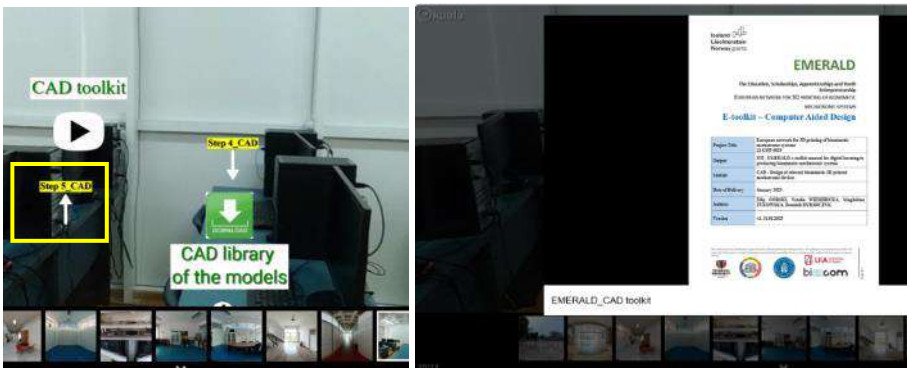


Figure 2.2.25. CAD toolkit part of the manual embeded into the e-learning platform in form of a video

In this part of the toolkit referring to CAD, there is presented on a very high detail how to a CAD model of a bio-mechatronic hand prosthesis (available on the CAD library of the platform) can be built and structured. Therefore in the beginning of the toolkit module, in the introduction section there are given discussions about the innovative design of a smart upper limb prosthesis model, notable for its modular nature.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

This model integrates a multitude of parts, each with standard connectors, into an assembly. Data generated from an Excel file is used to generate prosthetic components that anatomically match the user, as well as to mix and match parts for custom configurations. The idea for this model was developed under the "Automation of design and rapid production of individualized orthopedic and prosthetic products based on anthropometric measurements" project that has been developed at the Poznan University of Technology (Poland).

The main focus of the CAD toolkit module was oriented on the developing of a modular prosthesis, engineered with flexibility to answer to both pediatric and adult needs, with specialized designs for cycling activities. The prosthesis was designed using Mesh Lab software program, which allowed for precision and adaptability in creating the various components. A total of four key components were designed: the forearm section, the end effector or C-handle, the CRS socket, and the connection systems (see Figure 2.2.26.)

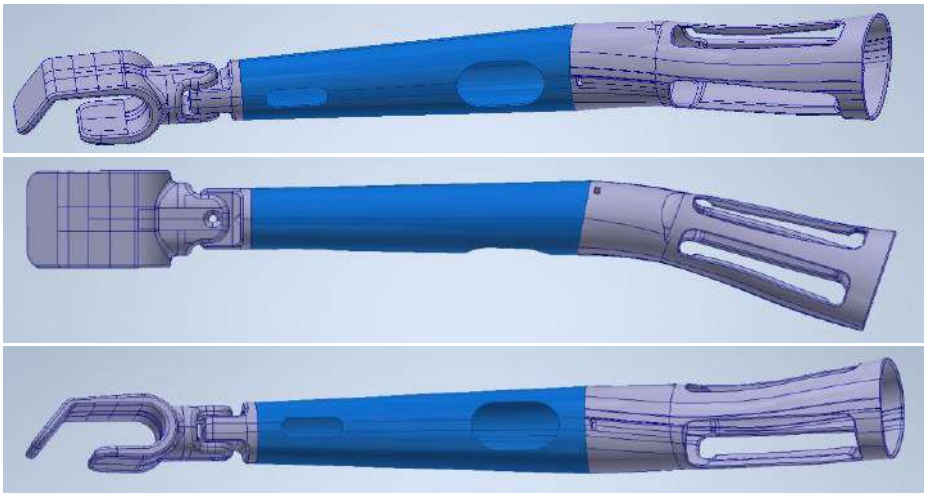


Figure 2.2.26. The final model of the prosthesis realized using MeshLab software.

The design process of the components presented in Figure 2.2.26 utilized an intelligent modeling technique to allow these prostheses to be customized according to individual scans and specific user requirements, like it is explained in the toolkit module. The initial phase involved creating basic shapes in the CAD program, which were then extruded or pulled into three-dimensional forms, like it is shown in Figure 2.2.27. This process was enhanced by introducing personalized adjustments, such as tilting and rounding off edges for comfort and safety.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

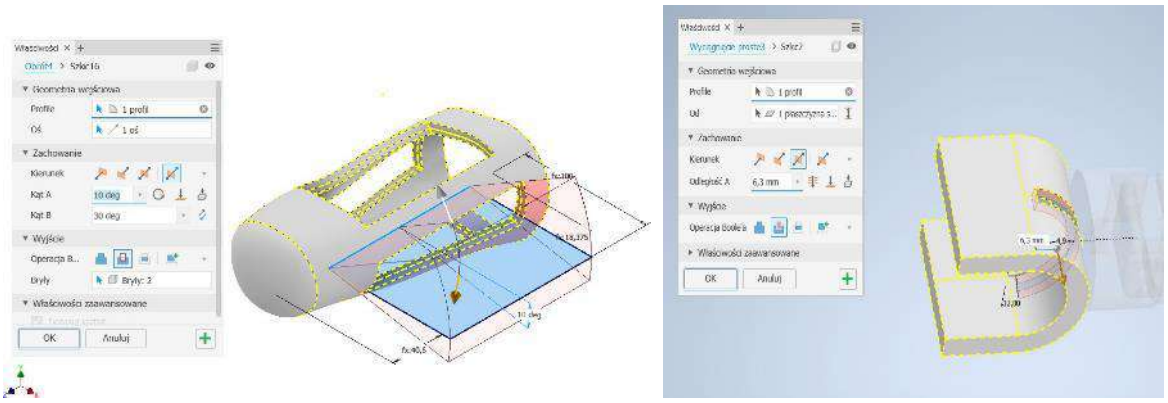


Figure 2.2.27. Creating basic shapes in the CAD program, which were then extruded or pulled into three-dimensional forms

All operations related to the components that were designed are explained step by step how they were made, including the role of some operations and degree of flexibility that is foreseen to be reached in some specific areas. For instance, in the case of the end effector, a C-handle was crafted, which was later modified based on user feedback to increase the grip stability and comfort— aspect that is crucial for controlling a bicycle. The design was refined by adding openings for hardware mounting and adjusting wall inclinations and contours for better ergonomics as well.

The CRS socket underwent a transformation to remove a movable connection that was not suitable for the adult prosthesis due to the increased load during cycling, leading to a fixed and more stable design, aspect that the users can much better understand in the end of the toolkit while following, replicating and realizing the laboratory exercise (see Figure 2.2.28).

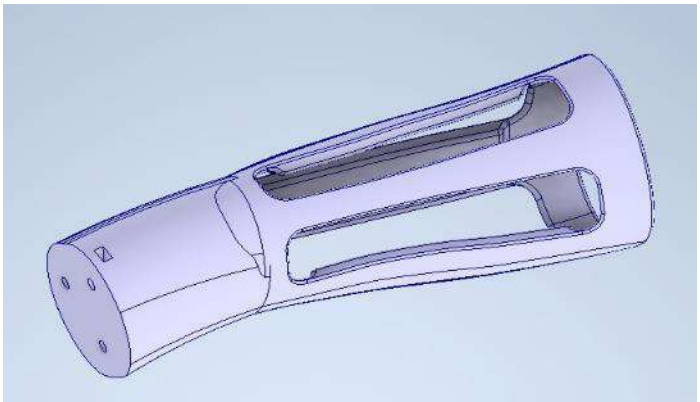


Figure 2.2.28. Removing of movable connection in the CRS socket

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Through the use of this advanced CAD technology, there is provided finally a comprehensive toolkit module for prosthetic creation, enabling a step-by-step approach to developing a tailored fit and adaptability for the patients. This method ensured that the resulting prosthetics were not only fit for purpose but also high in quality and comfort, designed with the precision necessary for everyday use in various activities, including sports and cycling.

2.2.8. Step 6 - CAD laboratory additional support

In addition to the existing toolkit module laboratory that has been created about CAD in the frame of O2, an additional supplementary laboratory support for students has been created in the frame of O3 as one may notice in Figure 2.2.29. CAD laboratory instructions can be accessed by accessing the following link:

https://drive.google.com/file/d/1pxNfFKNg7ZtxVWlqPXwml06yDg4rEC9U/view or in video format on the EMERALD YouTube link: https://www.youtube.com/watch?v=cPh5yP_pJtE

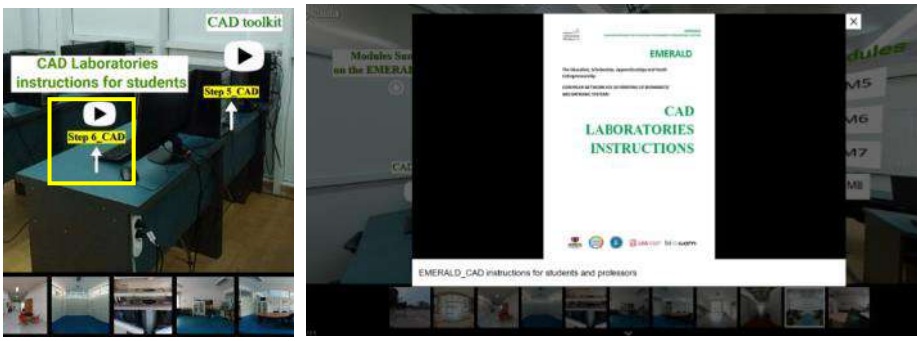


Figure 2.2.29. CAD laboratory instructions created in the frame of O3 by the EMERALD consortium

Within these created tutorials there are presented few examples on how to realize step by step CAD modeling of different bio-mechatronic components (like the ones presented in Figure 2.2.30) using a different CAD program than Mesh Lab and SolidWorks, namely Autodesk Inventor program.

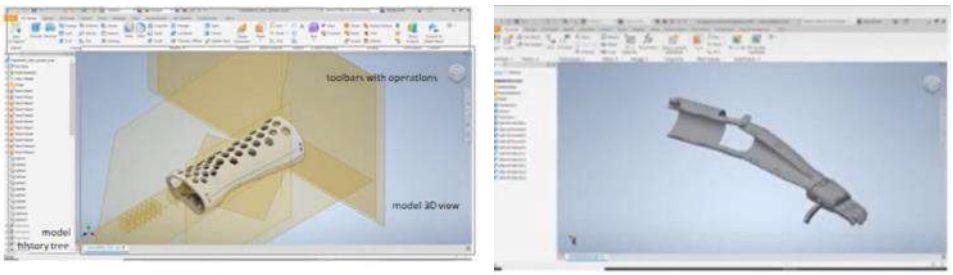


Figure 2.2.30. Bio-mechatronic components (orthoses, prostheses) given in the tutorials

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Parts that are presented in the laboratory instructions are personalized for real patients. Pre-settings of these parts / parametric of the design (CAD settings) needed are provided in the tutorial like shown in Figure 2.2.31 (these parameters have been generated using the AutoMedPrint system).

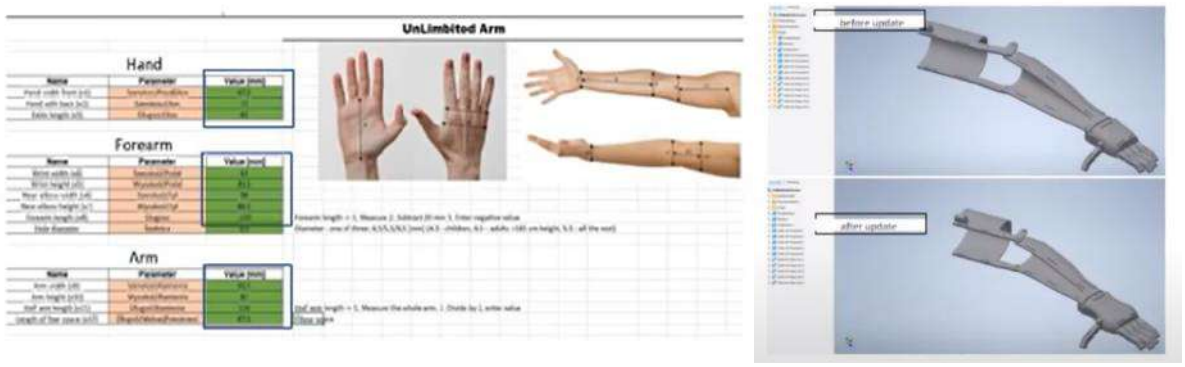


Figure 2.2.31. Parameter settings made using AutoMedPrint system and the updated CAD model with the new settings realized

Similar approach has been considered also in case of the orthosis needed to be customized with the need of a real patient. In this case all CAD necessary steps to realize the orthosis with lattice structure integrated are being provided in the tutorial like shown in Figure 2.2.32.

Figure 2.2.32. Cutting operations realized in CAD design to create the part with lattice structure embedded

Settings related to CAD design of the orthosis and all adjacent operations are presented along with the necessary parameters of cutting and relevant images of operations before and after they are being executed are also explained and provided in details in the tutorial.

At the end of this exercise the users (students) are encouraged to be creative and work on creating their own designed structures taking into consideration several constraints concerning the realized models, with regards to part aesthetics, improving the functionality of the products, flexibility, etc.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.9. Step 7 - CAD good practice examples realized by the students

Such exercises have been made by the students under EMERALD professor's supervision and with their support during several events that were organized within the EMERALD project, such as summer schools or different organized workshops. In order to encourage the users (students) which are accessing the e-learning platform to be stimulative, innovative and creative, within the CAD virtual laboratory of the e-learning virtual platform, there have been included few examples of presentations that were realized by the students, after they went through this learning process and have used the provided teaching resources that have been presented in this chapter above. The gallery containing Powerpoint presentations realized by the students during summer school and workshop activities can be accessed directly through the CAD virtual laboratory of the e-learning platform, as shown in Figure2.2.33. All these presentations have been posted on Google drive platform of EMERALD and can be accessed on the next following link: https://drive.google.com/drive/folders/1fbtGRY3yWfEb6zACgB2ZKsMBkZje06z4

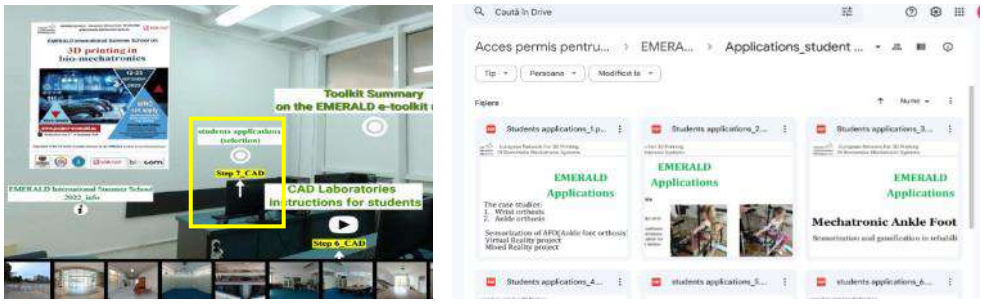


Figure 2.2.33. Examples of work done by students using the CAD virtual laboratory resources of the EMERALD e-learning platform

In Figure 2.2.34 are presented few of the most representative examples of results reached by the students in terms of CAD design as they are provided on Google drive platform.

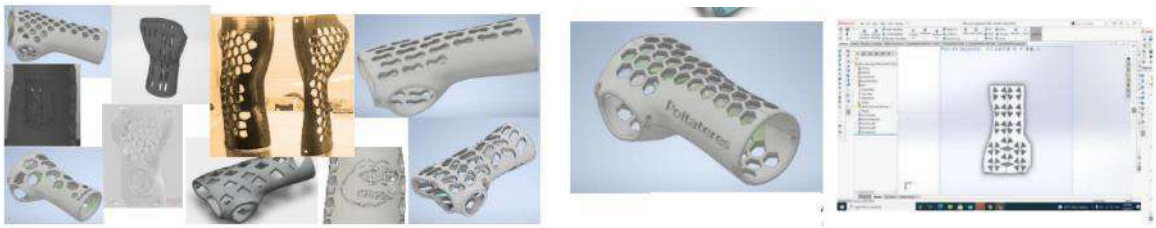


Figure 2.2.34. Examples of CAD models realized by the students following the provided teaching resources

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.10. Conclusions about CAD teaching resources of the e-learning platform

As one may notice concerning the CAD virtual laboratory of the EMERALD e-learning platform , teaching resources that have been provided by the EMERALD consortium aims not just to provide the users (students) only the basics and theoretical knowledge about CAD design, but aims to stimulate them through the provided laboratory educational resources (toolkit laboratory, CAD instructions, tutorials, videos, CAD models, etc.) to get practically involved in designing of specific bio-mechatronic components (like orthoses or prostheses) for people with amputated arms, with the main aim of coming up with innovative / improved solutions realized by the users (students in the end). Laboratory toolkit and provided tutorials, as well as the instructional videos are highly practical, providing the users step by step information data on how they have to do the designing of specific bio-mechatronic components for people with amputated arms (like orthoses, prostheses), guiding in this way the users (students) to go through the essential steps of designing specific models, building on the knowledge acquired from the introductory courses. To follow this plan is easy, since the CAD virtual laboratory of the e-learning platform is housing a CAD library of models, which corresponds to the models that are provided in the tutorials. Students can explore these models, can download them for free along with the necessary CAD software programs (educational variants) and use them as references to better understand the practical steps on how to realize CAD for bio-mechatronic components. After the students (users) are familiarized with the necessary steps that are realized about CAD and the reason why steps are realized to increase flexibility, to improve the aesthetic of the designed products or their functionality, they are encouraged to realize innovative variant / to come up with improved variant, since software programs they are using allow them to be flexible in modifying several CAD parameters, to incorporate various types of lattice structures in close correlation with the aesthetic or functional constraints that are being imposed by the designed products in concordance with the need of the patients and particularity of designed product (orthosis, prosthesis, etc). In conclusion, the e-learning virtual laboratory platform conceived by the EMERALD consortium aims to empower students (users) to seamlessly progress from fundamental CAD knowledge to practical application in the context of bio-mechatronic system design, by fostering a dynamic and interactive learning environment, equipping them with the skills and confidence needed to excel in this specialized field related to the CAD for bio-mechatronic components (orthoses, prostheses, etc.) for people with special needs (with amputated arms) in the end.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.11. Structuring of the teaching resources being provided about CAE in the e-learning platform

Like in has been presented in previous section about Computer Aided Design (CAD) stage, the e-learning virtual laboratory platform dedicated to the Computer Aided Engineering (CAE) stage aims in the same way to familiarize the users with the necessary steps that are required to be followed after the CAD stage in order to validate the shape of the model and type of material from which the bio-mechatronic components (such as robotic arms, orthoses and prostheses) will be made by 3D printing technologies in continuing. The main aim of the platform in relation to CAE aims to familiarize the users and facilitate their comprehensive learning by providing them a smooth advancement and gradual progression concerning the teaching materials and resources the users are following and are accessing on the e-learning virtual laboratory platform like it was presented in case of CAD. In this sense, upon entering the virtual laboratory room (CAE side), users gain access to a structured curriculum that starts with foundational course materials that cover the basics of CAE, then they have access to highly practical laboratory tutorials, completed with toolkits and instructional videos that are providing the users step by step information data on how they have to do the specific steps in terms of CAE in case of bio-mechatronic components for people with amputated arms (like robotic arms, orthoses, prostheses). The users have access to CAE library of models, which corresponds to the models that are being presented in the tutorials, toolkits and instructional videos, along with information for accessing the CAE toolbars of CAE software programs that the users can use to replicate all the necessary CAE steps they are seeing being made in the instructional materials so as they can use them in a very stimulative, creative or innovative way, by working further on their own case studies they have been generated in this way by using the EMERALD e-learning virtual laboratory resources.

2.2.12. Step 1 - CAE lectures

First step that has to be followed is related to the foundational course materials that cover the basics of CAE, as it is shown in Figure 2.2.35 is referring to the CAE course module that has been produced by the EMERALD consortium in the frame of O1 (by TUCN), course that can be accessed through the platform or can be downloaded as one may notice in Figure 2.2.35 – see: https://project-emerald.eu/wp-content/uploads/2023/02/EMERALD_IO1_module_2_CAE.pdf

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

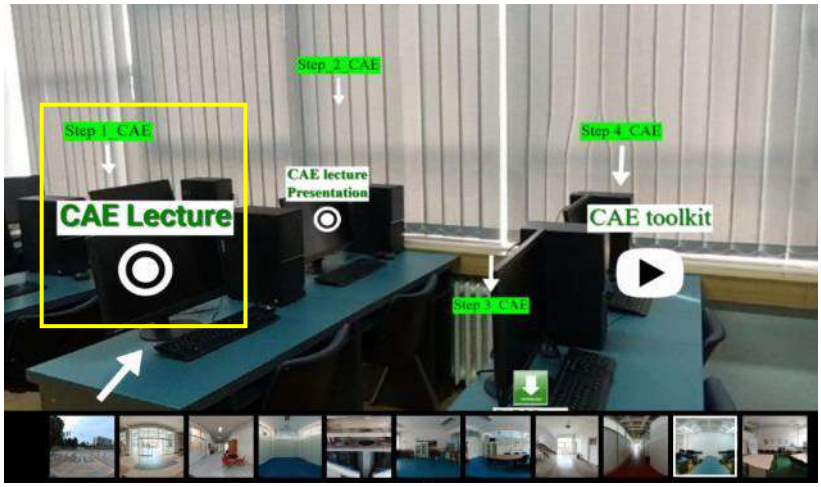


Figure 2.2.35. Accessing of CAE lecture for getting the basics

For the beginning it is important that the users (students) comprise the main conceptual elements and definitions that are related to Computer Aided Engineering / Finite Element Methods, etc. Therefore it is important for the beginning to understand that engineering calculations are key in designing components that meets various requirements like cost, size, reliability, and manufacturing processes. Calculations help determine if a certain component (part) can handle stress, strain, and other constraints. With the evolution of digital computers, two main methods for these calculations have emerged: exact and approximate methods. The finite difference method (FDM), finite element method (FEM), and boundary element method (BEM) are three numerical approximate methods that are prominent in engineering. FDM, which uses a grid to replace the domain of a problem, is simple but limited in handling complex shapes and boundary conditions. FEM is more versatile, allowing complex shapes to be meshed and modeled, but it requires significant data for setup. BEM, the newest method, uses boundary integral equations to reduce the problem size and data needed but struggles with inhomogeneous bodies and those with disproportionate dimensions. Among these, FEM is the most widely adopted due to its flexibility and compatibility with computer-aided design, continuing to evolve to meet diverse engineering needs and integrate with high-performance computing.

The Finite Element Method (FEM) is a powerful tool used to solve engineering problems typically described by complex equations. It works by breaking down a large problem into smaller parts or "elements," making it easier to manage and solve. This method starts by dividing the space the problem takes up into a mesh of these elements, using points called "nodes" as reference.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

These nodes help in constructing polynomials, which approximate the solutions across each element. After setting up these local solutions, FEM combines them into a global solution that covers the entire problem area. This solution tries to make the approximation as close to the real answer as possible by reducing the overall error. FEM is especially good at solving elasticity problems, which involve materials that stretch or compress. The method follows a series of steps for these problems, including choosing the right element types, creating a mesh, and constructing a potential energy approximation. It then minimizes the potential energy to produce a set of algebraic equations. Solving these equations gives the values for the problem's unknowns at the nodes, which FEM uses to create a comprehensive approximation of the solution over the mesh. The process of setting up and solving problems with FEM has been greatly improved by modern software, which automates many of the steps. These programs can create the mesh, apply forces and constraints, and solve the equations, often integrating with CAD programs to streamline the process. They also help engineers to analyze and interpret the results by providing visual representations of the data. In practice, using FEM allows engineers to tackle a wide range of problems by simplifying and automating complex calculations.

When employing the Finite Element Method (FEM), users must judiciously balance the precision of their numerical solutions against the required computational effort. The initial phase in FEM involves discretizing the problem domain, which necessitates decisions about the types, sizes, and numbers of finite elements. Typically, more elements in the mesh mean better solution accuracy, but also a larger system of equations and higher computational demands. It's crucial for analysts to apply their theoretical knowledge to optimize the mesh, refining it in areas with sharp variations and keeping it coarser where changes are smoother. The fidelity of the solution is not only a factor of mesh density but also the mathematical characteristics of the chosen finite element. A misstep in element selection can lead to imprecise outcomes. Common errors at this stage are usually due to a lack of understanding of the underlying problem theory or the mathematical properties of the finite elements used.

Finite elements are categorized primarily by dimensionality into one-, two-, or three-dimensional types (like shown in Figure 2.2.36), which can be simplistic for capturing all element features such as the polynomial approximation degree.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

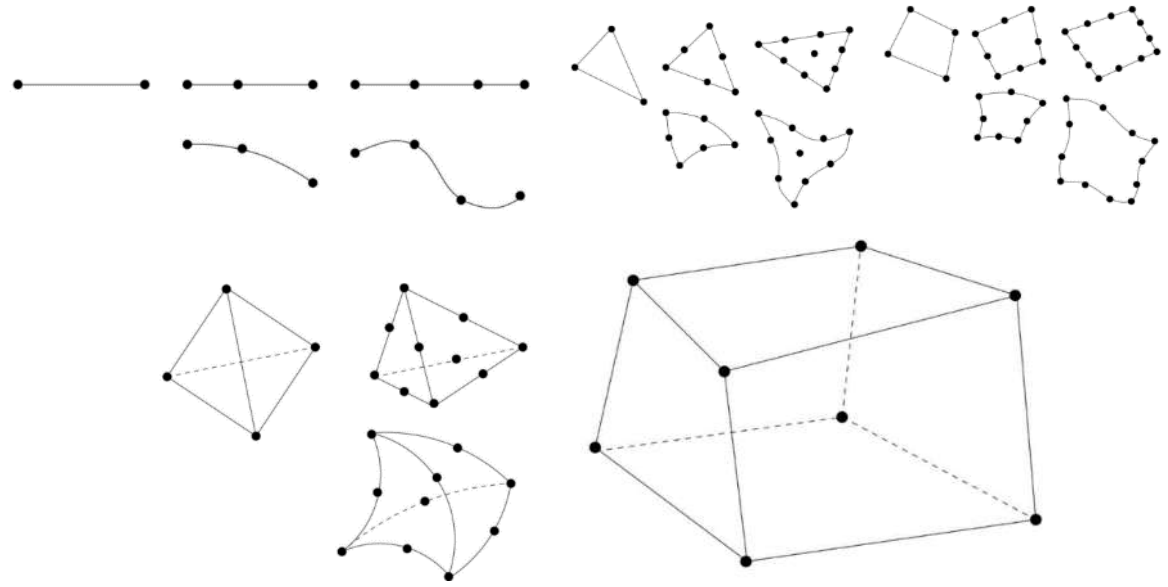


Figure 2.2.36. one-, two-, or three-dimensional elements

Subclasses within these include first-order or linear elements, second-order or quadratic, and third-order or cubic elements, with the latter two allowing for both end and internal nodes. In practice, elements with a polynomial degree higher than three are rarely used due to their computational intensity. In practical terms, for two-dimensional problems, bilinear quadrilateral elements are often chosen over linear triangular ones due to their higher-degree polynomial approximations, which can offer more precise solutions with a moderate increase in nodes. Similarly, for three-dimensional problems, trilinear hexahedral elements are commonly preferred to linear tetrahedral ones, as they offer improved accuracy for an acceptable increase in computational effort. However, elements with a polynomial approximation of the first degree are typically avoided in practical applications to prevent poor solutions. Ultimately, while higher-degree polynomial approximations can enhance accuracy, they also result in a greater number of element nodes, thereby raising the computational burden. The challenge lies in selecting finite elements that ensure accurate results without unnecessarily taxing computational resources. This decision-making process must weigh the complexity and expected precision against the effort and time available for analysis.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In order to exemplify the theoretical aspects provided above, one Finite Element Analysis (FEA), which consists in a critical computational tool for engineers and designers, allowing them to simulate and predict the response of materials and structures under various conditions is provided for the case of a wrist hand orthosis shown in Figure 2.2.37.

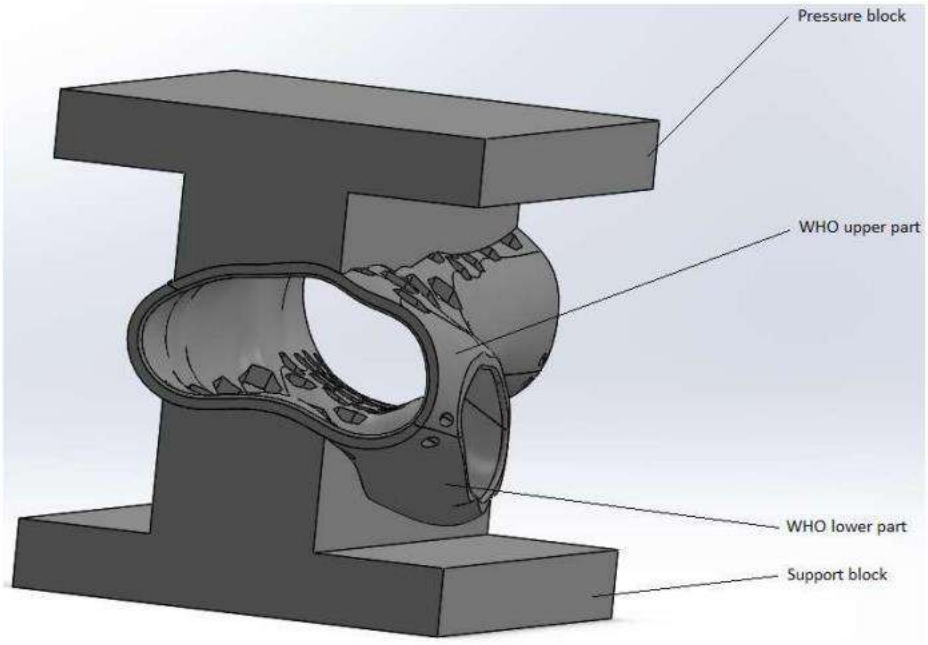


Figure 2.2.37. Wrist hand orthosis and basics of the realized FEA

In the specific case study presented, FEA was applied using SolidWorks Simulation to analyze the orthosis—a medical device designed to support or correct the function of a limb of a patient. The analysis aimed to determine the stress distribution and deformation experienced by the orthosis when it is subjected to different levels of normal force like shown in Figure 2.2.38, which is essential for ensuring its effectiveness and comfort for the user.

In continuing is essential to understand the main steps that a Finite Element Analysis of a component (part) is assuming to.

As one may notice in Figure 2.2.39, the first step in the process involves defining the material properties of the orthosis within SolidWorks (ABS material has been selected in the presented case), ensuring that the simulation accurately reflects the physical behavior of the device under load.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

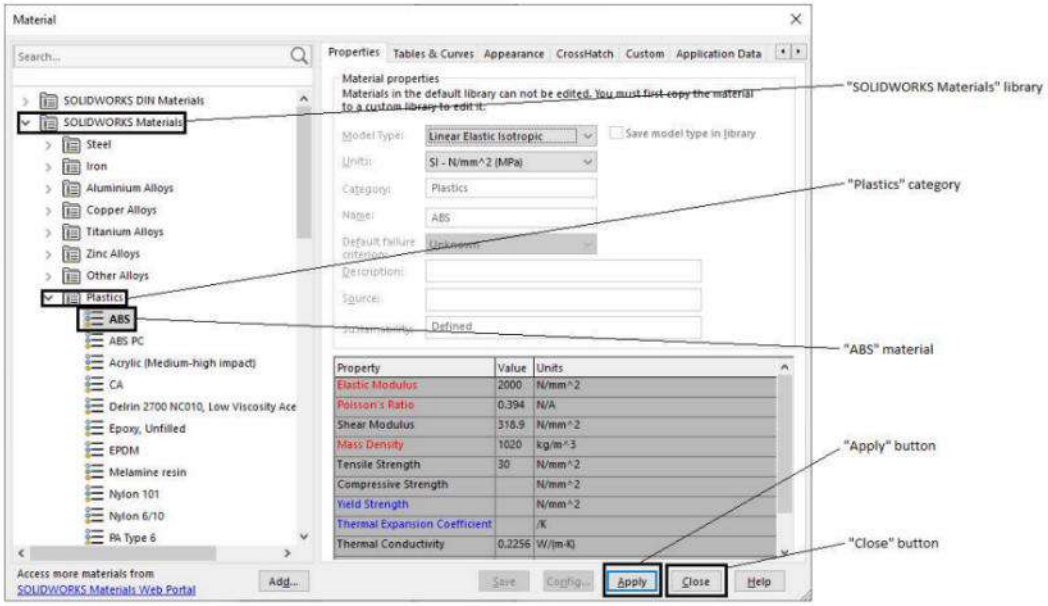


Figure 2.2.38. Defining of the main characteristics of the ABS material for the Finite Element Analysis

This is followed by fixing the lower face of the orthosis to mimic the constraint it would experience in actual use. A series of external loads are then applied, beginning with a default normal force of 1 Newton to set up the condition, which will later be adjusted to represent various load cases.

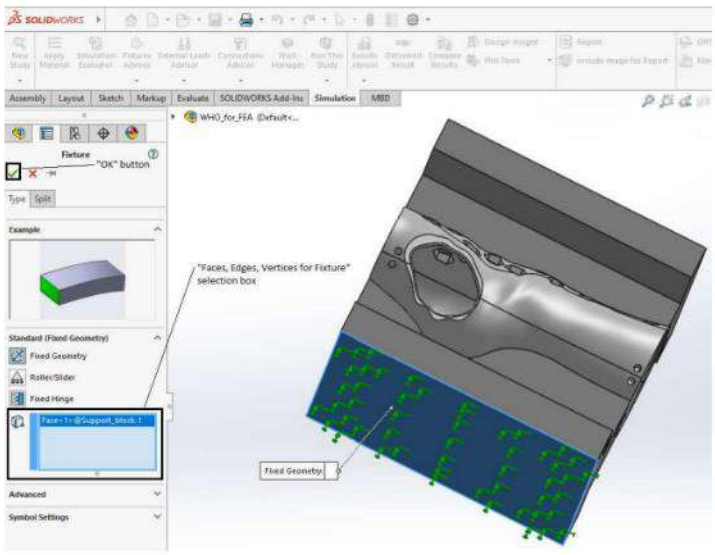


Figure 2.2.39. Constraints that are imposed in the Finite Element Analysis

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

After setting the materials and constraints, attention is turned to the mesh generation—a vital step in any FEA like shown in Figure 2.2.40. A curvature-based mesh was chosen in this case due to the irregular boundaries of the orthosis and specific mesh parameters were defined, including maximum and minimum element sizes, to ensure the mesh's fineness can capture the geometry's nuances and the stress concentrations accurately. Default settings were modified to employ a meshing algorithm tailored to the orthosis's unique shape, enhancing the precision of the subsequent simulation results.

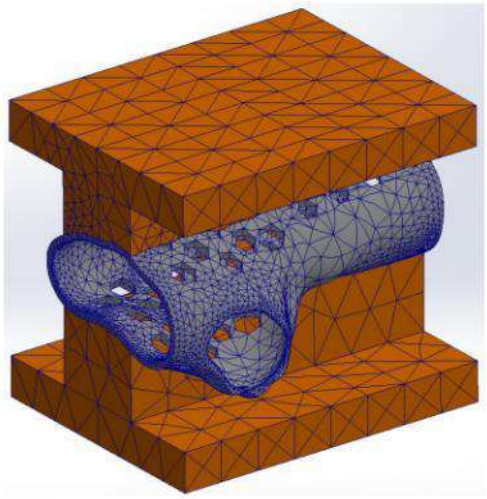


Figure 2.2.40. Generating the mesh for the Finite Element Analysis

Following mesh generation, the Load Case Manager was used to define multiple scenarios, each representing a different load level that the orthosis may encounter. These range from no load to a maximum of 4000 N, being applied incrementally across nine load cases. This step is essential for evaluating the design's performance across the entire expected range of forces during usage. In addition to stress analysis, sensors are configured to monitor specific results, like the von Mises stress across critical components and the deflection experienced by the orthosis. These sensors were set to track the maximum values within selected entities of the model, providing focused feedback on potential failure points or areas of excessive deformation (see Figure 2.2.41).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

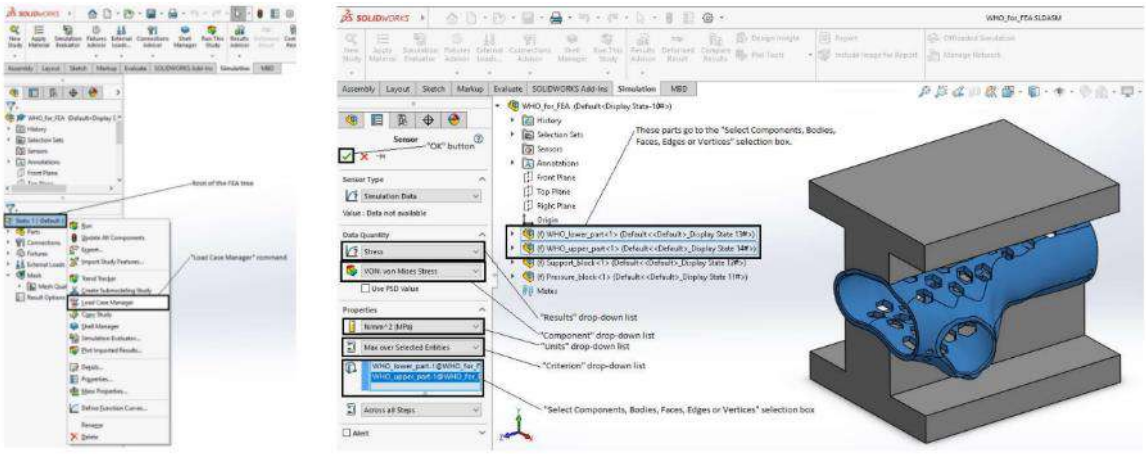


Figure 2.2.41. Load case manager and sensor definition realized for the Finite Element Analysis

Finally, the prepared model is run through SolidWorks Simulation's solver, executing the finite element analysis across all defined load cases. This step culminates in a comprehensive assessment of the orthosis's performance, highlighting the resilience and weak points of the design under physiological loading conditions. The output from the solver offers invaluable insights that can inform any necessary design modifications to enhance the device's safety, efficacy, and comfort before it reaches the end user. Upon completion of the finite element analysis in SolidWorks Simulation, the interpretation of numerical results is facilitated by the "Results View" tab (Figure 2.2.42).

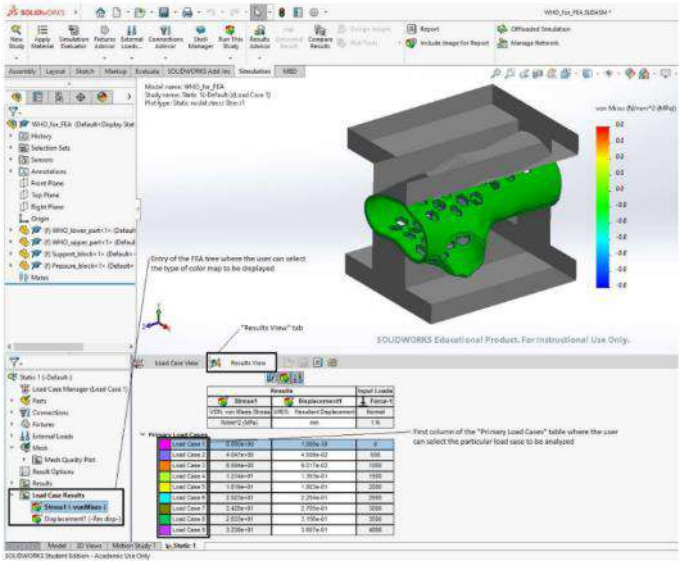


Figure 2.2.42. Visualizing of the results reached for the Finite Element Analysis that is being realized

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The solver's output, visualized as a color map, displays the distribution of von Mises stress for various load cases, with the capability for the user to switch between them for comparison (see Figure 2.2.43). Initially, the support and pressure blocks appear gray, indicating no stress since they are considered rigid bodies and thus irrelevant for stress calculations. These blocks are typically hidden to clear the view for stress and deflection analysis of more critical areas of the orthosis.

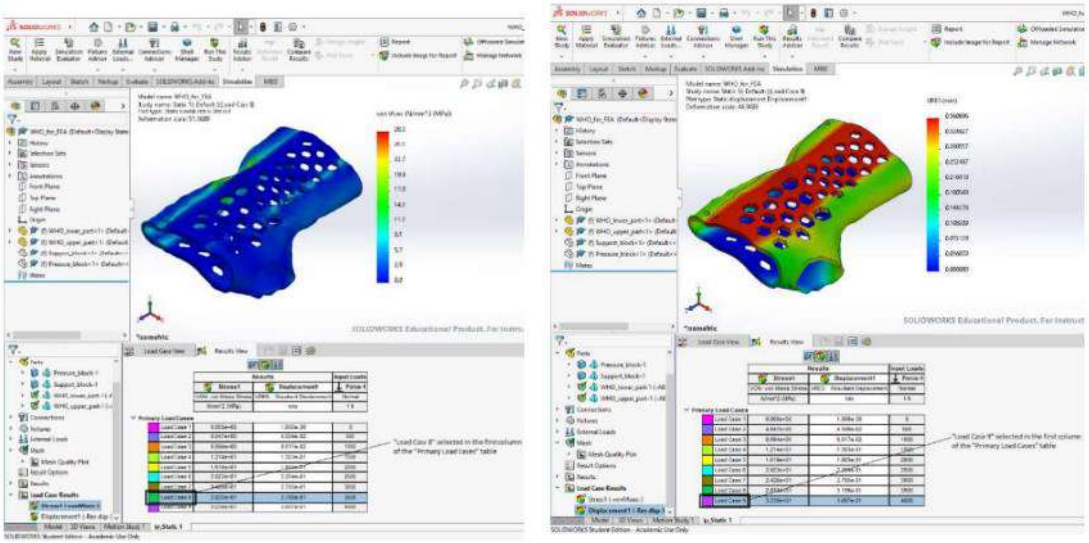


Figure 2.2.43. Distribution of the von Mises stress for various load cases

The simulation process involves adjusting the visualization settings to better examine the stress distribution and deflections for each load case by hiding and showing different components as needed. For instance, the exclusion of support structures from the display reveals the stress and deflection outcomes more clearly for the essential parts of the orthosis. This step is crucial for assessing the device's response to varying forces, which are analyzed by observing changes in color intensity corresponding to the stress levels and deflections across the orthosis in the simulation. The color maps for the eighth and ninth load cases clearly illustrate how stress and deflection increase with greater compression forces, culminating in a comprehensive table and corresponding graphs that present maximum stress and deflection against the applied forces. The linear relationship between the load applied and the resulting stress and deflection is plotted, demonstrating the material's response under increasing forces. This linearity is represented mathematically through regression equations, allowing for the prediction of stress and deflection for any given force within the analyzed range (see Figure 2.2.44).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

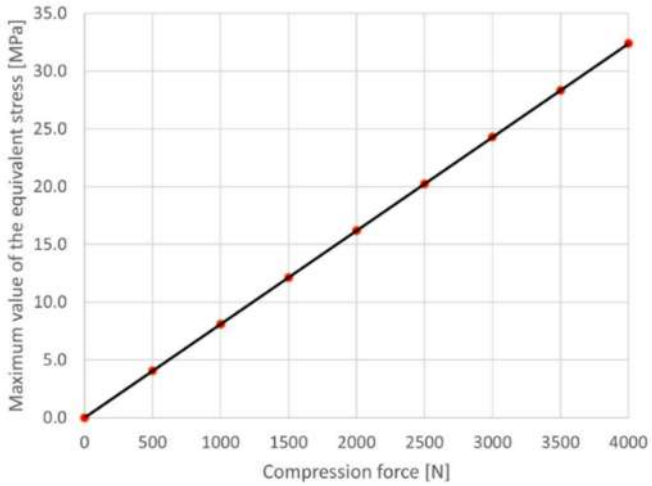


Figure 2.2.44. Plotting of the equivalent stress versus the compression force considered in the Finite Element Analysis

Critical analysis of the data shows that the orthosis can withstand significant loads, far exceeding the typical forces exerted during patient use. However, a compression force of approximately 3706 N is identified as the critical load beyond which the stress in the ABS material of the orthosis reaches its tensile strength limit, as sourced from the SolidWorks Materials library. This suggests that the design is robust for its intended application, yet further tests, such as a three-point bending simulation, are advised to fully validate the orthosis's structural integrity across a broader range of real-world conditions. The comprehensive analysis ensures not just the device's functionality but also its safety and reliability for patient use in the end.

2.2.13. Step 2 - CAE lecture additional presentation

In addition to the course lecture that has been realized by the EMERALD consortium in the frame of O1, one CAE lecture Powerpoint presentation has been prepared by TUCN in the frame of O3, aiming to familiarize the users (students) with similar case studies on which Computer Aided Engineering (CAE) methods were used for several case studies of real patients that needed support. The presentation can be accessed through the CAE laboratory of the EMERALD e-learning platform as one may notice in Figure 2.2.45 or by accessing the following link: https://drive.google.com/file/d/1m3X4iTvMDCz-Uskt8MyMZF-rkMX-qn-t/view

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

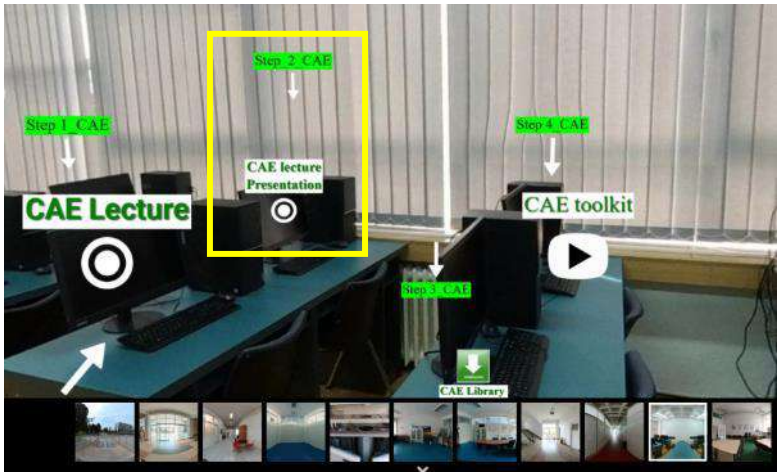


Figure 2.2.45. Additional CAE lecture presentation prepared by TUCN in the frame of O3

After providing some basics about CAE and FEA principles in general, within the realized presentation there are provided several types of professional CAE software programs that are used widely on the market (like ABAQUS, ANSYS, etc.) along with steps that are necessary to be followed for these types of analyses (the steps being similar to the ones provided in the CAE lecture presented in the preamble of this chapter), but for different concrete and particular case studies (like for robotic arms, bone structures or real implants) made of different types of materials (metallic ones like titanium or biocompatible materials like PEEK), with lattice structures being taken into consideration in few cases according to the type of application that has been subjected for the Finite Element Analysis.

Aspects related to biomechanical design linked with mathematical calculus are provided like shown in Figure 2.2.46.

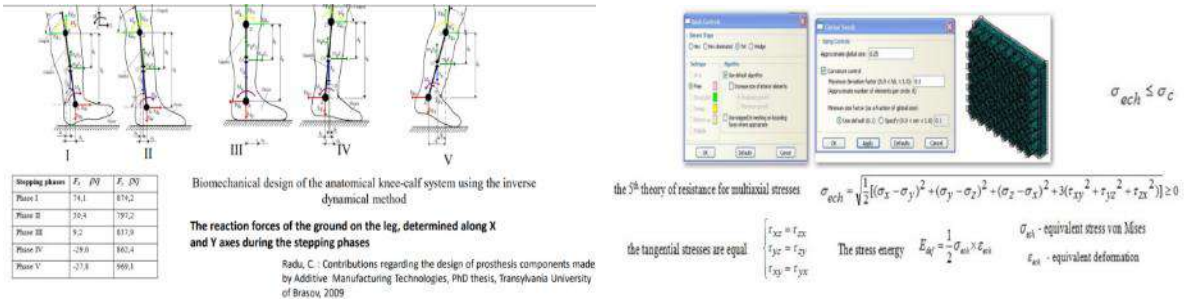


Figure 2.2.46. Biomechanical design and mathematical calculus for determining the admissible stress

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Concrete steps of the analyses linked with highly practical results that were reached in the end for biomedical domain, proving the importance of the Computer Aided Engineering / Finite Element Analysis in the chain of developing of a real product aimed to support people with special needs are being included in the presentation (as one may notice in Figure 2.2.47)

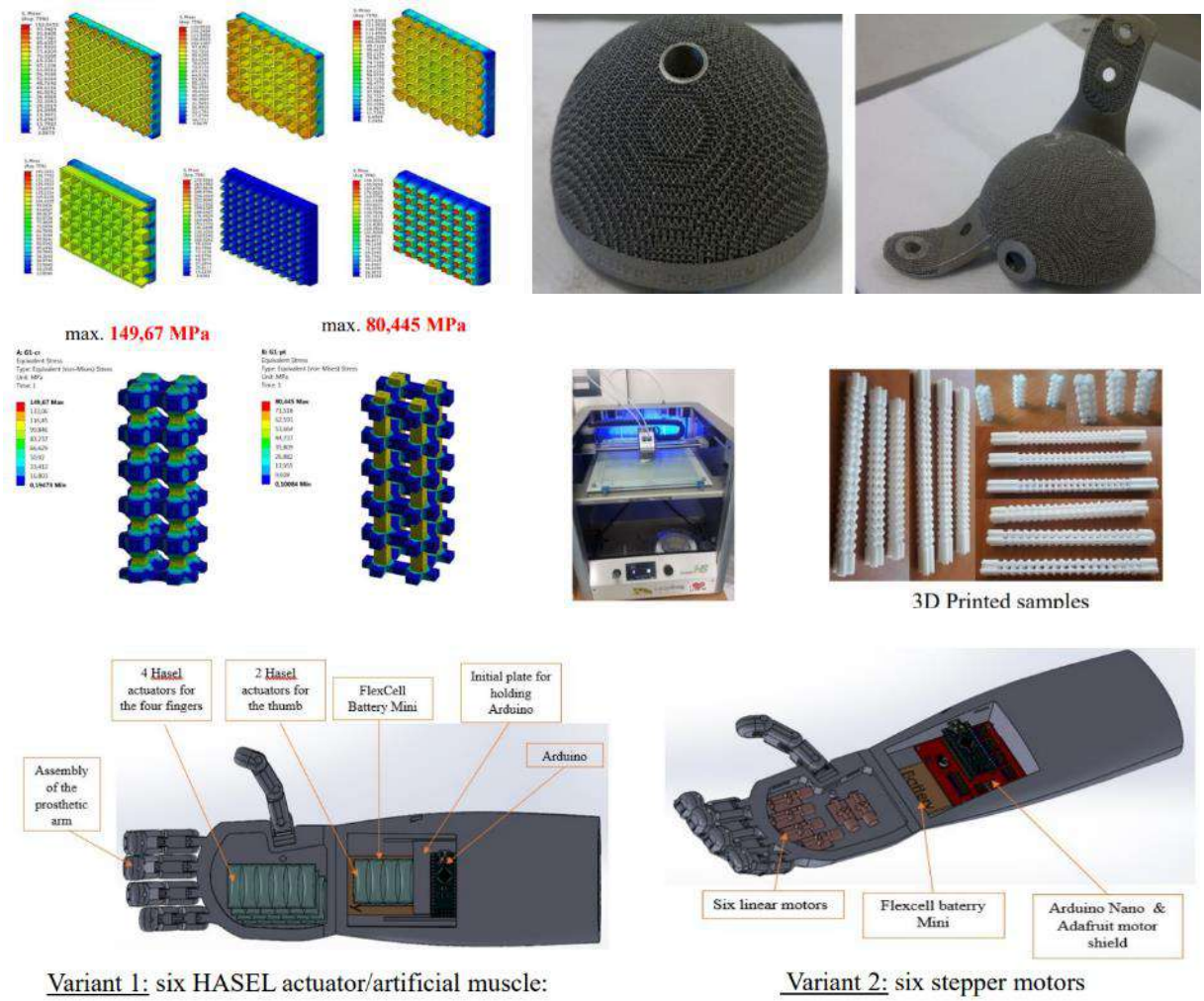


Figure 2.2.47. Examples of CAE made analyses for supporting real patient with special needs

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Besides providing the main steps of the made Finite Element Analyses for different concrete case studies (in Figure 2.2.47 there are presented just a selection), the main aim is for the users (students) to get highly motivated by the models and the examples they are seeing in the presentation, as well as to understand the role of the made analyses in selecting the adequate materials from which the parts are about to be 3D printed. Interpretation of data reached in the realized CAE analyses finally has lead in all cases to the selection of one type of material (e.g. TiAl6V4) in detriment of another (TiAl6Nb7) for the realized cases or validating of a type of lattice structure (cell) like rhombic in detriment of the other alternatives (like hexagonal, pyramidal, square, etc.) all these being proved through the realized Computer Aided Engineering (CAE) made analyses.

2.2.14. Step 3 - CAE laboratory work teaching resources

In terms of performing the CAE analyses, there has been created for the users (like in case of CAD) one CAE library of the models (in "step" format") that the users (students) can have access and can download on their laptops / computers along with models with CAE analyses performed, which the users (students) can open in the SolidWorks program. CAE library with the realized models can be accessed through the CAE virtual laboratory of the e-learning platform as one may notice in Figure 2.2.48 or by accessing the files directly on Google drive on the following link: https://drive.google.com/drive/folders/1ahUMZa8a-pCw1NTseSJbodygj_KPnYYM

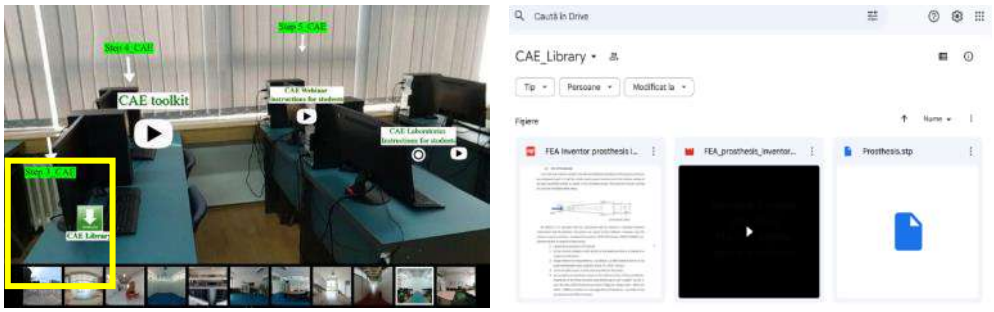


Figure 2.2.48. Accessing of the CAE library through the e-learning platform or directly on Google drive

In terms of software programs that the CAE analyses can be performed by the users (students) the main software programs to be used are Autodesk Inventor and SolidWorks Simulation – same software programs that have been used for CAD and students have previously installed on their laptops (these programs have specific dedicated FEA modules incorporated into the programs).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.15. Step 4 - CAE laboratory toolkit

Having all steps established, the next step is to access the toolkit module that has been produced in the frame of O2 (CAE section) through which users (students) can follow the instructions step by step, reading and following the provided indications. CAE toolkit instructions can be accessed directly through the platform as indicated in Figure 2.2.49 or on the following link: https://drive.google.com/file/d/1Z38wpzj5qDYHBoKftHFP6WVeSX9XQxsv/view

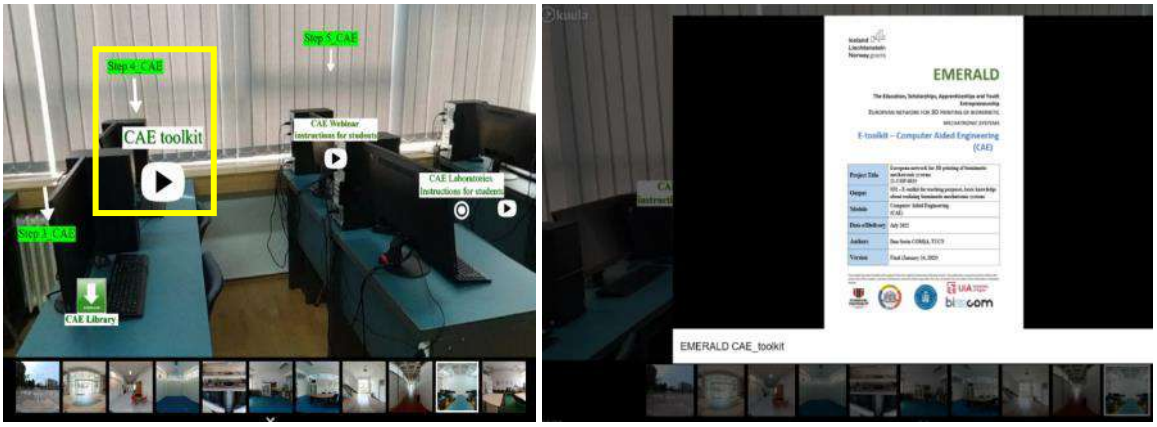


Figure 2.2.49. Toolkit instructions on CAE

The provided description in the toolkit module concerning the computer-aided engineering (CAE) analysis, specifically using SolidWorks Simulation was oriented on the analysis of upper-limb prosthesis that has been subjected to a tensile test (see Figure 2.2.50). The main aim of the analyses was focused on determining of its strength and deformation characteristics under various traction forces. The prosthesis in question was set to be made from PETG material, a choice likely due to its desirable properties for such medical applications. Additionally, to determine the response of the prosthesis, sensors were set up within the software to measure variables such as the von Mises equivalent stress and the deformation of the entire finite element model (FEA model) of the prosthesis. The steps of the tensile test analysis for the upper-limb prosthesis within the CAE environment of SolidWorks Simulation began with the careful definition of material properties.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The chosen material, PETG, was defined in the simulation based on its yield strength, modulus of elasticity, and other relevant mechanical properties, as cataloged in the software's material library. This initial step is critical as it determines how the material will behave under the simulated load conditions.

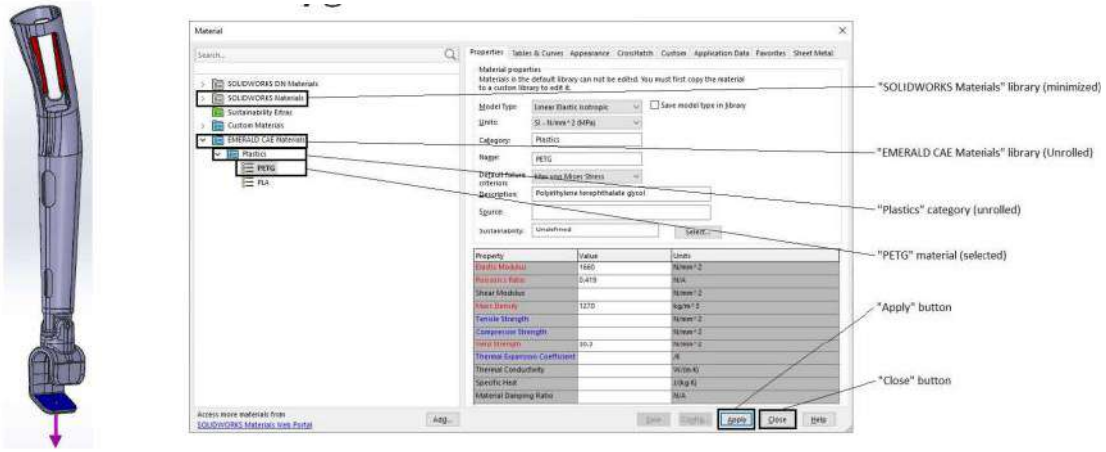


Figure 2.2.50. Tensile strength of the prosthesis and defining of the PET-G materials' characteristics

Following the material setup, the next step was to apply the necessary constraints to the prosthesis model to replicate the conditions of a real-world tensile test. In this case, fixtures have been applied to the ends of the prosthesis to hold it in place, mimicking how it would be clamped in an actual tensile testing machine (see Figure 2.2.51).

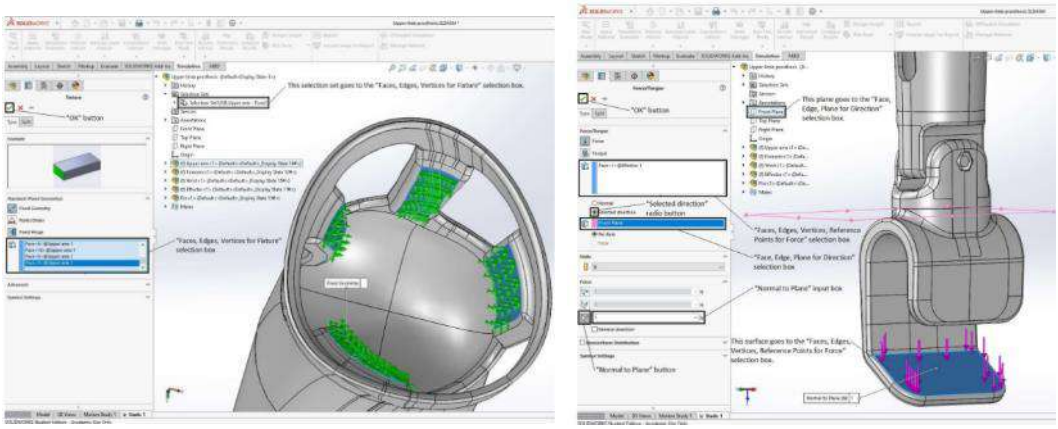


Figure 2.2.51. Constraints established within the realized finite element analysis

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

After establishing the constraints, the model was subjected to a mesh generation process. Meshing is a finite element method step that divides the model into small elements that can be individually analyzed. The mesh needs to be refined enough to capture the detailed behavior of the prosthesis under stress, yet not so fine as to make the calculations impractically long. The quality of the mesh directly affects the accuracy and convergence of the simulation results. Importance of these aspects as well as setting and importance of control parameters of the finite element mesh are explained in detail in the toolkit manual (see Figure 2.2.52).

Figure 2.2.52. Mesh generating and setup for the Finite Element Analysis

With the material defined, constraints set, and mesh generated, load cases were then established. These load cases were designed to simulate varying traction forces, incrementing from 150 N to 750 N. Each load case was applied to the model to understand how different levels of stress would affect the prosthesis. The simulation software allowed for the precise input of these values and the tracking of resulting stresses and strains at specific points or over the whole model. Once the setup was complete, the analysis was initiated by clicking the "Run" button within the "Load Case View" tab (see Figure 2.2.53).

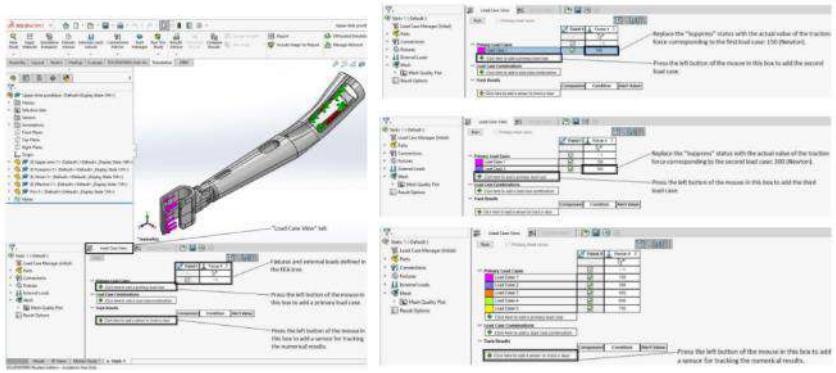
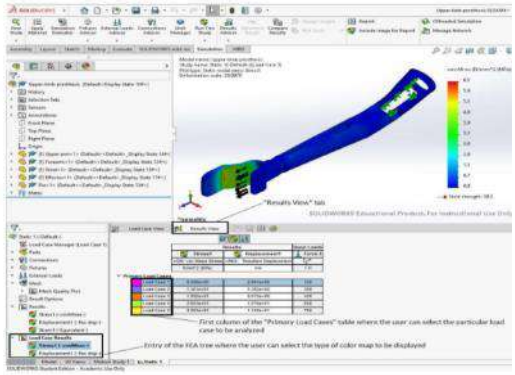


Figure 2.2.53. Load case and traction forces defined in the Finite Element Analyses

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The SolidWorks Simulation solver took over, processing the input data through its algorithms to produce the results. Upon the completion of the calculations, the solver presented its findings in the "Results View" tab. The primary visual output was a color map that indicated the von Mises stress distribution across the prosthesis for each of the load cases. This color map is a gradient representation where different colors correspond to different levels of stress, allowing for easy identification of high-stress concentrations. Additionally, the maximum deflection (deformation) of the prosthesis was displayed, showing how much it bent or stretched under each applied force. The numerical results, namely the maximum von Mises equivalent stress and maximum deflection values, were interpreted in the context of the material's behavior. These values were plotted against the applied traction forces to examine the linearity of the response, like shown in Figure 2.2.54.



Load case	Traction force F [N]	Maximum value of the von Mises equivalent stress $\sigma_{eq,max}$ [MPa]	Maximum deflection d_{max} [mm]
1	150	6.51	2.691
2	300	13.01	5.382
3	450	19.52	8.073
4	600	26.03	10.764
5	750	32.53	13.455

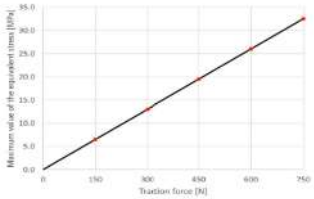


Figure 2.2.54. von Mises stresses generated by the CAE program and plot of stresses versus Forces as result of the Finite Element Analyses that have been performed

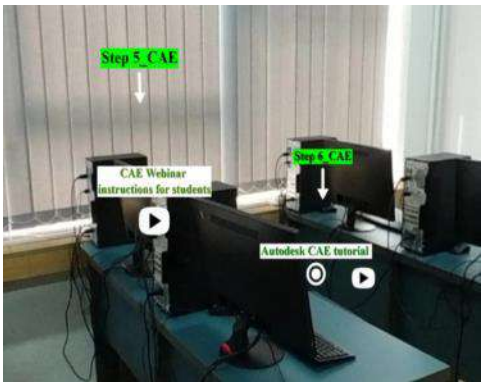
From the plots shown in Figure 2.2.54, the critical load at which the prosthesis would begin to yield, meaning permanently deform, was determined. This critical load is of particular interest as it represents the maximum load that the prosthesis can handle before failing, an essential factor for ensuring patient safety. Following the interpretation of results provided in case of PET-G material, further work, the evaluation of the prosthesis using PLA or ABS material by simulating the tensile test and assuming an isotropic linear elastic behavior for all components is proposed. The mechanical properties of PLA or ABS materials, provided in separate tables would be utilized for a new FEA model, and the user is encouraged to develop another design for the prosthesis to compare strength characteristics under similar test conditions. This implies an iterative design process where different materials and designs are to be evaluated to ensure optimal performance of the prosthesis in the end.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.16. Step 5 - CAE video webinar

Taking into consideration the importance of this aspect and based on the suggestions received from the students (users) who evaluated the resources of the e-learning virtual laboratory platform (in terms of CAE) there have been created additional resources (by TUCN) that have been included in the e-learning platform in forms of videos or webinars. The students (users) found easier to follow the instructions being provided in form of a video in which they are able to visualize things or to hear them being explained step by step in this way. Therefore an additional webinar and few videos + instructional materials have been supplementary created at TUCN being used for as instructional materials for realizing CAE analyses of the presented models (available in the CAE library) made of different types of materials (like ABS) as the ones provided in the course module or toolkit manual for having an idea of comparison in the end and interpreting of data emphasizing in this way when a choice is needed to be made in between two types of materials (alternatives) why one type of material is preferred to be selected in detriment of the other in the end.

Therefore one additional module of CAE has been created in the frame of O3 concerning the CAE analysis that has been done concerning an upper limb prosthesis like shown in Figure 2.2.55. The webinar that has been created providing instructions with highly detailed explanations about the CAE analyses can be accessed directly through the e-learning platform (CAE virtual laboratory) or by accessing the next following link: https://drive.google.com/file/d/1vPehdpQwJ2_cnEDenu-IXOa28Uvgyqru/view



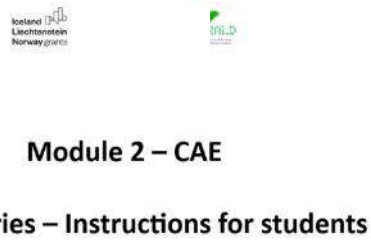
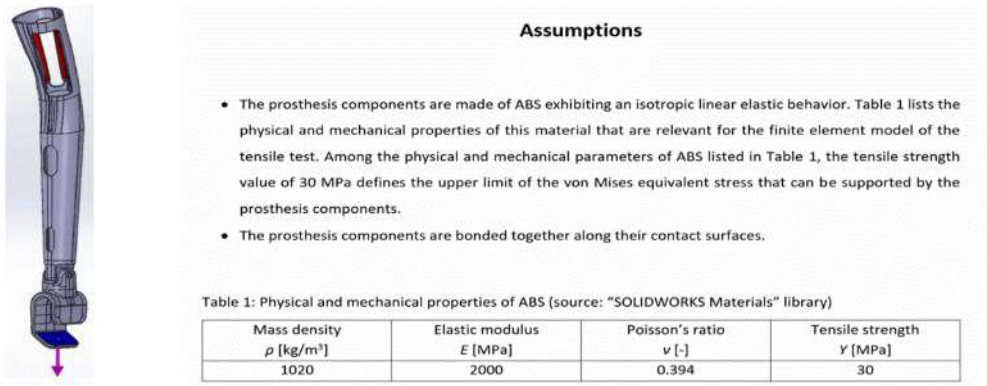


Figure 2.2.55. CAE module (webinar video) created in the frame of O3

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The webinar present like in the case of the CAE toolkit module step by step of made finite element analysis. For the students (users) that are following the tutorial, it is easy to comprise the made analysis since the CAD model used is the same like the one that was used in the toolkit module. The students (users) are able to watch the tutorial and put video on pause mode until they are executing the steps that are seeing being done in the video accompanied by professional explanations. Also as one may notice from the assumptions presented in figure 2.2.56, the analysis that is being presented in this case was for ABS material (not PET-G as it was presented in the toolkit manual).



Assumptions

- The prosthesis components are made of ABS exhibiting an isotropic linear elastic behavior. Table 1 lists the physical and mechanical properties of this material that are relevant for the finite element model of the tensile test. Among the physical and mechanical parameters of ABS listed in Table 1, the tensile strength value of 30 MPa defines the upper limit of the von Mises equivalent stress that can be supported by the prosthesis components.
- The prosthesis components are bonded together along their contact surfaces.

Table 1: Physical and mechanical properties of ABS (source: "SOLIDWORKS Materials" library)

Mass density ρ [kg/m^3]	Elastic modulus E [MPa]	Poisson's ratio ν [-]	Tensile strength Y [MPa]
1020	2000	0.394	30

Figure 2.2.56. Part subjected to made analysis and the main assumptions taken into consideration for ABS

Experience with video tutorial (webinar) is highly positive since in this way presentation is more dynamic / students (users) can see part being rotated and discussions that are realized being more focused concerning certain areas that are important for the made analysis (e.g. in Figure 2.2.57 are indicated the main areas of interest and ABS materials' characteristics uploaded from the library of the SolidWorks Simulation program.

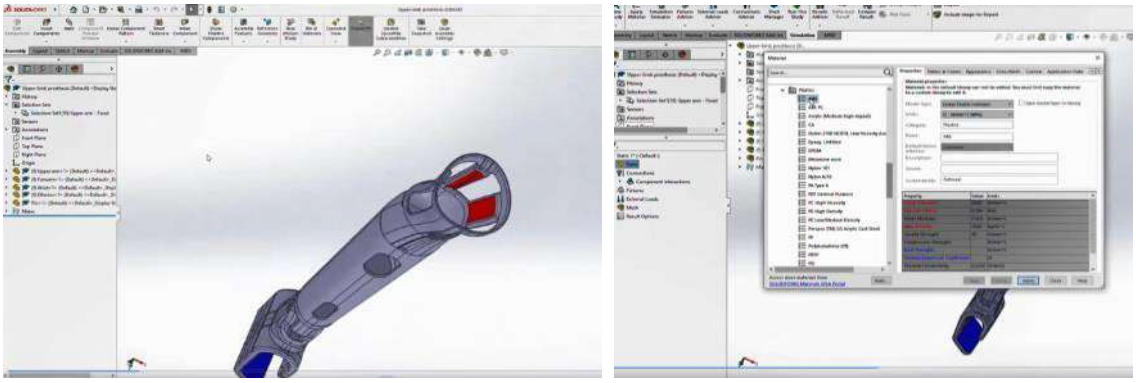


Figure 2.2.57. Main area of interest and ABS materials' characteristics of SolidWorks library program

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

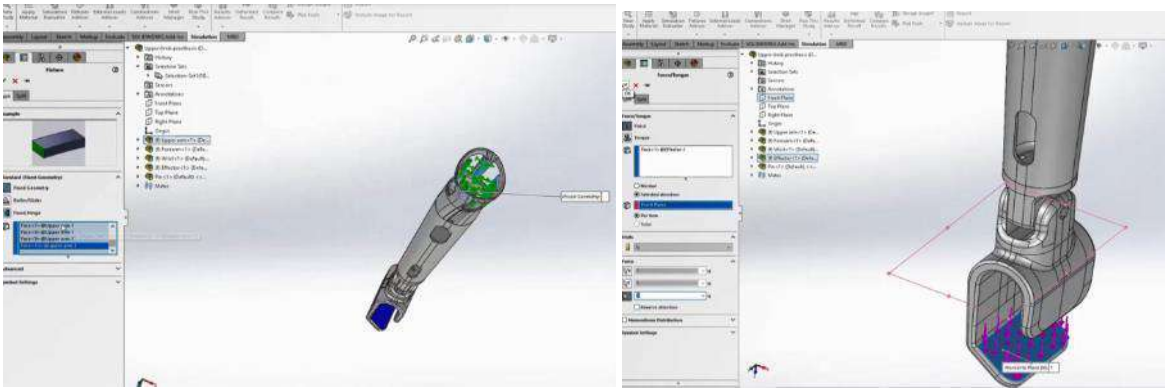


Figure 2.2.58. Boundary conditions and technological constraints applied in the CAE analysis

In Figure 2.2.58 are presented the constraints that are being imposed in the CAE analysis (kinematical and technological constraints (setting up of the traction force in the SolidWorks Simulation program). The analysis is continued as any classical CAE analysis by setting up the mesh and by defining the load case studies in different variants that are suitable for the part to be made of ABS material (Figure 2.2.59).

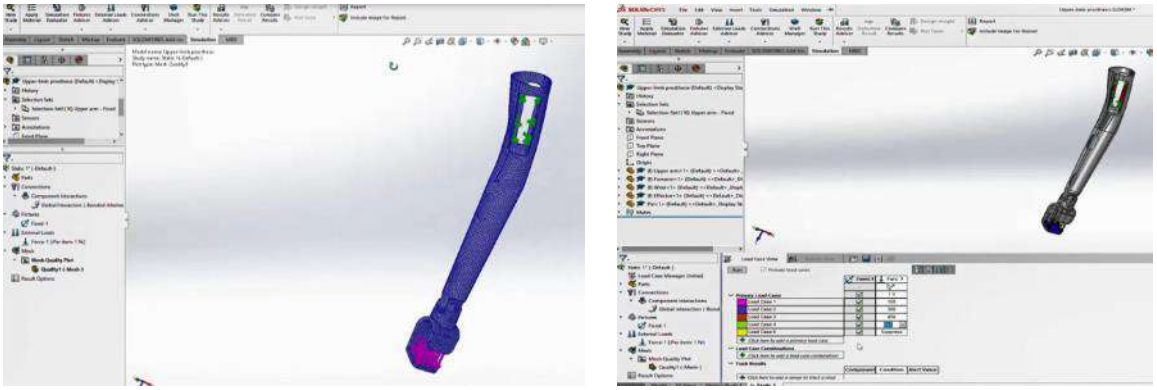


Figure 2.2.59. Generating of mesh and load case studies suitable for ABS material

In the end of tutorial provided in the webinar there are presented the results that are being reached in the case of the upper limb prosthesis made by ABS material in terms of von Mises stresses (see Figure 2.2.60). Plots providing the stresses versus the tensile strength that is reached to level of specific forces that are stressing the part are given in the graph presented in Figure 2.2.60 and some appreciations are realized comparing this graph with the similar one presented in Figure 2.2.54 for the analysis realized in case of PET-G material, providing the advantages of using ABS material in detriment of PET-G material to be used for such part to be made by 3D printing technologies in the end.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

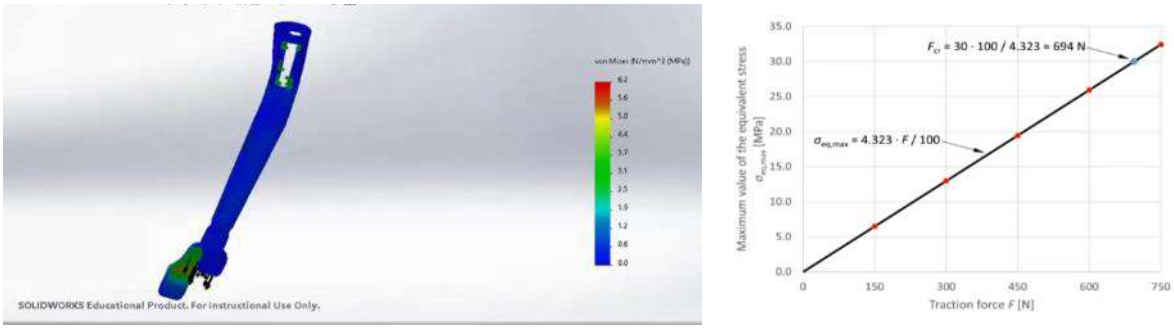


Figure 2.2.60. von Mises stress and forces versus stresses reached in the case of part made by ABS material

2.2.17. Step 6 – Autodesk CAE tutorial

In the same way, a tutorial with instructions has been prepared by PUT in the frame of O3 providing a CAE analysis for the bicycle prosthesis, but using the Autodesk Inventor program, not SolidWorks (for the case of analysis done about ABS material). Practical laboratory tutorial can be accessed directly on CAD/CAE virtual laboratory of the e-learning virtual laboratory platform as one may notice in Figure 2.2.61 or by accessing the following link:

https://drive.google.com/file/d/1XNjCYc3bio6nKaWiph5WpyyK0yfK8Rdg/view

Figure 2.2.61. Accessing the Practical laboratory and video for realizing the CAE analysis in Autodesk Inventor

This was needed so as students (users) can comprise the fact that basically the steps of the CAE analysis are the same, but also to compare the results reached using SolidWorks simulation to the ones obtained in Autodesk inventor program. The aim of the proposed exercise in this case was to assess the prosthesis's ability to withstand static loads, simulating the action of leaning on bicycle handlebars as shown in Figure 2.2.62.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

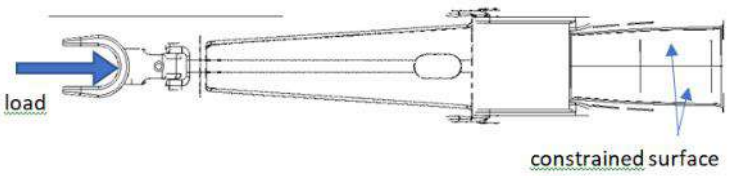


Figure 2.2.62. Assessing the prosthesis ability to withstand static loads

The steps for the analysis include importing the prosthesis model in STP format and configuring the model as a single part through the correct setup of contacts between solids. Material properties have been assigned to the prosthesis (ABS plastic). The setup for FEA requires constraining the internal surface of the prosthetic socket where it would attach to the limb and applying an axial load to the end effector that corresponds to the weight categories of different users (figure 2.2.63). The importance of selecting an appropriate magnitude of force is highlighted, with base values provided for various age groups and the option to vary these forces for a comprehensive evaluation.

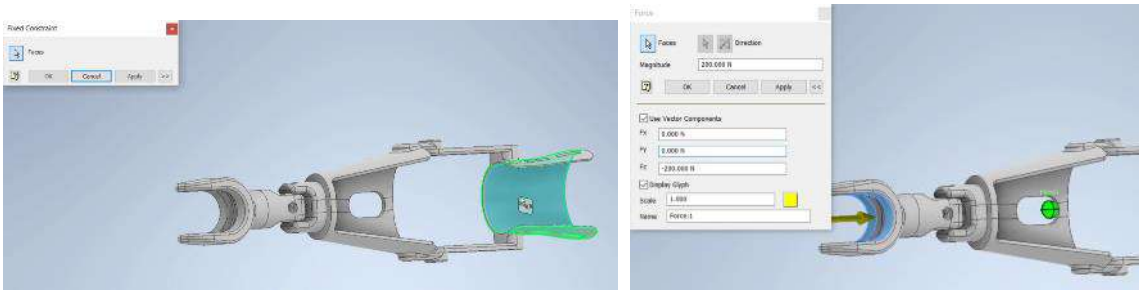


Figure 2.2.63. Kinematical and technological constraints imposed in Autodesk Inventor

In continuing, like in any other case of a CAE analysis, it is important to generate a fine-tuning the mesh resolution to capture the geometry with high accuracy, as shown in Figure 2.2.64.

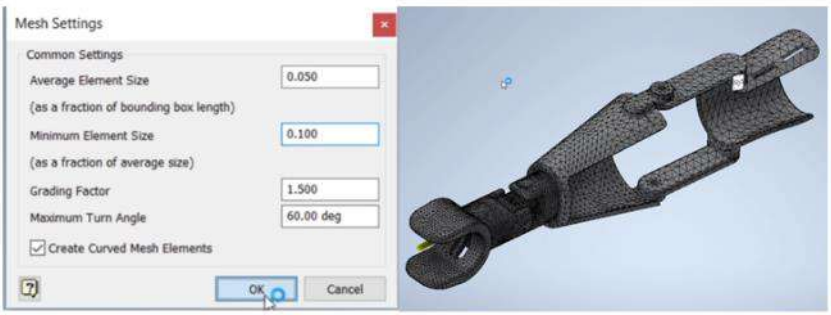


Figure 2.2.64. Generating the mesh in Autodesk Inventor

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Last step of the analysis consists in performing of calculations and result interpretation. The results that are being shown are helpful to identify areas of high stress, particularly focusing on weak spots that may fail under load, as one may notice in Figure 2.2.65.

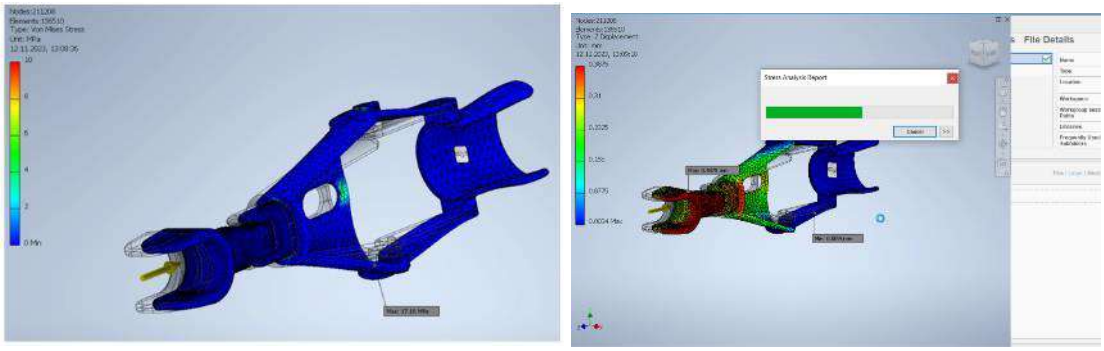


Figure 2.2.65. Results reached in Autodesk Inventor in terms of strains and stresses

After performing the analysis, results are to be documented in a report, ideally in PDF format, with visual aids depicting stress concentrations. In the end students (users) are encourages to set up similar simulation studies, applying constraints and loads, meshing, and solving the model, encouraging them to explore variations in different loading conditions, using of different types of materials and mesh sizes, which can help in understanding the behavior of the prosthesis under different scenarios.

2.2.18. Step 7 - Autodesk CAE video tutorial

After students (users) are finishing this Practical laboratory they are invited to go through video tutorial (like shown in Figure 2.2.66) that is accessible also on the next following link: https://drive.google.com/file/d/1gRCKFGxkmIGuN43HXwX99rMMpI2NiEXU/view through which they can create new parts or new scenarios for the CAE analyses to be realized in Autodesk Inventor.

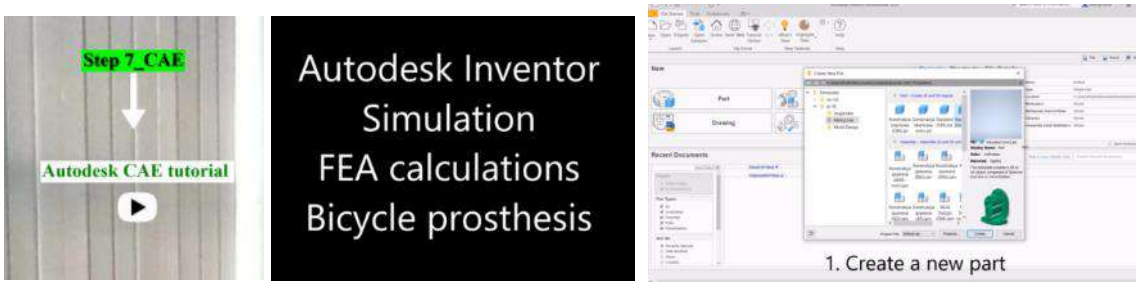


Figure 2.2.66. Instructions provided in form of video tutorial

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Different important details of the CAE analysis are explained in the video, like setting up of automatic contacts in between the created solids or different other aspects on how to generate the mesh (see Figure 2.2.67).

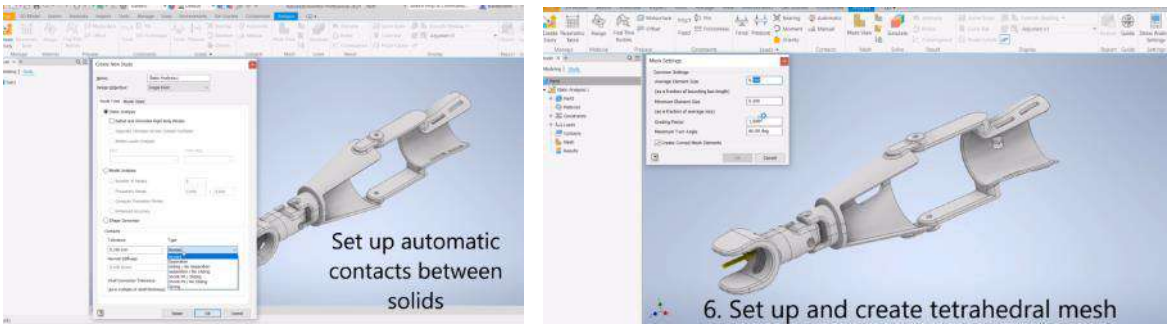


Figure 2.2.67. Setting up contacts in between solids and generating the mesh with tetrahedral elements

Important aspects on how to select proper materials in concordance with the type of the product and mechanical characteristics, as well as on how to generate and interpret the results (how to generate the reports) are also being explained in detail in this video tutorial (see Figure2.2.68).

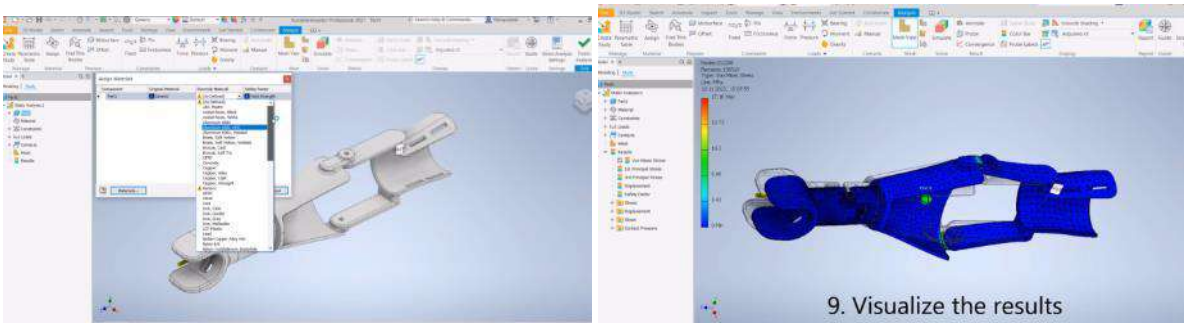


Figure 2.2.68. Assigning of the materials, visualizing and generating of the results and reports

2.2.19. Step 8 - Additional CAE video tutorial

In addition to this video tutorial, an instructional video has been created in the frame of O3 for a hand orthosis that was presented in the course module that has been given as an example in the frame of O1 presenting a CAE analysis done in SolidWorks simulation. Here, before the CAE analysis itself, there were necessary to be performed some CAD changes / operations to realize splitting operations concerning this type of part and integrating of different types of lattice structures within

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

the realized model in the end. Video with this tutorial can be accessed through the EMERALD e-learning virtual laboratory platform directly (see Figure 2.2.69) or by accessing the following link: https://drive.google.com/file/d/1PWS8JOEPjk7sTiHwsrtr7wOfrCJxJ1dO/view

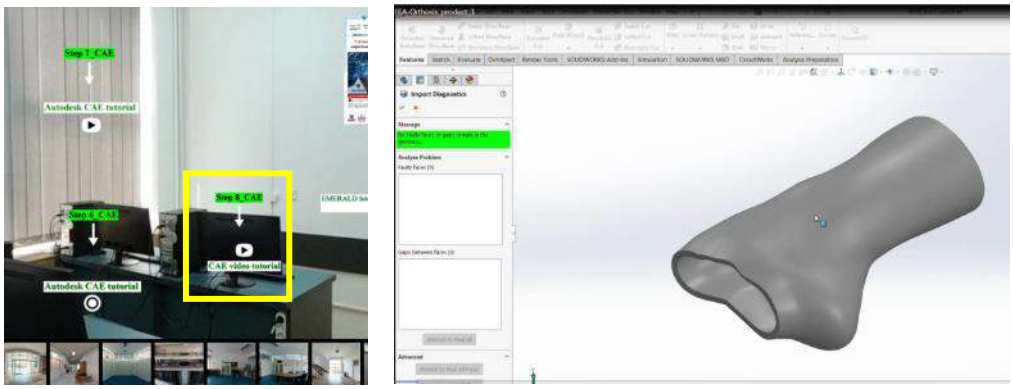


Figure 2.2.69. Tutorial for CAE analysis of hand orthosis made of ABS material by 3D printing

After the part has been split using cut operation, the CAE analysis has been made considering the ABS materials' characteristics that can be found in the library of the SolidWorks Simulation CAE software, as one may notice in Figure 2.2.70.

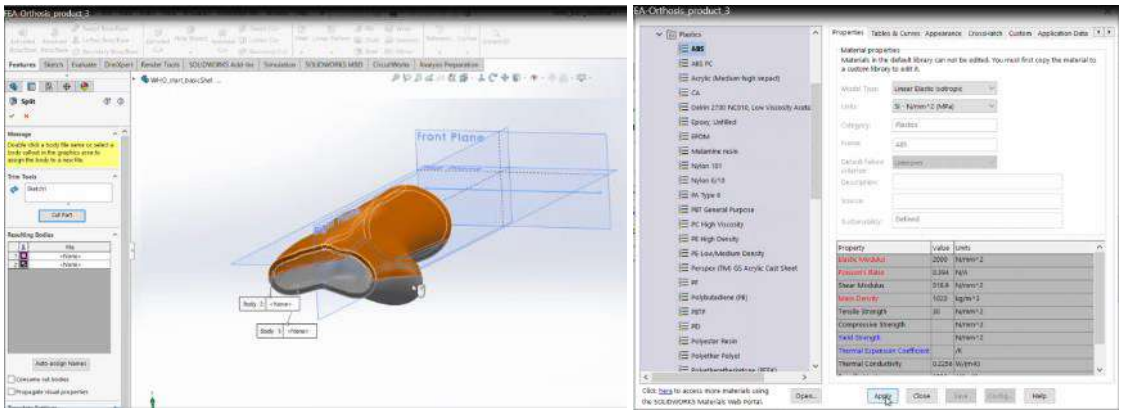


Figure 2.2.70. Split operation and ABS material characteristic set for the CAE analysis

Tutorial continues by emphasizing in a very dynamic way (with part being rotated and all steps how to select different faces being shown in the video) with the emphasizing of the kinematical constrains (like shown with green arrows in Figure 2.2.71) and kinematical constrains (area indicated with magenta color in last image of Figure 2.2.71)

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

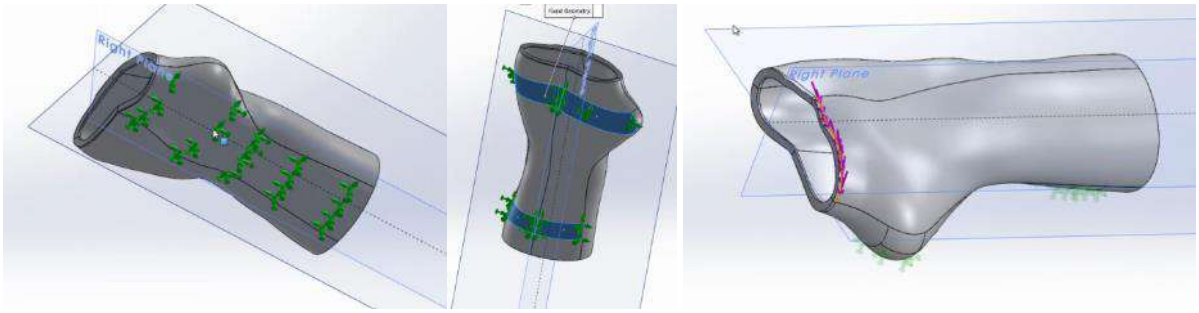


Figure 2.2.71. Kinematical and technological constrains of the analyzed part

Last step consists in generating of the mesh and running of the CAE analyses to get the values for the von Mises stress in case of the orthosis to be made of ABS material by 3D printing (see Figure 2.2.72).

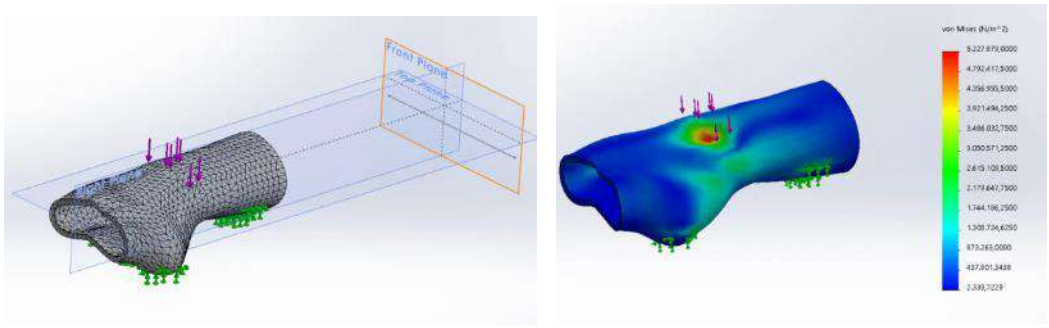


Figure 2.2.72. Mesh generating and von Mises stress reached after running the CAE analysis.

2.2.20. Step 9 - Good practice examples realized by students in CAE

After the students (users) of the CAE virtual laboratory of the e-learning platform have been experiencing all these resources that have been presented in terms of CAE, during the International summer schools that have been organized in the frame of the EMERALD project, as well as through the organized workshops, they were able to realize their own analyses for different types of CAD models (in which they have integrated also different types of lattice structures) or for different other types of materials, like TPU/PLA for example. Part of their work (good practice examples that proves the utility of the provided resources) was integrated into the CAE virtual laboratory of the e-learning virtual laboratory platform as shown in Figure 2.2.73. The good practice examples in terms of CAE (presentations realized by the students) can be accessed on the following link on the EMERALD Google drive: https://drive.google.com/drive/folders/1Zg7WsYbr9JAsmUziV6wgGR3bgqtuD7g9

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

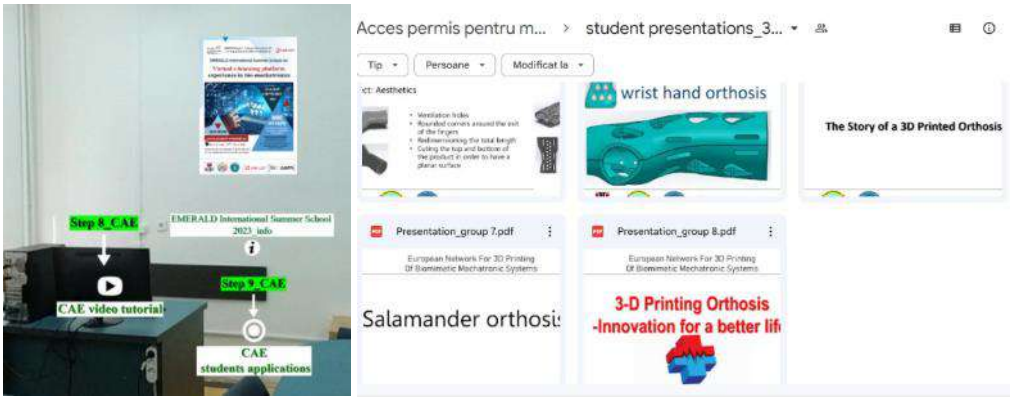


Figure 2.2.73. Good practice examples (library) of work done by students uploaded on Google drive

In Figures 2.2.74 and 2.2.75 are given one of the examples done by the students using the EMERALD resources that can be found on CAE virtual laboratory of the EMERALD e-learning platform.

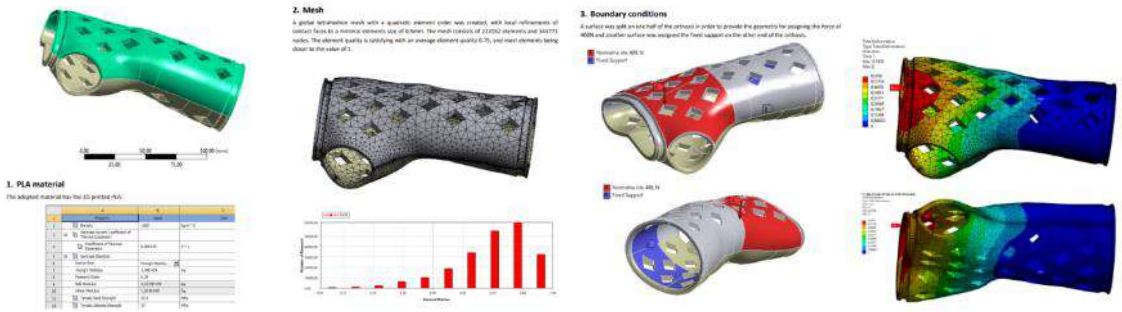


Figure 2.2.74. Example of report that can be found on the library of work done by students

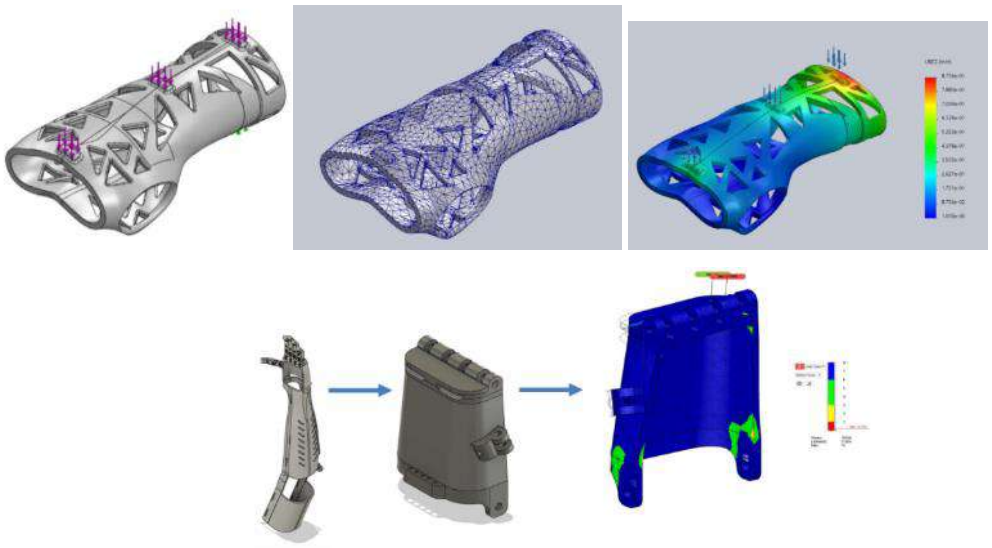


Figure 2.2.75. Other examples of CAE analyses realized by the students (selection)

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.2.21. Conclusions about CAE teaching resources of the e-learning platform

As one may notice concerning the CAE virtual laboratory of the EMERALD e-learning platform , teaching resources that have been provided by the EMERALD consortium aims not just to provide the users (students) only the basics and theoretical knowledge about CAE analyses following CAD step, but aims to stimulate them through the provided laboratory educational resources (toolkit laboratory, CAE instructions, tutorials, videos, CAE library, etc.) to get practically involved in performing the CAE analyses of specific bio-mechatronic components (like orthoses or prostheses) for people with amputated arms that have been realized in the previous step by CAD, with the main aim of understanding how a CAD variant and one type of material (among more that can be selected) can be validated in the end in concordance with the functionality /mechanical characteristics of the realized parts. Laboratory toolkit and provided tutorials, as well as the instructional videos are highly practical, providing the users step by step information data on how they have to do the CAE analyses of specific bio-mechatronic components for people with amputated arms (like orthoses, prostheses), guiding in this way the users (students) to go through the essential steps of a CAE analysis to be realized for specific models to be made of different types of materials like ABS, PET-G or PLA by 3D printing, building on the knowledge acquired from the introductory courses. To follow this plan is easy, since the CAE virtual laboratory of the e-learning platform is housing a CAE library of models, which corresponds to the models that are provided in the tutorials. Students can explore these models, can download them for free and can use them to perform CAE analyses that can be made using the CAD software programs (educational variants of SolidWorks or Autodesk Inventor) and use them as references to better understand the practical steps on how to realize the necessary CAE analyses for final validation of bio-mechatronic components that have been designed in the previous case by CAD software programs. After the students (users) are familiarized with the necessary steps that are necessary to be followed for validating the adequate solution to be selected in terms of CAD variants and materials (one in detriment of the other) based on the results reached in the CAE analyses, they are encouraged to realize innovative variant / to come up with improved variant in terms of CAD variants to be validated by CAE (there are several variants of lattice structures that can be integrated into the CAD models) as well as concerning the type of materials to be selected for 3D printing of the realized models (there are other alternatives for printing beside ABS, PET-G or PLA, like TPU for example), the realized CAE analyses being necessary to be realized taking into account the functionality of the products and mechanical characteristics that are highly important in the case

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

of the analyzed products. In conclusion, the e-learning virtual laboratory platform conceived by the EMERALD consortium aims to empower students (users) to seamlessly progress from fundamental CAD knowledge, followed by CAE analysis for validating the CAD proposed solutions, to make on step further for realizing of bio-mechatronic system design, by fostering a dynamic and interactive learning environment, equipping the students (users) who are accessing the e-learning platform with the skills and confidence needed to excel in this specialized field related to the CAD / CAE solutions for bio-mechatronic components (orthoses, prostheses, etc.) that are destined and are aimed to be customized / realized for people with special needs (with amputated arms) in the end.

2.3. Testing & Materials virtual laboratory room (UPB)

2.3.1. Accessing of the Testing & Materials virtual laboratory room (UPB)

Testing & Materials virtual laboratory room which has been assigned to the University Politehnica Bucharest (UPB), as one may notice in Figure 2.3.1 can be accessed from the www interface of the EMERALD project (https://project-emerald.eu/?page_id=404) or directly by accessing the next following link: https://bizzcom.viewin360.co/share/collection/7JhlB?logo=0&info=0&fs=1&vr=1&sd=1&initload=0&thumbs=1

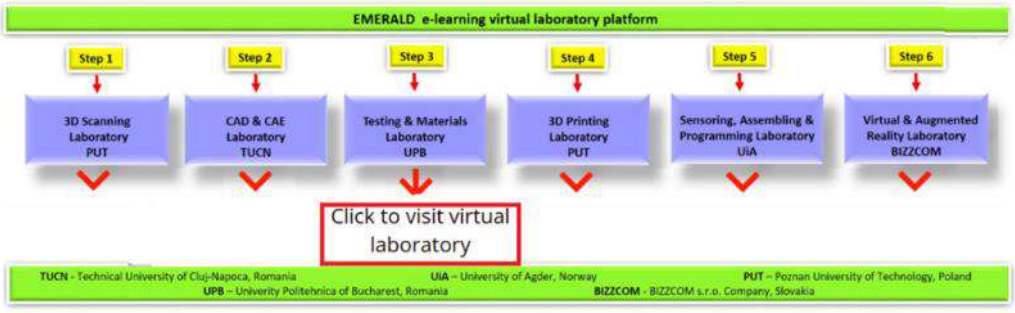


Figure 2.3.1. Accessing of the Materials characterization & testing virtual laboratory room from the e-learning platform

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The Virtual Laboratory begins with one of the main laboratory room of UPB institution related to the Testing & Materials characterization (like it is shown in Figure 2.3.2).

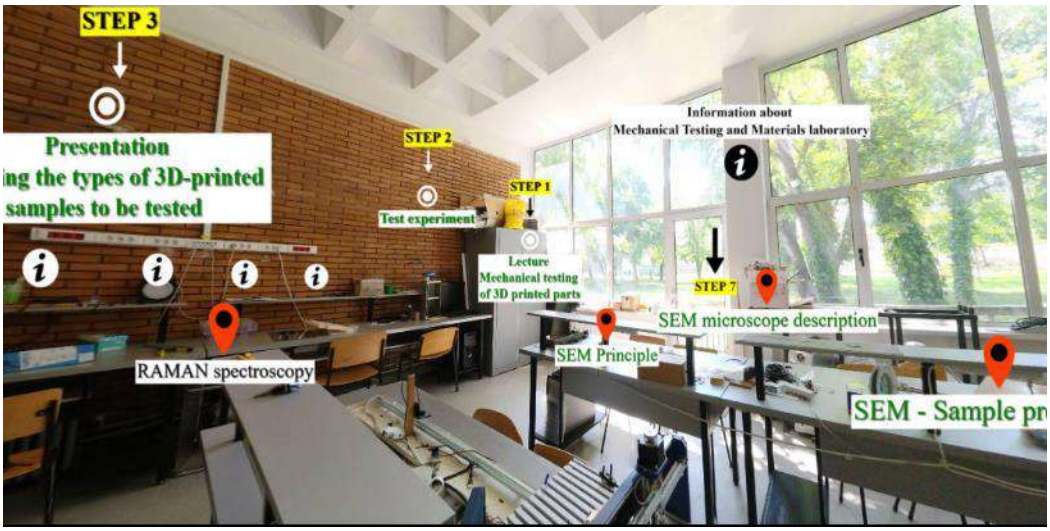


Fig.2.3.2. Testing and Materials characterization laboratory

The Testing & Materials characterization laboratory room of UPB that can be seen in Figure 2.3.2 has been realized using Insta 360 camera, the captured images undergoing in further processing using Kuula software, allowing the integration of educational materials related to the Material characterization and testing for the bio-mechatronic components that have been developed within the EMERALD project related to this topic, including mechanical testing (with the description of the main methods that are used for such testing, like tensile strength testing, compression testing, hardness, etc), continuing with different types of microscopy analyses (like SEM / TEM) or other characterizing methods (like FTIR, etc) and ending up with other additional important methods of analyses, like quality engineering (tolerances) or aspects related to the plastic aesthetics.

2.3.2. Structuring of the teaching resources being provided about Testing & Materials virtual laboratory in the e-learning platform

Concerning the educational resources that are provided within the e-learning platform in relation with the Testing & Materials virtual laboratory, these are referring to the course module that has been realized by the UPB partner in the frame of O1, completed by an additional lecture that has been realized by the UPB partner within O3 concerning the Polymeric materials, referring in principle

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

to the ones that can be processed by 3D printing technologies. In this lecture there are provided valuable information about the new types of materials that have been lately developed for the 3D printing technologies, including new types of bio-materials. Second set of information refers to different types of microscope analyses that are being explained in terms of working principles, settings, equipment items (types, performances, etc) so as the user can get easily familiarized with these type of equipment / instruments and the importance of the evaluating that is being realized based on microscopy and other types of analyses like X-ray, spectroscopy, etc. Information related to preparing of the samples for different types of analyses, are being provided in the laboratory. In terms of mechanical testing one additional lecture (and presentation) has been added in the frame of O3 focusing on the presenting of different types of methods that are used for the realized testing, like Tensile strength, hardness determination, toughness tests, etc. These aspects were integrated within the room by short descriptions that have been made (while different spots in the room are being accessed by the users), by short relevant photos that are providing steps that are followed on different procedures or by videos that have been realized / filmed while different components (like a hand orthosis) has been mechanically tested. Mechanical testing of several samples made of different types of materials in order to determine the mechanical characteristics to be included in the CAE analyses for a much reliable assessment of the results in terms of CAE done not relying on data undertaken from library of the programs / catalogues from the internet are being provided also. Last, but not least, an additional lecture related to highly important aspects regarding the prescribed precision and manufacturing precision of implants, prostheses and orthoses has been prepared by the UPB partner (in the frame of O3) to emphasize the importance of quality control / quality assurance / precision and tolerances of the realized bio-mechatronic systems, aspects that come in completion to the already provided information about the Materials characteristics and testing methods. Presentations on different other topics like Plastic aesthetics has been included in the virtual laboratory on Testing & Materials also. In this laboratory, taken into consideration the complexity of the methods and the fact that these methods are depending on the existing logistics and infrastructures existing on the physical laboratories, on the e-learning virtual laboratory platform of EMERALD it was hard to integrate practical laboratory work for the students, since this type of laboratories are highly dependent on hands-on experience (it is not like CAD or CAE where some files can be simply processed, software programs are associated for certain types of equipment items that are used for the realized testing or for the realized microscopy analysis), therefore in this case there

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

were used images or videos when there have been explained practical things. For the students (users) it was important to understand the role of these methods in determining real characteristics of the testing that are being made and the importance of these determined characteristics for selecting the proper materials for certain type of bio-mechatronic components. In order to support the students (users) with the selection of proper materials, in the toolkit manual that has been prepared in the frame of O2 and have been integrated into the e-learning platform, students (users) are being teach and can do a real practical thing by accessing the Total Materia database that is widely used for determining of the materials properties in concordance with the type of bio-mechatronic component they are aiming to realize. In this way, step by step, following this tutorial students (users) are being teach how to select the proper material (from several alternatives) in concordance with the requirements of the bio-mechatronic components to be made from different types of materials (plastic, metallic, ceramic) in close correlation with the mechanical characteristics (mechanical resistance) in the end.

2.3.3. Step 1 - Mechanical testing lecture

Mechanical testing lecture that has been prepared by the UPB partner in the frame of O3 is the first step that the students (users) has to be followed in continuing to the work that they have been doing concerning the previous step that they have been followed concerning the realized CAE, to understand better which are the arguments in terms of mechanical characteristics needed when a type of material is to be selected in detriment of another that has been considered as an alternative. The lecture related to the Mechanical testing can be accessed through the Testing and Materials virtual laboratory of the e-learning platform or can be downloaded as one may notice in Figure 2.3.3 – see: https://drive.google.com/file/d/1mP9-ia5td6GB8JhNsKnJe7YcSMvczQ2z/view

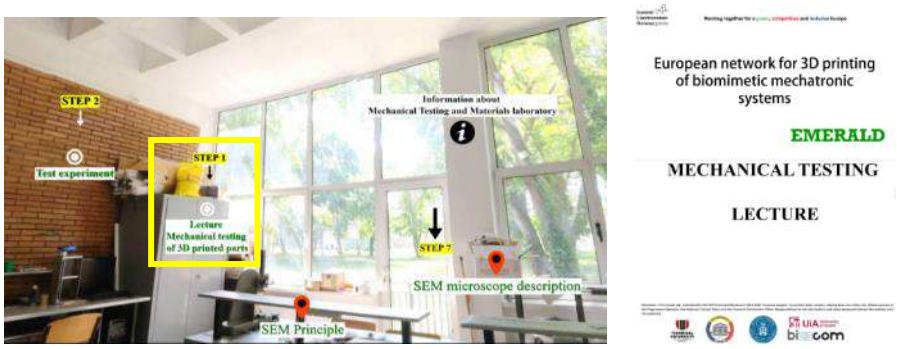


Figure 2.3.3. Mechanical testing of 3D printed parts lecture realized by UPB in the frame of O3

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

This lecture that has been created by UPB additionally in the frame of O3 has been highly important for the students (users) to comprise the chain related to bio-mechatronics, in continuing of the CAE they have just realized in the previous step. At one specific stage of the CAE analysis it was necessary to assign materials characteristics that have been simply selected from the library of the CAE program. An alternative option is to take the characteristics of specific materials (like ABS, PLA, PET-G) from the producers' websites and used them / defines them in the program software used for the CAE analysis being performed. But the students (users) must know that the most realistic way of assessing some characteristics is through real experiments that can be made in laboratories for determining the mechanical characteristics of real samples, these sets of characteristics for specific materials tested (same type of material but from different producers or different types of materials) and to use these determined characteristics for the realized CAE analyses. Through real experiments they can much better understand the importance of using different settings or orientation of the parts when they are realizing the samples of the components which influence directly the reached characteristics (like mechanical resistance of the realized components) in the end.

The standard specimens and outcomes of the mechanical tests are critical for ensuring that biomechatronic components like orthoses and prostheses meet the necessary performance standards. The interpretation of these test results provides insight into material selection, design considerations, and predicted performance in real-world biomechatronic applications.

In terms of methods that are considered for the mechanical testing regarding bio-mechatronic components, there are several methods that can be considered widely used by the mechanical engineers who are performing the testing, such as tensile testing, compressive testing, flexural testing, impact testing and fatigue testing.

The tensile strength test is considered to be the primary assessment of a material's capacity to withstand tension. It is performed on a universal testing machine, which stretches a normalized specimen until failure at a constant rate, recording the tensile force against the elongation of the sample like it is shown in the first image of Figure 2.3.4. The plot from this test is a stress-strain curve, from which tensile strength, Young's modulus, yield stress, and strain at fracture are derived as shown in second image of figure 2.3.4.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

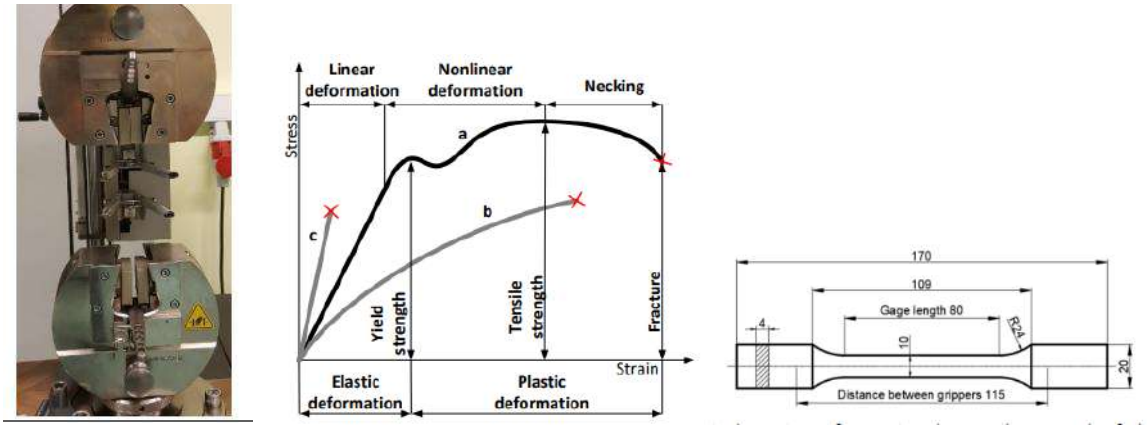


Figure 2.3.4. Tensile test machine, diagrams and specimens

There are standardized specimens for each type of material to be tested (plastic, metallic, etc). These standards dictate the specimen dimensions and gripping requirements, ensuring that the grip part does not affect the test's uniaxial stress state. Characteristics such as the material's elastic limit, ductility, and ultimate strength are outcomes that are critical for designing biomechatronic devices that require precise mechanical properties for functionality and safety, this is the main reason why such characteristic (as tensile test) has to be well determined in order to select one or another material for the realizing of bio-mechatronic component to be made (orthosis, prosthesis, etc).

One second important testing method is represented by the compressive strength testing that can be used to determine a material's behavior under compression, with the sample's lateral expansion often restricted by frictional forces. In case of plastics there are standards which provide the shapes and dimensions of test specimens, which may be cuboidal or cylindrical. Metal and ceramic compressive strengths are not explicitly standardized by ISO, but guidelines exist, such as using dog-bone-shaped specimens for brittle materials.

Outcomes of this method are important since it includes the material's maximum bearable stress before deformation or failure, aspect that is highly relevant for biomechatronic components subjected to compressive forces in particular.

Flexural strength testing presented in the first image of figure 2.3.5 is a third category of mechanical testing that can be used to ascertain a material's capacity to withstand bending forces, using either three-point or four-point bending setups on specimens whose dimensions are standardized depending on the material (plastic or metallic – there are specific standards about each category of material).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The data from these tests indicate the stress level at which a material yields or breaks under bending, informing the design of biomechatronic devices that rely on material integrity under flexural loads.

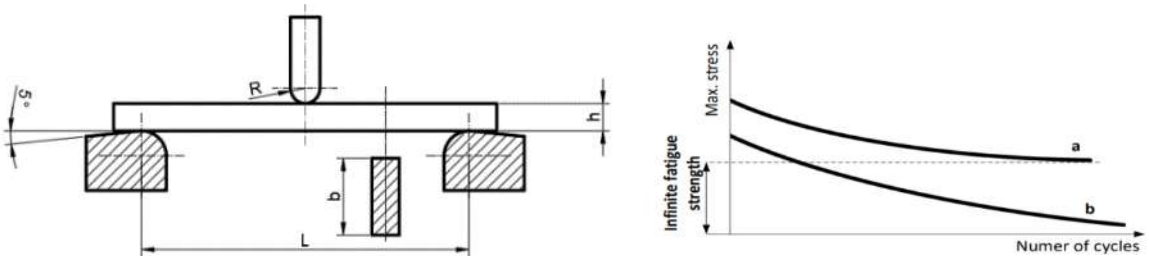


Figure 2.3.5. Flexural testing and diagram reached after fatigue testing

Another category of mechanical testing experiments is referring to the fatigue strength testing evaluates material longevity under cyclic stress, predicting failure points below the ultimate or yield strength. The so called Wöhler curve presented in the second image of figure 2.3.5 illustrates the relationship between stress levels and the number of cycles until failure.. The test outcomes help in understanding the fatigue behavior of materials used in biomechatronics, ensuring the reliability of devices such as joint replacements and movable braces, which are regularly subjected to varying stress levels over their service life.

One last category that is being presented and explained in the lecture about mechanical testing is referring to the impact strength testing which is used to determine the materials' toughness under dynamic loading, and its ability to absorb energy and resist cracking in particular. The Charpy test shown in figure 2.3.6 is a standardized method that use a pendulum hammer to break a notched specimen (of U or V-type) to reveal the energy absorption characteristics of materials, crucial for parts that are prone to impact loads in biomechatronic applications.

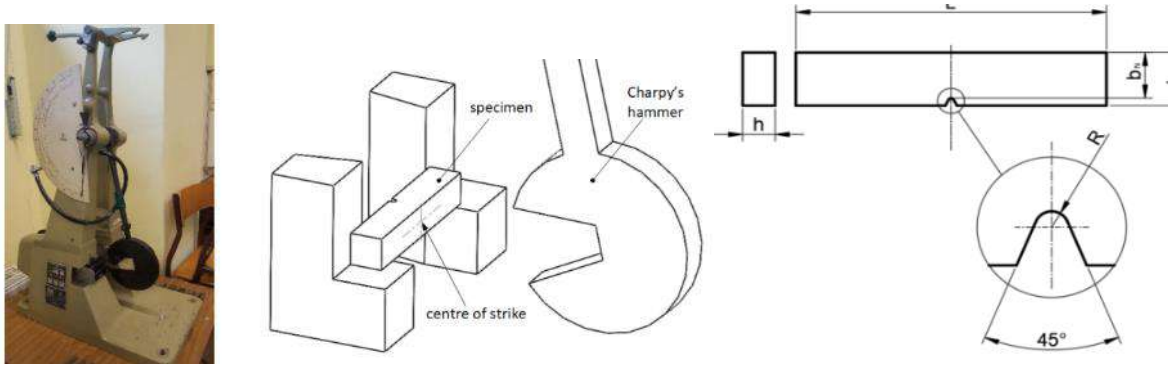


Figure 2.3.6. Charphy test machine, diagrams and specimens

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In order to emphasize a practical example of a mechanical testing that is being realized for bio-mechatronic components, performing of a bending testing experiment realized in the case of a wrist hand orthosis is included, described and presented in the end of the lecture. The case study of wrist-hand orthosis presented in figure 2.3.7 that has been tested was used in case of a post-stroke home therapy of a real patient to improve upper limb functions.

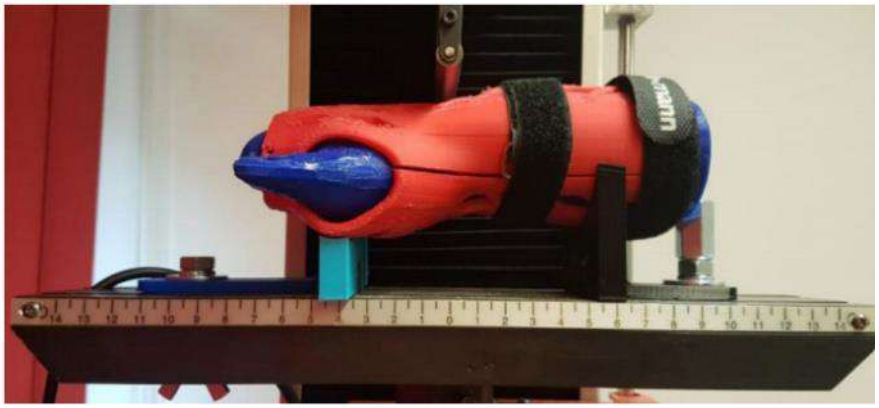


Figure 2.3.7. Bending test of a wrist hand orthosis

The orthosis shown in Figure 2.3.7 was tailored to the patient using a laminate plate heated and formed directly on the limb, followed by attaching a 3D-printed framework. For thermal protection during this process, flexible thermoplastic polyurethane (TPU) layers were used for this purpose. The thermal properties of these TPU coatings and their flex resistance were tested according to ISO 32100 standards.

Orthosis was designed based on 3D scans being further on manufactured by 3D printing of PLA, ABS and nylon materials and finally being subjected to quasi-3-point bending tests to assess durability and deformation under load, using a dual-material forearm phantom for simulation. The tests were conducted until the orthoses cracked or deformed significantly, with a pass threshold of 300 N, equivalent to the weight of a 30 kg mass. Results reached based on the made experiments indicated that PLA material is suitable for regular use when the orthosis is not subjected to dynamic loads or high temperatures, while in contrast, ABS material is preferable to be used when higher durability and temperature resistance is needed. For cases requiring high load bearing, elasticity, and skin compatibility, nylon is recommended despite its higher cost. This information assists in material selection for orthosis based on the practical load requirements and patient-specific needs.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.3.4. Step 2 - Mechanical experiments video and laboratory presentation

In completion to the provided example in the lecture presented on section 2.3.3, one video has been produced by Poznan University of Technology (PUT) in the frame of O3 explaining step by step how performing of a bending test of a wrist hand orthosis can be performed on a specific equipment that is destined for this purpose to determine the mechanical characteristics that are relevant and adequate for such type of parts (see Figure 2.3.8). Video can be accessed directly on the Testing & Materials virtual laboratory of the e-learning platform or by accessing the following link on the EMERALD YouTube page: https://youtu.be/znzxJKah_1E

Figure 2.3.8. Video of bending test experiment of a wrist hand orthosis

Every step of the performed testing experiment is explained in the video, starting with the initial setting experiment (importance of loading and position of the supports of the machine) to avoid friction, and continuing with concrete data of force used for the bending, finalizing with the results that have been reached in the experiment and interpretation of the reached data (Figure 2.3.9).

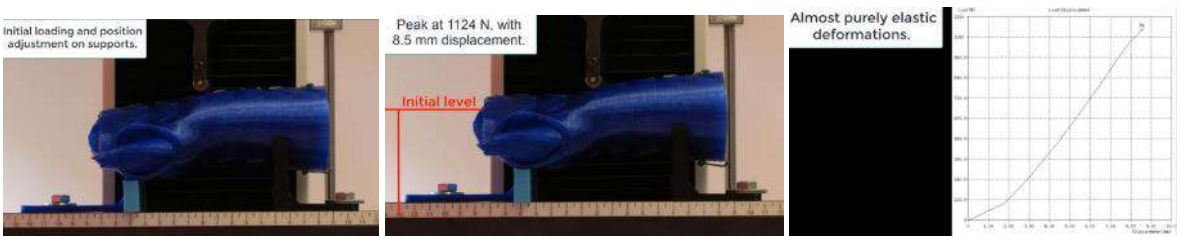


Figure 2.3.9. Steps of the real bending testing experiment presented and explained in the video

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Since there have been realized tests for orthoses that were realized with different types of lattice structures by 3D printing, in the video (with very professional and concrete explanations) are provided not only the reached results, but also explanations concerning the mechanical behavior of the orthosis realized with different types of lattice structures leading to different results in terms of mechanical resistance (in the case when the orthosis was made of same type of material) (figure 2.3.10).

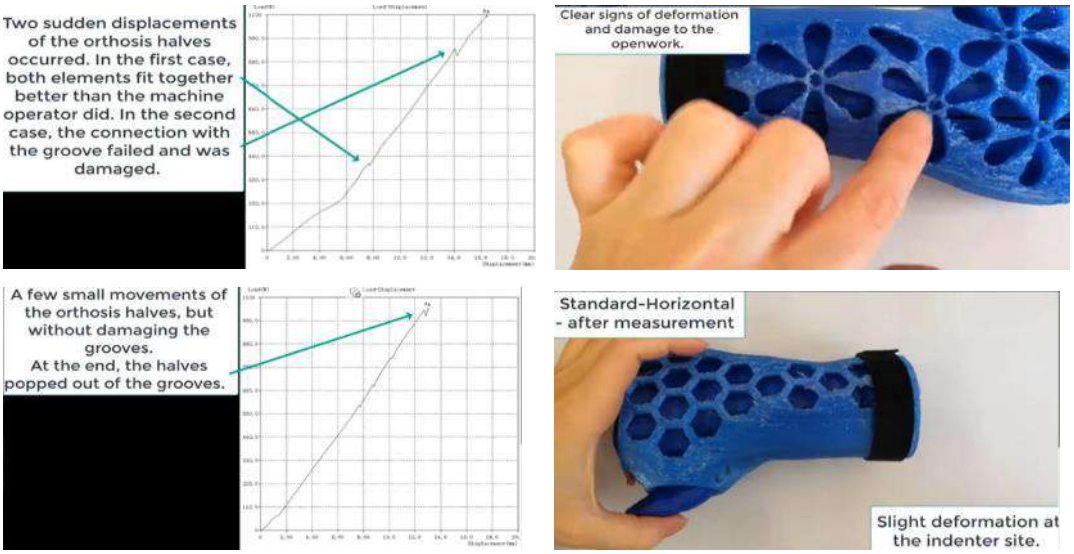


Figure 2.3.10. Mechanical testing results and explanations on different results reached in case of 3D printed tested orthoses

Results presented in the video are highly important in terms of teaching resource integrated in the Testing & Materials virtual laboratory of the e-learning platform since all the experiments were realized based on wrist hand orthosis that were realized by the students with different lattice types of lattice structures integrated into the part. In the way the video is presented it shows highly clear how much selecting of a type of lattice structure compared to another in CAD design stage is influencing the mechanical behavior and mechanical characteristics of realized parts in the end.

2.3.5. Step 3 - Mechanical testing seminar

Few aspects related the integrating of lattice structures in specific standard specimens to be realized by 3D printing for tensile testing have been approached within the presentation that

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

has been realized by TUCN in the frame of O3 being integrated into the Testing & Materials virtual laboratory room of the e-learning platform (like shown in figure 2.3.11), this presentation being possible to be accessed also on the following link:

https://drive.google.com/file/d/12T4uh2l5_cbvEIjlw-U661wHN8eIzVge/view

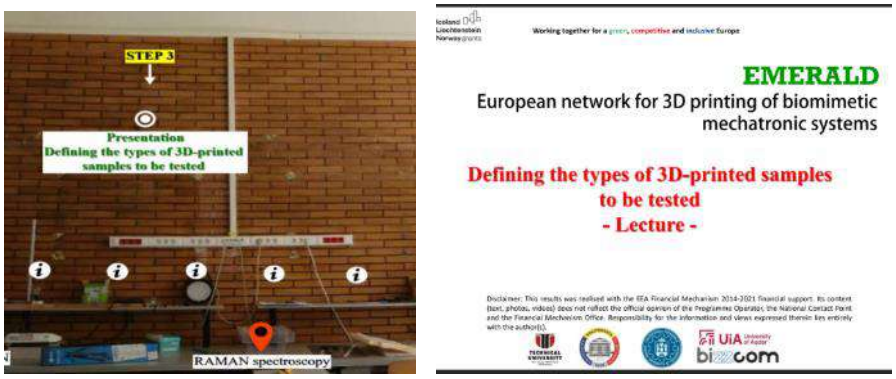


Figure 2.3.11. Defining the types of 3D printed samples to be tested – principle presentation

Within the realized presentation there are explained first the importance of material parameters describing the linear elastic response of isotropic bodies, correlated with the minimal set of material parameters that are required on the CAE analyses done with specific software programs, like SolidWorks Simulation to define the linear elastic response of the isotropic bodies. General principles and standard methods used for performing tensile test experiments in case of plastic materials (e.g. standard ISO 527) are being provided along with type of the specimens stated by this standard (see Figure 2.3.12).

Figure 2.3.12. Tensile testing and specimen configuration according the ISO 527 standard

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Information related to the results expected to be reached by performing the testing according to standard ISO 527 and interpretation of the data reached after the made experiments (stress /strain curves) along with the importance / definitions of other highly important characteristics that can be reached through the tensile testing experiments (e.g. elastic modulus) are explained in detail as one may notice in Figure 2.3.13.

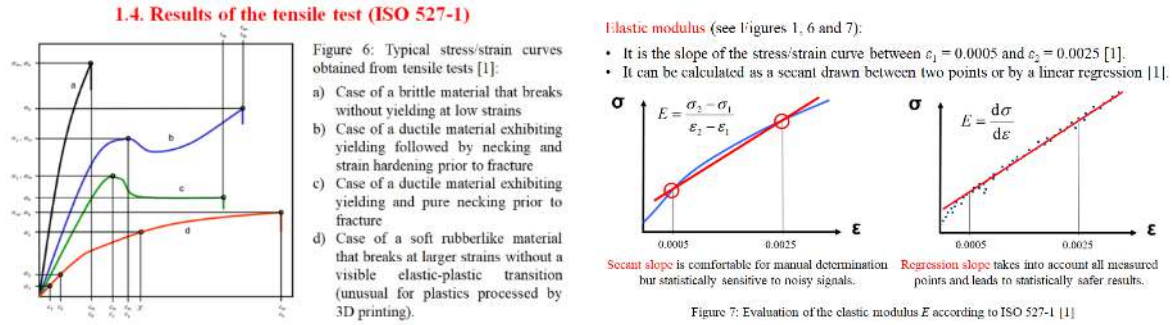


Figure 2.3.13. Interpretation of data reached after tensile test experiments performed according to ISO 527 standard and other important characteristics like elastic modulus being defined

Different types of specimens have been designed according to the standard and differences in between specimens' characteristics are presented like shown in Figure 2.3.14. Beside this aspect and taking into consideration the results presented in Figure 2.3.15 in which the importance of lattice structure type over mechanical characteristics obtained in case of a wrist hand orthosis is being obtained, in the made presentation also important details on lattice structure to be integrated on the 3D printed specimens are being presented.

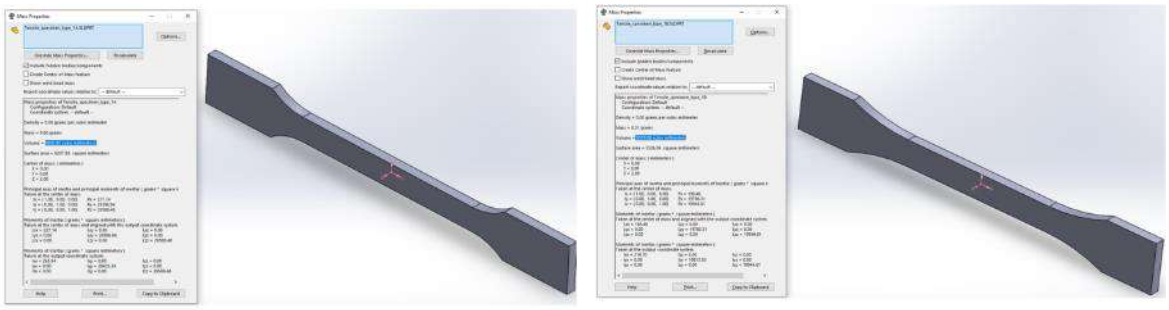


Figure 2.3.14. Specimens' characteristics for different types of samples according to ISO standard

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Definition of lattice structures as well as the most used types of lattice structured cells is being explained in the beginning of this section along with the influence of their shape on mechanical reached characteristics (e.g. compression – one specific model to be realized by 3D printing and tested on compression has been proposed and realized by the TUCN partner of the EMERALD consortium) as one may notice in Figure 2.3.15.

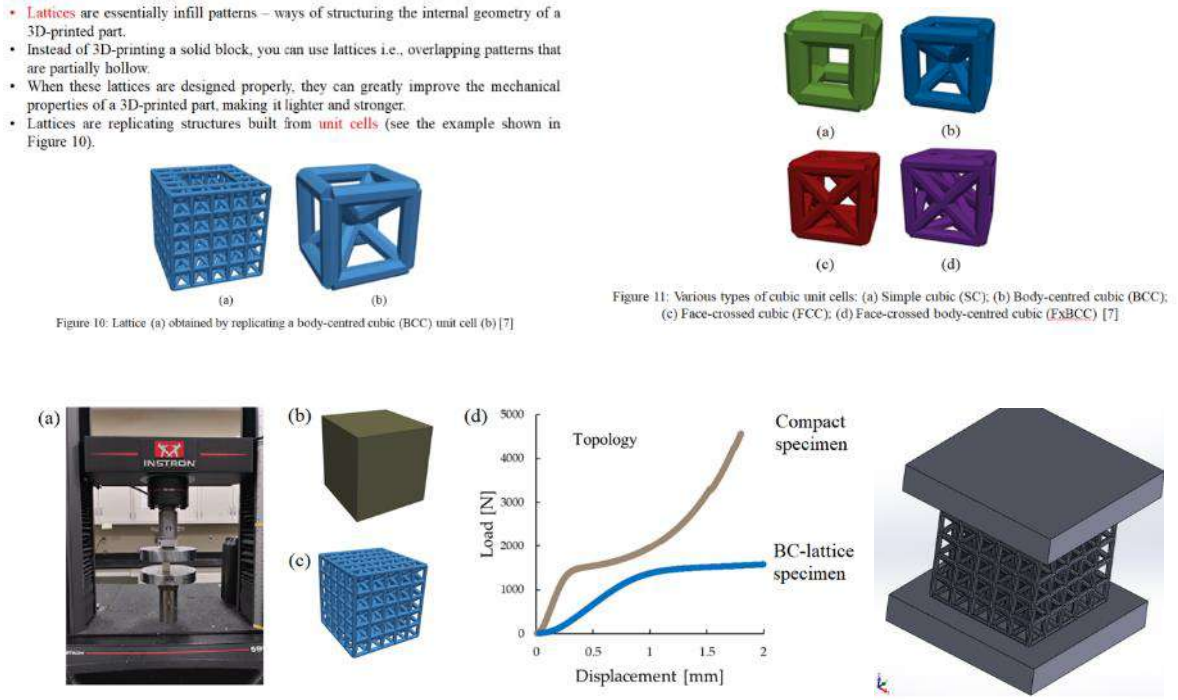


Figure 2.3.15. Different types of lattice structures and their influence on the mechanical characteristics. CAD model with lattice structure conceived at TUCN for compressive testing

In the end, TUCN has prepared one set of standard specimens to be realized by 3D printing and to be tested at tensile / compression (with various types of lattice structures integrated into the CAD models of specimens). These specimens have been prepared in various formats (like sldprt, step, stl, etc) being finally integrated into the testing & Materials virtual laboratory in the e-learning platform like one may notice in figure 2.3.16. The e-library of CAD specimens can be accessed also directly on Google drive platform of the EMERALD project at the following link: https://drive.google.com/drive/folders/1_53Wosgm63kqzQWK-KPIJhnG6zizXjdD. CAD specimens can be used also for performing CAE analyses in similar way using the same steps that have been described at CAE section using characteristics defined in the library of the CAE program using

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

characteristics that can be defined in the library of the CAE program after reaching the results from the mechanical testing experiments that are to be realized as it has been described in this last presentation.

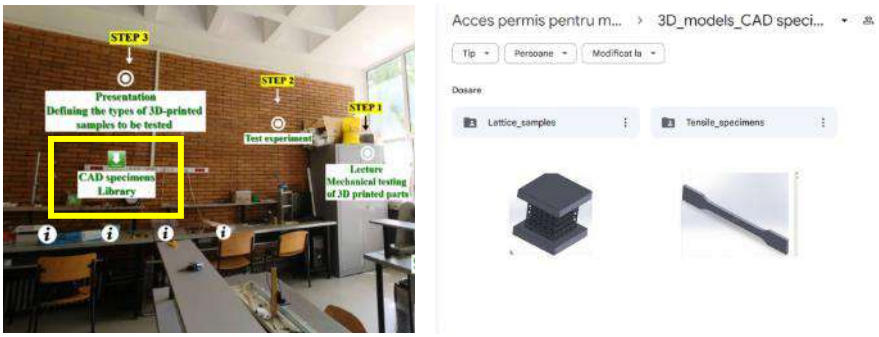


Figure 2.3.16. CAD library of tensile and compressive strength testing models conceived by TUCN

2.3.6. Step 4 - Aspects regarding the prescribed precision and manufacturing precision of implants, prostheses and orthoses lecture

Prescribed precision and manufacturing precision of bio-mechatronic components (e.g. orthoses, prostheses, etc.) are representing other important characteristics of the realized parts of this type to be made by 3D printing technologies. In this sense one module has been prepared and has been realized by UPB in the frame of O3 regarding the importance of this aspect. The module produced by UPB partner can be accessed directly from the Testing & Materials virtual laboratory room of the e-learning platform (like shown in figure 2.3.17) or by accessing the following link: https://drive.google.com/file/d/1gKesaeT04uVzMLF78astdkZZNtOAs8rD/view

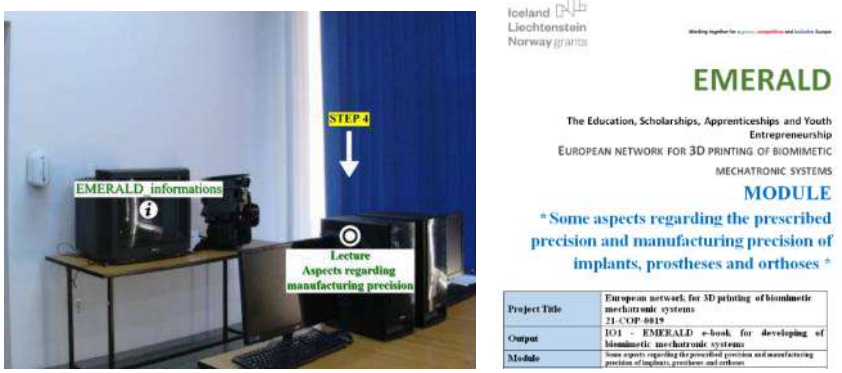


Figure 2.3.17. Aspects regarding the prescribed precision and manufacturing precision of implants, prostheses and orthoses realized by UPB in the frame of O3

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The precision of bio-mechatronic components such as implants, prostheses, and orthoses is challenging in modern medicine, where the confluence of design, functionality and patient-specific anatomy is highly important and crucial. The advent of high-performance additive technologies has empowered the production of these components with high level of accuracy, ensuring they meet the prescribed precision for various critical dimensions and tolerances. The precision of realized bio-mechatronic components is highly important both in case of macrogeometric to microgeometric shapes, affecting the relative positions of the surfaces of components that are aimed to be realized using 3D printing technologies. These stringent requirements are highly important for components that interact directly with the human body, demanding an anatomy-mimicking finish, functional assembly surfaces, and tolerances tight enough to ensure comfort and durability of the bio-mechatronic components or implants realized for the patients. Manufacturing of highly complex components like the ones presented in Figure 2.3.18 must be correlated to the existing standards that state important aspects related the accuracy and tolerances that are necessary to be reached in case of such type of components . For instance, the dimensional precision of an implant must align with the external tissues, requiring specific classes of tolerances, while maintaining the functionality of ball joints and other assembly features. The standardization process, governed by ISO and ASME standards, establishes clear guidelines for tolerances that dictate the quality of these fits and the smooth assembly of the realized components of the assembly in the end.

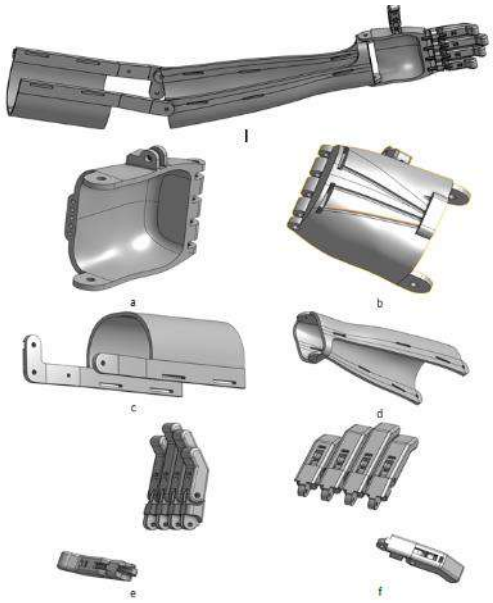


Figure 2.3.18. The main components of robotic hand prosthesis

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In this context, when reaching of high precision is representing a must, LabView programming plays a strategic role in optimizing the manufacturing process by offering a visual and interactive platform for defining and assessing tolerances (see Figure 2.3.19). With LabView, engineers can simulate the conditions that components will undergo during manufacturing and use. The software's capacity to model straightness, roundness, and cylindricity under different tolerance conditions allows for a precise understanding of how each part will fit within the assembly. This understanding is crucial when prescribing the precise accuracy needed for the prosthesis to function as intended without being highly influenced by the manufacturing technology selected in concordance with tolerances that are needed to be reached in the end. The power of LabView is its ability to translate complex ISO and ASME standards into tangible prescriptions correlated with the manufacturing processes of 3D printing.

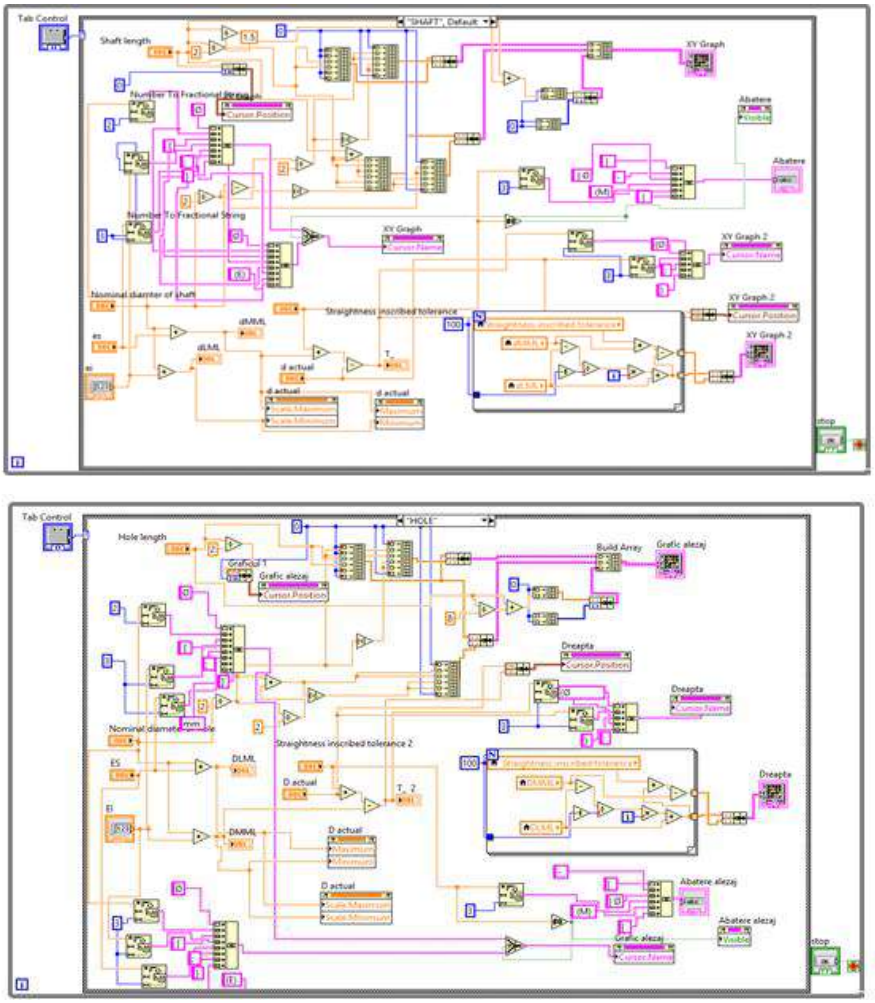


Figure 2.3.19. LabView programming block diagrams used for holes and for shafts

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

LabView program enables the visual demonstration of maximum and minimum material conditions – concepts that are essential for engineers to comprise when designing of parts must fit together with zero clearance or minimal tolerance. The applications developed in LabView provide a graphical representation of tolerance zones and allow for the analysis of how variations in material size can affect the overall fit of a component. By inputting nominal size data, upper and lower deviations and tolerance values, engineers can predict how a part will behave in its assembled form, adjusting the design parameters to achieve the desired precision in the end.

In a practical sense, LabView facilitates the creation of detailed visual aids for each stage of the design and production process, ensuring that the minimum wall thickness between critical components, such as the gap between a cylindrical shaft and its housing, is maintained (see Figure 2.3.20).

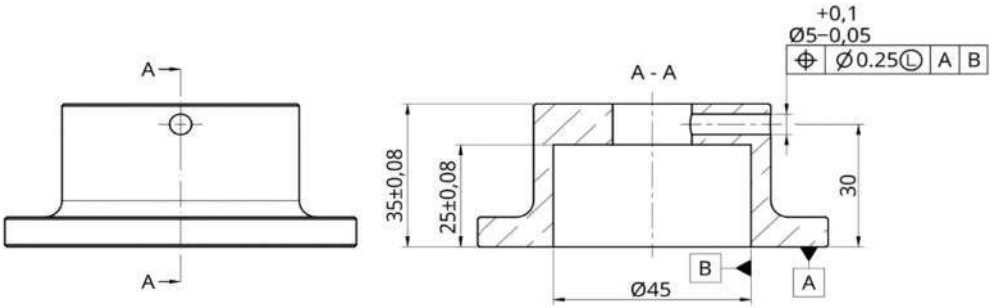


Figure 2.3.20. Prescribing of nominal position based on minimum material principle

This precision is vital not only for the function of the device but also for its economic manufacture, as it helps avoid the cost implications of over-engineering or the risks associated with under-specification. Moreover, LabView assists in the design process by allowing for iterative testing and refinement of parts before they are physically produced. By simulating different scenarios, design engineers can foresee potential production and assembly issues, thus optimizing the design for manufacturability (see Figure 2.3.21). This iterative process is critical for custom-made devices, where patient-specific dimensions must be accurately replicated to ensure device compatibility and patient comfort in the end.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

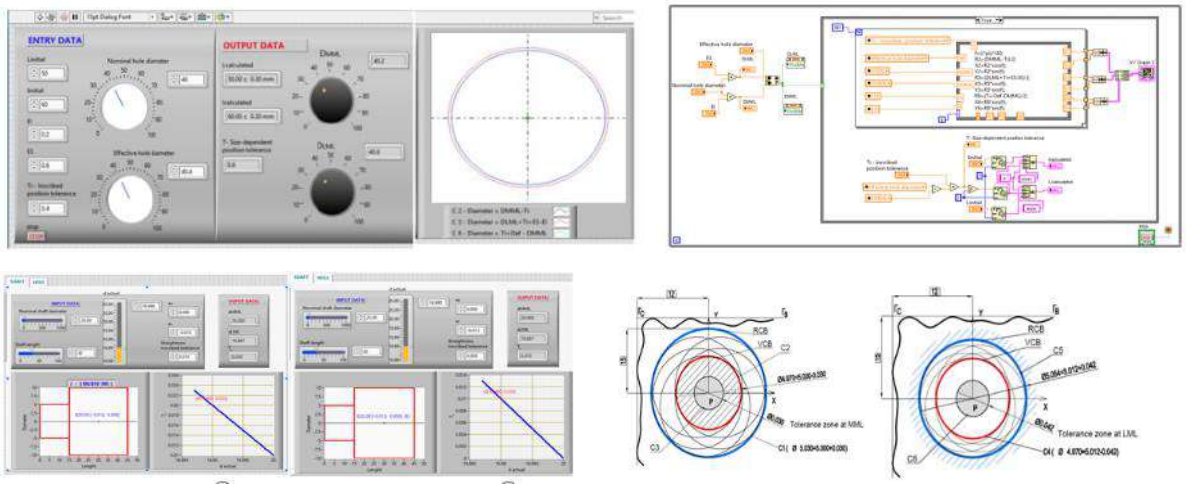


Figure 2.3.21. LabView programming used for optimizing the design from the manufacturing point of view to ensure highest accuracy and patient comfort in the end

In conclusion of the presented module, based on provided theoretical and experimental aspects that have been emphasized, it is underlined the importance of LabView programming and its contribution to ensure a highest control in terms of precision of bio-mechatronic components, especially in the case of the ones that assumes several parts to be assembled like is the case of a robotic arm shown in Figure 2.3.21 in this section related to this module. LabView program acts as a one sophisticated, complex, but also powerful tool that bridges the gap between theoretical design and practical application, ensuring that the products not only align with technological and medical standards but also respond to the particularized requirements of individual patients in the end.

2.3.7. Step 5 - Smart (intelligent) materials lecture

In terms of Smart (intelligent) materials lecture, the first resource that is to be considered is the course module that has been realized by the UPB partner in the frame of O1, which is recommended to the students (users) to be accessed first. Course module of Smart (intelligent) materials can be accessed directly on the Testing and Materials virtual laboratory room of the e-learning platform as one may notice in Figure 2.3.22 or can be downloaded from the following link: https://project-emerald.eu/wp-content/uploads/2023/02/EMERALD_IO1_module_8_Intelligent-Smart-Materials.pdf

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

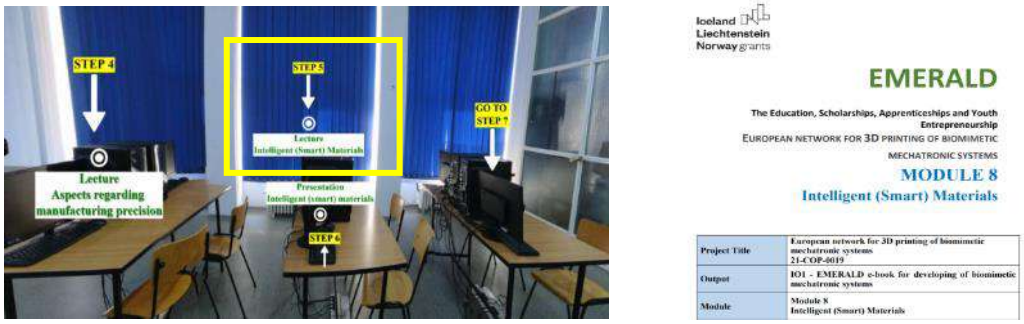


Figure 2.3.22. Intelligent (Smart) materials course module accessible through the e-learning platform

The course module explores smart materials and additive manufacturing (AM) technologies in depth, providing insights into their application across various domains of applicability including medical. For the beginning it is essential for the students (users) to comprise to what term of smart or intelligent materials is referring to much precise. In essence, smart materials, also known as intelligent materials are those that have properties that can be significantly changed in a controlled way by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields. Smart materials stand at the heart of many applications in additive manufacturing (AM) because of their ability to respond to changes in their environment, which can be particularly useful in creating adaptive structures and devices using such types of materials. In the domain of additive manufacturing (AM) technologies, the use of smart materials allows for the creation of objects with complex, customized geometries and functionalities that are not possible to be realized with traditional manufacturing methods. Materials like photopolymerizable resins, metallic powders and specific polymers such as ABS and PLA are utilized based on their responsive properties. For example, in medical applications, smart materials can be used to fabricate implants that adapt to the physiological conditions within the human body or change based on stimuli post-implantation. The module delves into the specifics of photopolymerizable resins used in Stereolithography (SLA) and Digital Light Processing (DLP), highlighting their applications in the medical domain due to their precise curing with light sources. Further there are discussed the use of metallic powders in additive laser manufacturing (ALM), explaining various laser sintering and melting techniques, such as Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), and Electron Beam Melting (EBM) and how these processes enable the fabrication of detailed and structurally complex parts suitable for immediate use or requiring post-process sintering to enhance their mechanical strength in

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

concordance with the type of application these components are destined to be used for (figure 2.3.23).

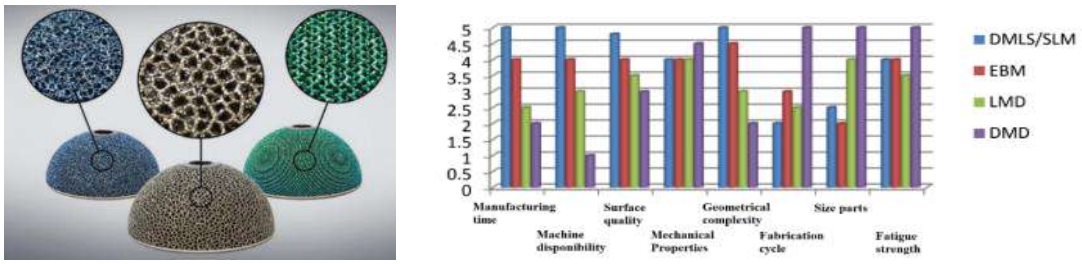


Figure 2.3.23. Applications of AM technologies for metallic components, alternatives and characteristics

Besides comprising the classification of AM technologies, it is important when a material is being characterized to comprise the advantages and limitations related to residual stresses and the fine details that can be achieved through several types of technological variants (in case of metallic components to be realized by AM technologies, powder granulometry is an important characteristic that can limit or enhance the reached characteristic of the realized component in the end). In this context it is explained the superiority of processes like Direct Metal Deposition (DMD) for realizing of the metallic parts and producing of the components with high mechanical characteristics (mechanical resistance) as compared to the producing the same components through other alternative solutions like DMLS, EBM or LMD. For the assessing of the material characteristics, several methods that are used for this purpose are being explained in the module along with some results and interpretation of the results in concordance with the described ways for the material characterizing being explained together with its importance in the assessing process / characterizing of a material in general.

Characterization of these smart materials is crucial for understanding their behavior and ensuring their effective performance in their intended applications. Therefore, techniques like Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are commonly employed for detailed examination of material microstructures. SEM provides high-resolution images of the surface topography and composition, while TEM offers insight into the internal structure, being capable of imaging at a molecular level, thanks to its higher resolution. Transmission Electron Microscopy (TEM) offers a higher resolution image, revealing the internal structure of materials at the molecular or atomic level. The use of TEM can be particularly insightful when examining the nanostructured features of smart materials, which contribute to their unique properties. (Figure 2.3.24).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

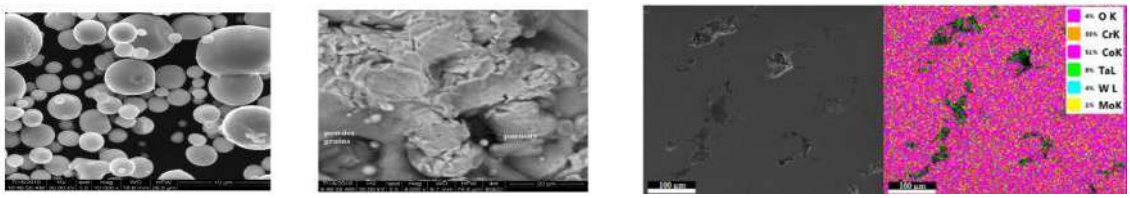


Figure 2.3.24. Microscopy images of a structure taken with different types of microscopes (SEM and TEM)

Optical microscopy is another fundamental characterization tool, often used as a complementary technique to electron microscopies. It provides a more accessible and non-destructive means to observe the surface and structural details of materials. While it doesn't offer the same resolution as SEM or TEM, optical microscopy is beneficial for rapid, initial assessments of material quality and the examination of larger sample areas. It can also be used in various lighting conditions, including transmitted, reflected, and polarized light, to reveal different features of analyzing the surfaces and structures of components made by AM technologies (Figure 2.3.25).

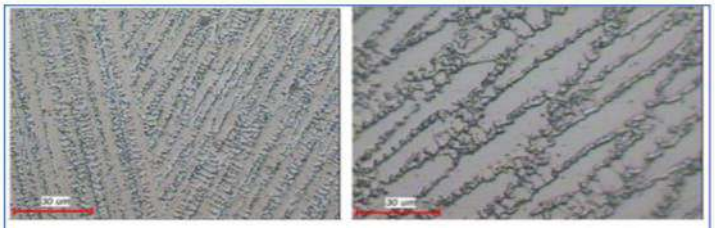


Figure 2.3.25. Examples of structures analyzed with the optical microscope

For a more in-depth analysis, Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDS or EDX) can also be used. EDS/EDX methods are essential for determining elemental composition and distribution within a sample, providing a detailed view that complements the topographical and morphological data from SEM. X-ray Diffraction (XRD) analysis is another vital tool, particularly being used for metallic powders used in Additive Manufacturing technologies. XRD helps in determining the crystalline structure, enabling an understanding of the material's phase composition and crystallinity, which influences mechanical properties such as strength and fatigue resistance. Similar to XRD, Fourier Transform Infrared Spectroscopy (FTIR) methods are used to examine molecular bonding and structure, particularly useful for polymeric materials in Fused Deposition Modeling processes. These techniques ensure that the materials'

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

properties align with design requirements for specific applications involving lightweight structures or medical components' strength (see Figure 2.3.26).

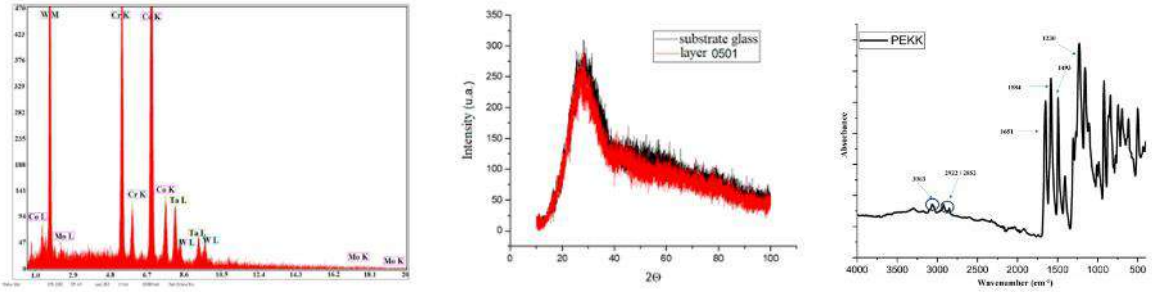


Figure 2.3.26. XRD, EDS and FTIR analyses

2.3.8. Step 6 - Smart (intelligent) materials additional presentation

Since these methods are so diverse and not so easy to comprise, an additional presentation to the provided lecture is recommended to be followed in continuing like can be shown in figure 2.3.27, this presentation being able to be accessed directly from the Testing and Materials virtual laboratory room of the e-learning platform or by accessing directly on the following link: https://docs.google.com/presentation/d/1_tIat3Oj67Vb2MWZJf9y7yQk3K__4lwX/edit?usp=sharing&ouid=106989522759795910234&rtpof=true&sd=true

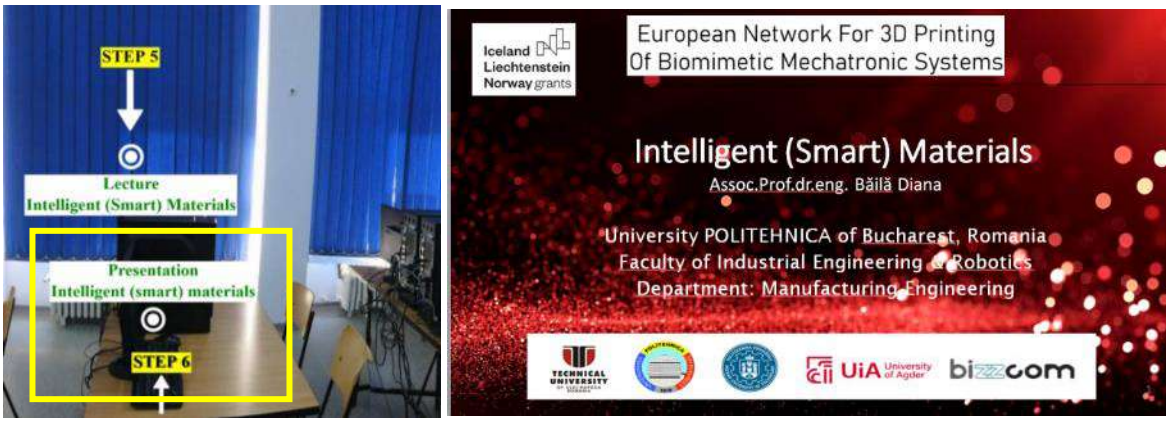


Figure 2.3.27. Intelligent (smart) materials presentation additionally prepared by PUT in the frame of O3

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Besides going into the presenting of the basics provided in the course module as it was shown in this chapter, the presentation makes one step further into the 3D bioprinting domain, approaching interesting aspects about new types of materials that have been recently developed (like PEGDA or GELMA) revolutionizing in this way the domain of regenerative medicine and tissue engineering. There are approached in the presentation as one may notice new types of structures that can be realized through the 3D bioprinting methods, including bi-materials or multi-material structures like shown in Figure 2.3.28.

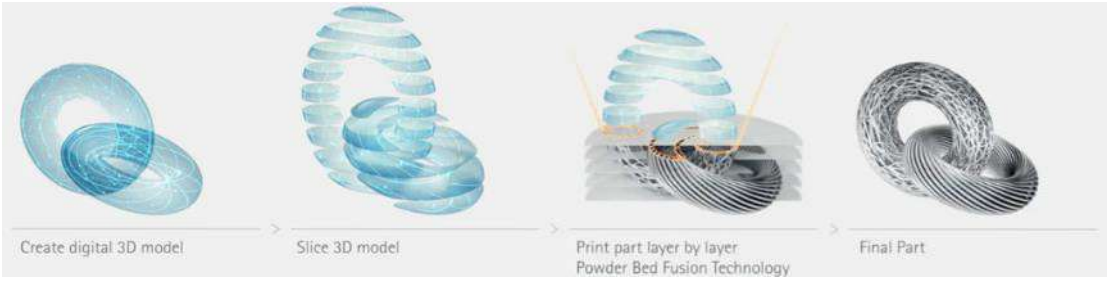


Figure 2.3.28. Multi-material structures realized by 3D printing / 3D bio-printing methods

Besides providing examples at macro-level (including the integrating of lattice structures in several types of applications, the presentation goes deeper to provide fundamental details about the micro-level of 3D printed components (see Figure 2.3.29) in close correlation to the methods of assessing the characteristics of materials (like SEM, TEM, etc) and influence of the lattice structures on the reached characteristics motivated and explained by the bounding at micro-level in the structure of the material in between struts that are realized through different 3D printing methods / Additive Manufacturing technologies.

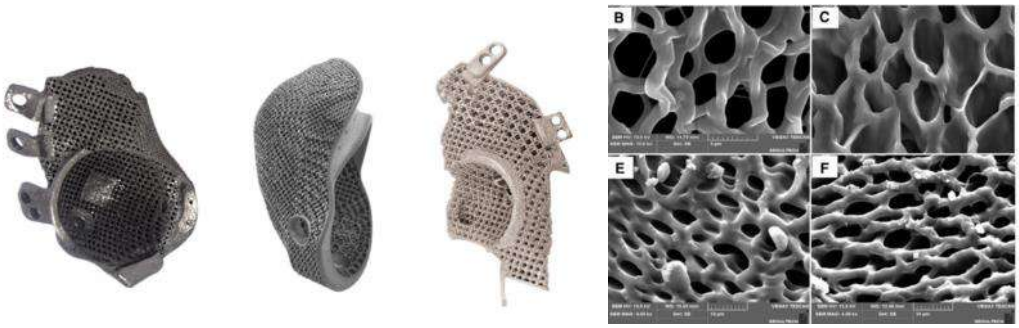


Figure 2.3.29. Macro and micro-geometries of realized components analyzed based on SEM images

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Additional information is being brought to emphasize much clearly the differences in between the most used methods for analyzing the structure of the materials in terms of microscopy (like SEM and TEM) in terms of working principle, advantages / disadvantages, like they are shown in Figure 2.3.30 / applicability of the methods, etc .

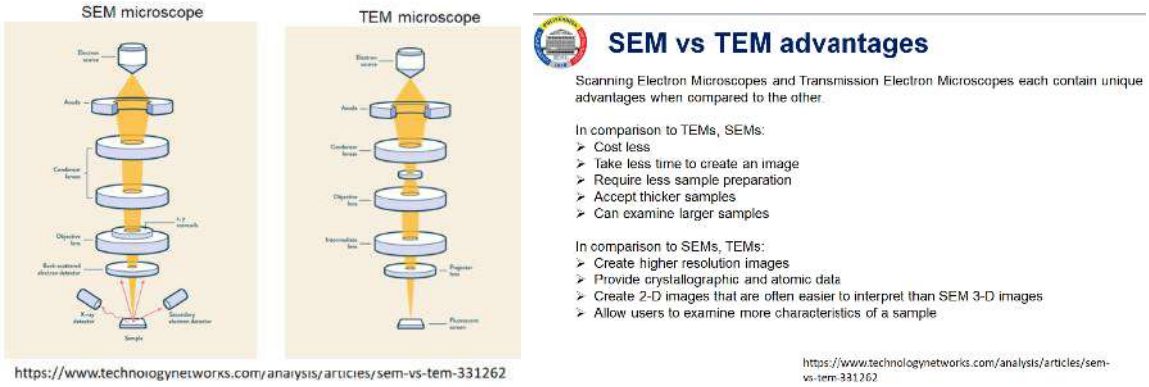


Figure 2.3.30. Working principles of SEM and TEM microscopies along with the advantages and applicability of the methods.

The rest of the presentation is focused on providing examples of research that was realized at the level of the EMERALD consortium in which several case studies (structures) were 3D printed and were analyzed with the help of the SEM / TEM microscopes, completed with the other methods that have been described in this section related to EDS / XRD analyses, there results being published by the EMERALD consortium in prestigious articles with impact factor/ open access as they have been provided in the frame of O4. Beside underlying the role and the use of different methods for assessing of the materials' characteristics, in the presentation is underline also the importance of coating methods that are used in case of structures that have been produced by Additive Manufacturing technologies like SLM, influencing in this way the structure of the material, but also the determined characteristics that were seen through such methods of analyses, like XRD analyses (see for example the results presented in Figure 2.3.31 concerning Ta2O5 and ZnO coatings that has been realized on Co-Cr alloy substrate in a research that has been realized in a research that has been realized and published by the EMERALD consortium within an article related to this topic in the frame of O4 (article is with open access and can be accessed / downloaded by accessing the following link: https://www.mdpi.com/1996-1944/15/16/5580)

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

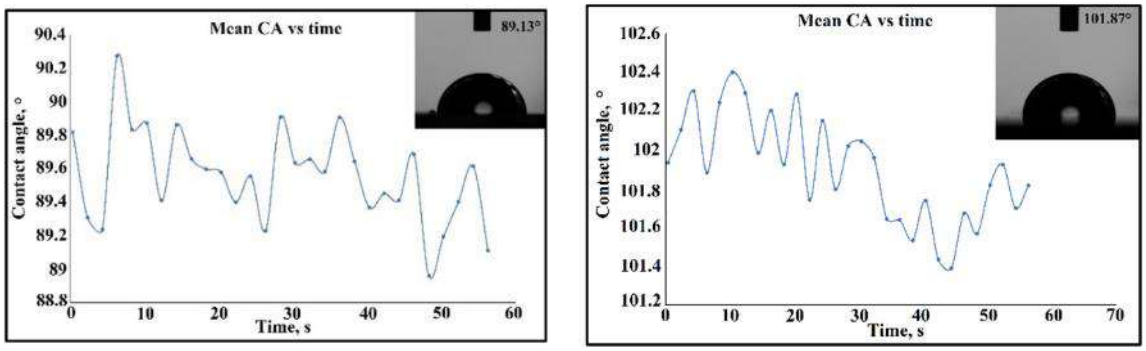


Figure 2.3.31. Results reached in the case of different type of coatings realized on structures that were made by Selective Laser Melting at the level of the EMERALD consortium in a common research

2.3.9. Step 7 – Equipment items presentation and tour of the lab

In addition to the provided course module and presentation, in order to comprise much better the methods / the existing equipment items / characteristics of the equipment items (different types of microscopes to be used (which exist in the infrastructure of UPB), in the laboratory room of UPB have been included a series of images in which the users can visualize these types of data by walking virtual (realizing a tour of the virtual laboratory room).

Examples of information that the students (users) can see in the laboratory explaining different aspects (like working principles, description of the testing methods, way of preparing the samples for the realized analyses, description of the equipment (type / characteristics / settings) are provided in the Figure q as they can be visualized or accessed by pop-up images in the Testing and Materials virtual laboratory room of the e-learning platform (see Figure 2.3.32).

In the same way as one may notice in Figure 2.3.33 are provided in a systematic way details about similar methods that have been explained and provided in the course module and in the presentation that has been provided concerning the main methods of characterizing of the materials, so students (users) can comprise as easy as possible the steps needed for performing the practical analyses, working principles and needed settings, along with the advantages and applicability of each described method that has been integrated into the virtual laboratory room.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

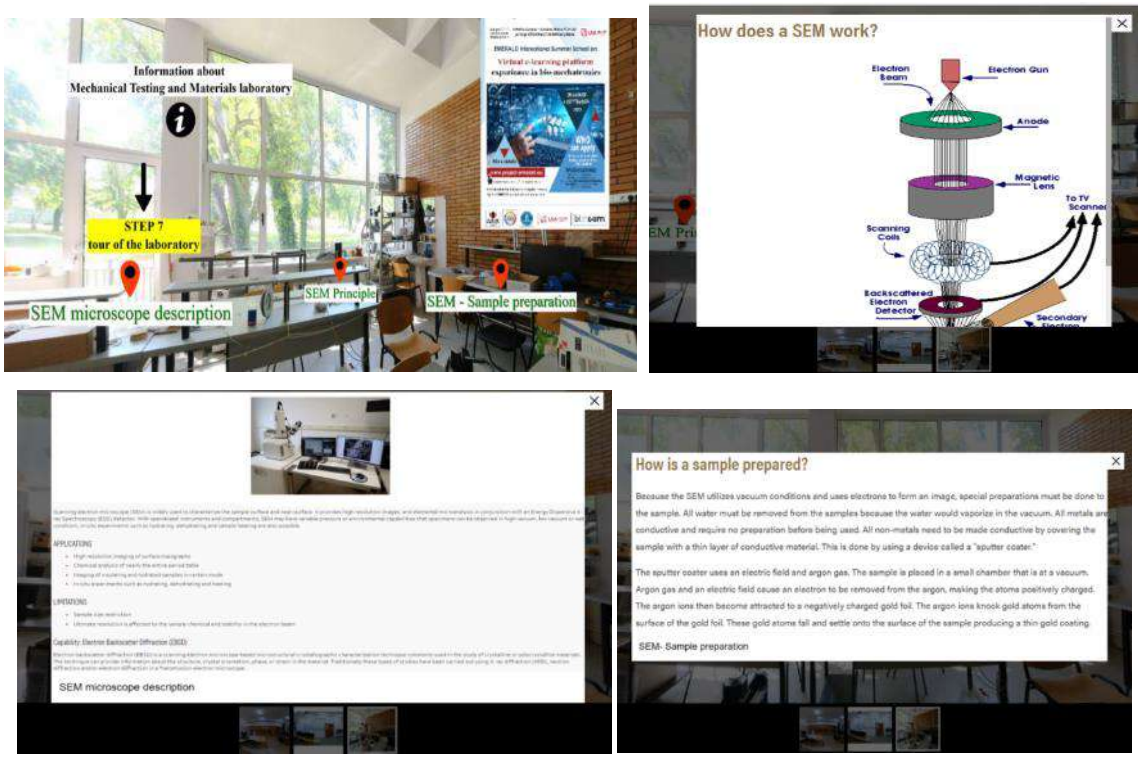


Figure 2.3.32. Examples of information that can be found in the Testing and Materials laboratory of the e-learning platform (UPB) room concerning working principles, type of equipment, information about pre-processing / post-processing of the data, etc in case of SEM microscopy method.

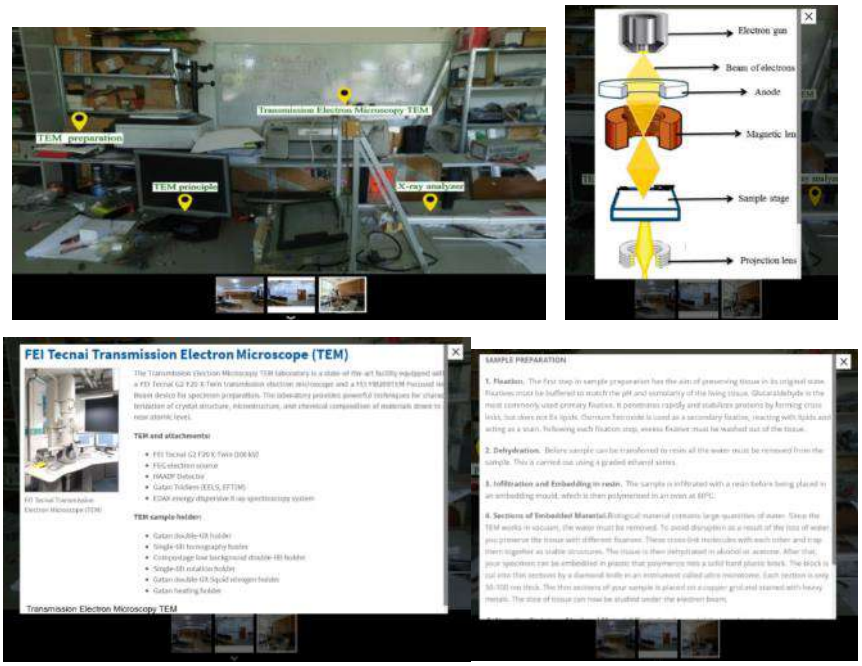


Figure 2.3.33. Same systematic method of providing information about similar method that is commonly used for performing the materials' characterization

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.3.10. Step 8 – Additional lecture on Smart (intelligent) – polymeric materials

In addition to all the existing resources provided about Materials characteristics presented in this section an additional module about Smart (intelligent) materials (in printed and in video format) has been prepared by one UPB in the frame of O3 concerning the Polymeric materials, since the existing course module and presentations that were given in the previous courses and lecture presentations were mainly oriented on the metallic materials / metallic applications of Additive Manufacturing technologies. The additional course module about Smart (intelligent) materials of Polymers can be accessed from the Testing and Materials virtual laboratory of the e-learning platform as one may notice in Figure 2.3.34 or can be accessed, visualized and downloaded from the next following link: https://drive.google.com/file/d/1kZFGg6peTSMEIp1WChIILkdA0hOZUuh9/view The video with the presented course made by UPB can be accessed and downloaded on the EMERALD Google drive on the next following link: https://drive.google.com/file/d/1y5mioTqXp3kjqWjgIJJRbd5PjFn3QzJ_/view

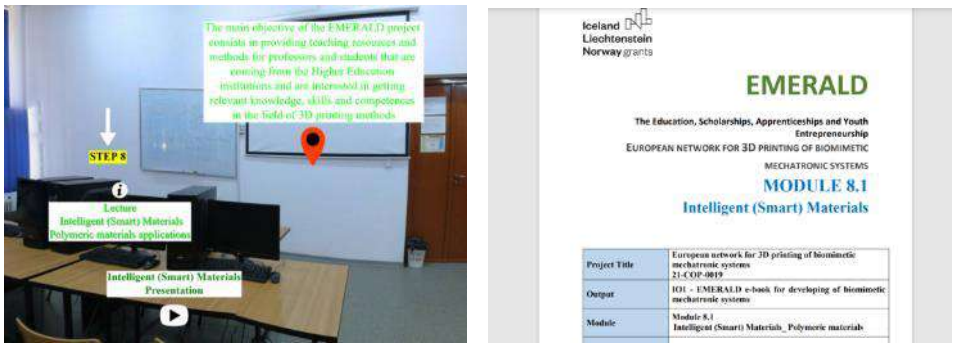


Figure 2.3.34. Intelligent (smart) Polymeric materials additional lecture prepared in the frame of O3

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In addition to the already provided details, the Director of Advanced Polymer Materials group of UPB has provided in this module a comprehensive overview of the various polymers that can be used in AM technologies, their properties, applications, and the challenges associated with their use, etc. (all theoretical fundaments necessary to be known in relation to this domain). The importance of this type of materials from the intelligence point of view consists in the adaptability and their functions and characteristics that make them smart choices for pushing the boundaries of what's possible in manufacturing, with significant implications for healthcare, electronics, and other industries seeking innovative solutions. These polymers comprise a wide category, starting from standard thermoplastics like PLA and ABS to specialized ones such as PEEK and TPU, offering diverse functional properties. Since the category of the applications and types of polymeric materials are highly diverse in the realized video presentation made by Director of Advanced Polymer Materials group of UPB have been included certain applications that the group is currently doing at UPB from different types of polymeric and bio-polymeric materials.

In terms of the most well-known FDM 3D printing technology, its versatility has been expanded through the use of composite filaments, which incorporate reinforcing agents like carbon or glass fibers, improving the mechanical strength and introducing new functionalities such as electrical conductivity. In the context of smart materials, these polymers adapt to specific needs, such as biocompatibility for medical applications or the ability to conduct electricity for electronic components. The utilization of composite materials also contributes to innovation in design, allowing for the creation of parts that are lightweight yet durable, potentially replacing traditional metallic components. In the made presentation there are discussed opportunities of using of new types of materials like PLLA for realizing highly complex parts for the bio-mechatronics domain (e.g. 3D printed prostheses – see Figure 2.3.35).

Figure 2.3.35. Prostheses realized by FDM 3D printing technologies from new types of materials

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Resin-based 3D printing technologies, including SLA, DLP, and LCD, use thermo-reactive polymers to produce a range of products with properties tailored to specific applications. The commercial resins are categorized based on their qualities, offering options from standard to flexible resins, each serving distinct purposes like high detail, transparency, toughness, and flexibility. Innovations in this area have resulted in high-resolution, durable, and robust products though handling and post-processing remains complex and can require careful management and disposal.

Selective Laser Sintering (SLS), another polymer-based 3D printing technology, uses a high-power laser to sinter powdered materials into solid forms, favored for its efficiency and broad material applicability. Nylon, a popular choice for SLS, is appreciated for its strength, durability, and heat resistance, though it does have limitations such as water absorption and sensitivity to UV light. Advances in nylon composites have introduced materials with enhanced properties, including electrostatic discharge capabilities, elasticity, and fire resistance (see Figure 2.3.36).

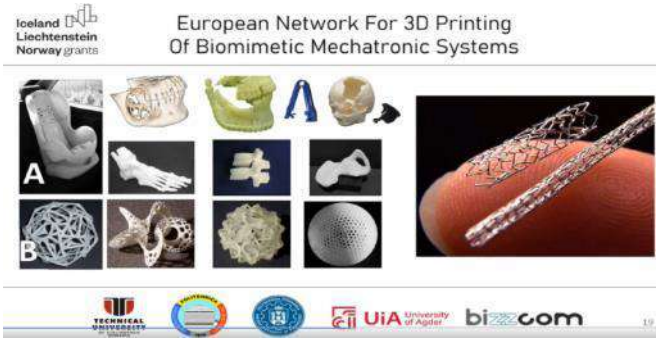


Figure 2.3.36. Examples of parts made of new types of polymers by SLS and SLA technologies

The medical sector greatly benefits from 3D printed polymers in applications ranging from prosthetics and orthotics to surgical tools and models. The ability to produce patient-specific designs on-demand supports the move towards personalized medicine, allowing for more accurate and effective treatments. The field of tissue engineering also utilizes 3D printing to create structures that replicate natural tissues, with ongoing research into improving biocompatibility and functionality as it was emphasized in the made presentation. In Figure 2.3.37 are presented few examples of 3D printed medical applications realized by bio-polymers (UPB has such highly advanced equipment items for bio-printing in the Laboratory of Advanced Processing Methods for Polymers and Nanomaterials.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

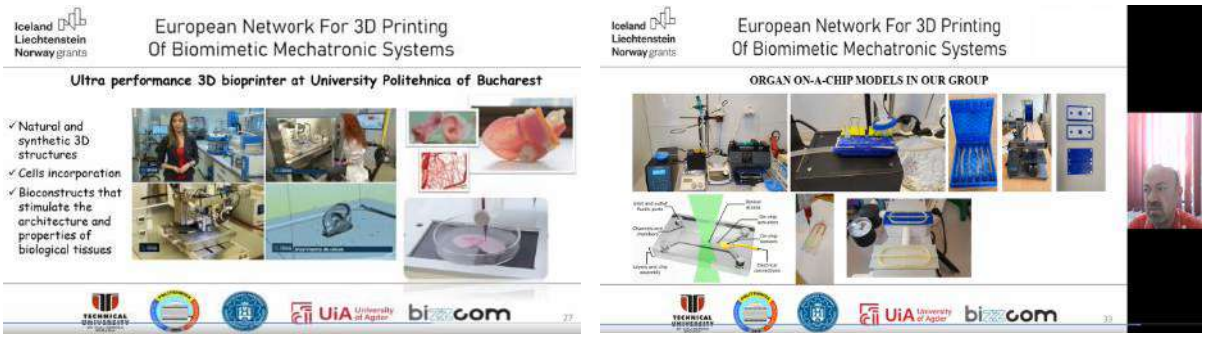


Figure 2.3.37. Examples of parts realized by 3D printing of bio-polymers at UPB

Applications realized by the group of UPB professors in the field of 3D bio-printing along with the new types of materials the group is testing (e.g. alginate materials), along with different types of coating that are used in close-correlation with the bio-polymeric materials, as well as the biomimetic concept in this context are very well emphasized in this presentation as one may notice in Figure 2.3.38.

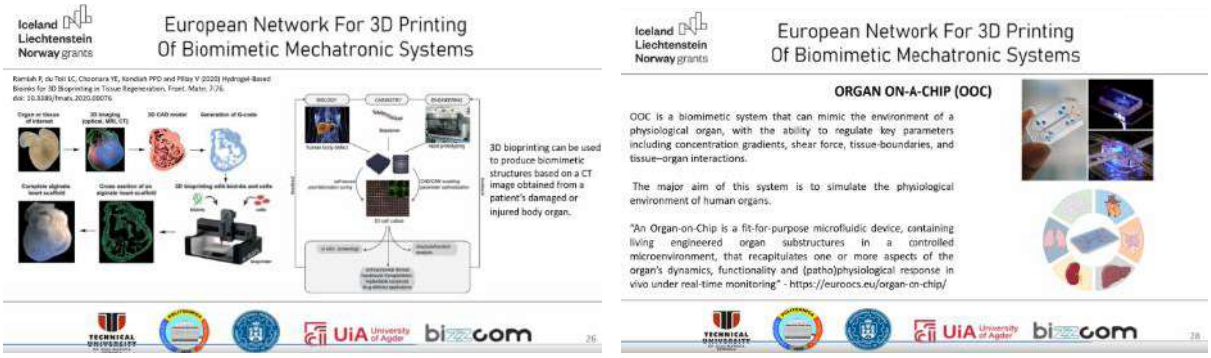


Figure 2.3.38. Biomimetic concepts (definition, structure, systems) integrated in UPB research activities

2.3.11. Step 9 – Additional lecture on Plastic aesthetics

Continuing with the route of plastic (polymeric) materials in completion of the already realized teaching resources (lectures) one additional presentation on the importance of Plastics and product Aesthetics have been prepared by UPB (in the frame of O3), being integrated into the Testing and Materials virtual laboratory room of the e-learning platform as one may notice in Figure 2.3.39, this presentation being possible to be accessed on the following link: https://drive.google.com/file/d/12ufNTdevtwbO2JvUW7a09WDg1yLGT-pq/view

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

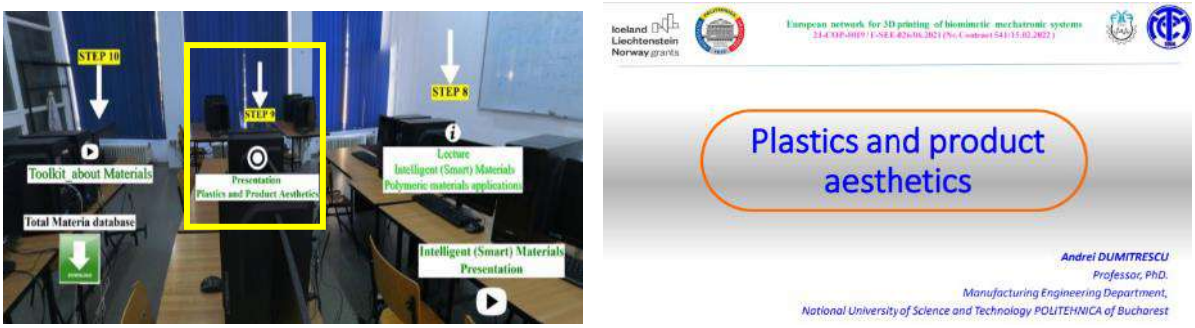


Figure 2.3.39. Plastic and product aesthetics lecture prepared by UPB in the frame of O3

The provided course presentation realized by UPB highlights the evolution of materials, aesthetics, and processes that have shaped the plastic industry, underlining the material's significant impact on design and consumer culture. Evolution and impact of plastic materials in design, highlighting the transition from natural polymers to synthetic plastics, and ultimately to advanced polymers in modern applications is explained in continuing. Natural plastics, characterized by their heterogeneity and craftsmanship, stood in contrast to the homogeneous nature of synthetic plastics, which are mass-produced and have a direct relationship between the material properties, manufacturing technology, and aesthetic outcomes (see Figure 2.3.40).

Figure 2.3.40. Differences between natural and synthetic plastics

In continuing the main differences between thermosetting plastics, like Bakelite, and thermoplastics, such as polyethylene and polystyrene are being explained as one may notice in Figure 2.3.41, along with the main definitions of thermosetting / thermoplastics (see Figure 2.3.41). As one may notice from Figure 2.3.41, thermosets, which emerged in the early 20th century, are molded into a permanent shape and possess notable properties like strength, electrical and thermal

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

insulation, and heat resistance, while, on the other hand, thermoplastics, which became prominent after World War II, offer a wide array of properties and are valued for their ease of processing, ability to be molded into various shapes and potential for color variation.

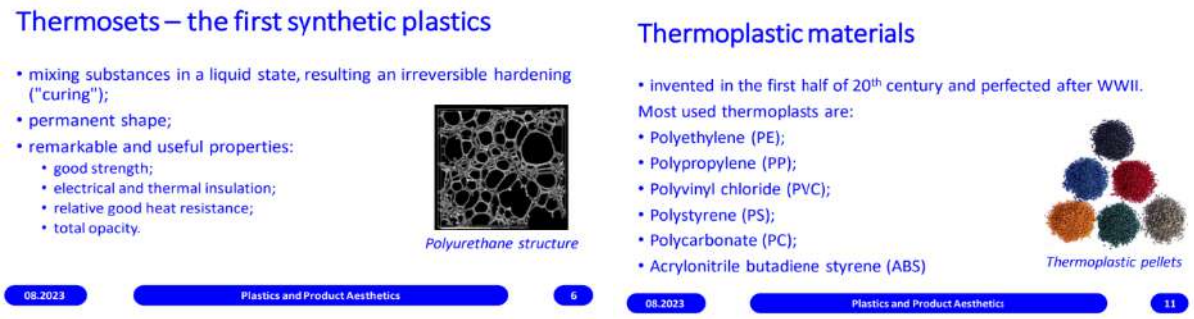


Figure 2.3.41. Thermosets and thermoplastic materials definition, examples and properties

In terms of processing techniques, there is a range of methods including injection molding, additive manufacturing, extrusion, and more, each with its specific applications and advantages, like shown in Figure 2.3.42.

If in the case of additive manufacturing there is more freedom in terms of designing of models and constraints, in case of Injection molding, for example the technology has some limitations and certain design constraints as one may notice in Figure 2.3.42, but injection molding technology is still widely used for its efficiency, especially in the case of mass production.

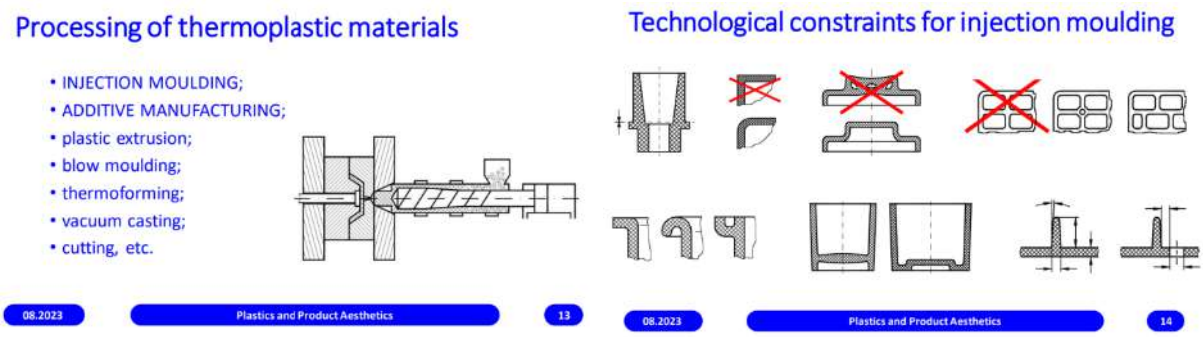


Figure 2.3.42. Processing of thermoplastic materials and technological constraints of injection molding

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.3.12. Step 10 - Smart (intelligent) materials laboratory work

Taking into consideration that material characterization methods (like SEM, TEM, EDX, FTIR) requires hands-on experience and access to equipment items that are mainly used for research (even if this step is highly important in the processing of selecting of the proper materials to be used in case of bio-mechatronic components to be manufactured (like robotic arms, orthoses, prostheses, etc.), the practical laboratory work in this case has been limited to the part of the toolkit module that has been produced by UPB partner in the frame of O2.

The toolkit module related to Materials part can be accessed directly on the Testing and Materials laboratory of the e-learning platform like it is shown in figure 2.3.43 or by accessing the following link: https://drive.google.com/file/d/1WxRRw1Zx_4Pt7TI0Ve17grOimDqokX1V/view

Figure 2.3.43. Accessing of the Materials toolkit part on the e-learning platform

In terms of its content, after students (users) are familiarized with all material characteristic methods, differences in between several categories of materials (polymeric, metallic, etc.), close correlated with the mechanical characteristic that is foreseen to be considered in closed correlation with the functionality requirements and constraints of the realized bio-mechatronic component, through the realized part of the toolkit related to the Materials section, the students (users) are being invited to get familiarized with databases of materials that exists on the market (e.g. Total Materia database (see Figure 2.3.44 - https://www.totalmateria.com/page.aspx?ID=Home&LN=EN – that can be accessed for free / trial version – link to the Total Materia database is indicated on e-

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

learning platform also along with the provided toolkit module as one may notice in Figure 2.3.43, so students can have quick access to it while they are preparing to follow the instructions and explanations that are provided in the toolkit module – link to be inserted on the e-learning platform) and are used by many researchers when they are asked to select the adequate type of material to be considered for certain stresses of the components to be realized by 3D printing technologies, going step by step in the database for the selection, being guided to select the proper type of material in the end.

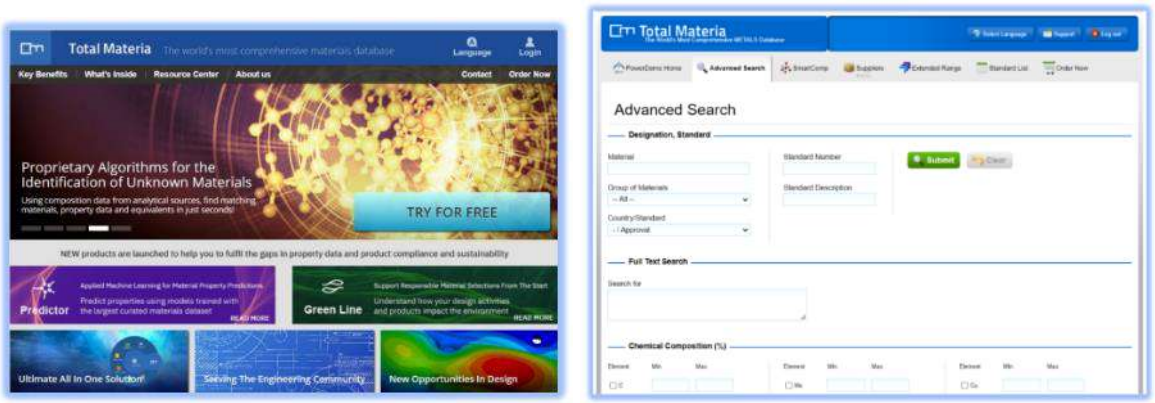


Figure 2.3.44. Total Materia database for proper selecting of the materials to be used for realizing of bio-mechatronic components using 3D printing technologies

Therefore, Total Materia database stands as an indispensable tool for engineers, researchers, and professionals in various fields, being used as a guide for the material selection process, ensuring that choices are made based on comprehensive and accurate data that are being provided in this database with materials characteristics (tensile strength, fatigue strength, etc) relying on more than 74 standards in the World. Selection of the material in concordance with the desired characteristics ensures that applications like orthoses and prostheses in the bio-mechatronics sector are not only functional but also optimized for the specific needs and challenges of their use in relation with the proper selected materials. Total Materia database stands as a high powerful resource in the materials science domain boasting over 20 million property records for more than 450,000 materials, both metallic and non-metallic that are accessible in 26 languages.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The power of Total Materia stands in its detailed and easily accessible data, which empowers professionals to make informed decisions, ensuring that the materials they select are fit for purpose, adhere to required standards, and are the best possible choice for the application they are working on, including bio-mechatronics.

In order to make it highly practical, through this part of the toolkit related to the Materials, an example for the selecting of a metallic material to be searched for a prosthetic component for the bio-mechatronic sector is presented. In this case, the engineer might start with a known material like Ti6Al4V, a titanium alloy renowned for its strength and biocompatibility. Using Total Materia's Advanced Search method, it is possible in this way to filter the search by referring to the European Union standard to locate the alloy, then to continue in searching / filtering for the specific properties / characteristics being analyzes in more details, like tensile strength or fatigue strength (characteristics data) that are relevant to the prosthetic's performance requirements (figure 2.3.45).

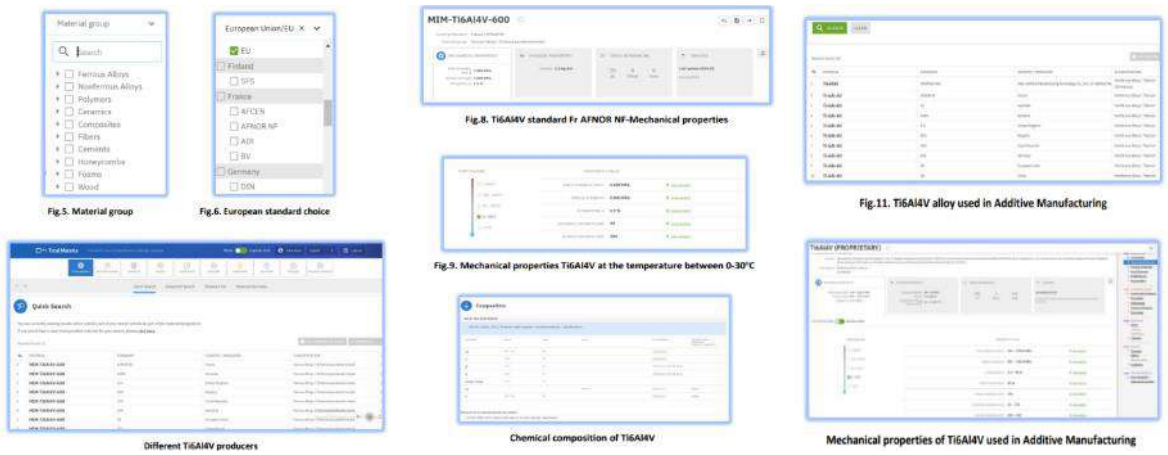


Figure 2.3.45. Searching and exploring characteristics of a well known material (TiAl6V4) in Total Materia

Further on, through the Total Materia database can be explored and found out additional information about heat treatment options and benefits of these heat treatments, can be found details about the metallography / materials' structure in order to be absolutely sure that the chosen material will perform reliably under the stresses that the component (prosthetic component in this case) will be subjected to (see Figure 2.3.46).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

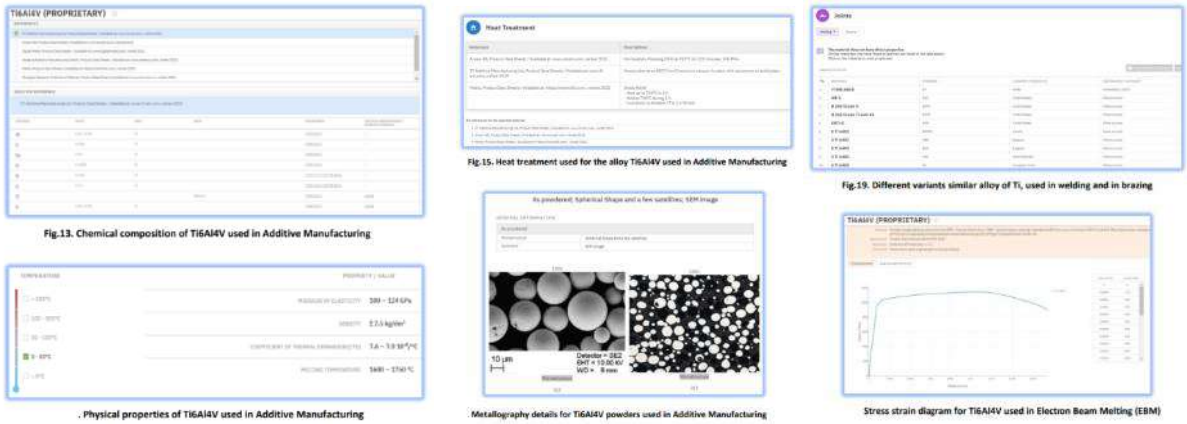


Figure 2.3.46. Exploring additional data on heat treatments, metallurgy and properties of TiAl6V4 alloy

In addition, one of the key features of Total Materia stand in its proprietary algorithms, which allow for the rapid identification of unknown materials by comparing analytical composition data to find matching materials and desired properties within seconds. Knowing the material's composition but not its name, Total Materia's algorithm can quickly identify and suggest materials with similar compositions from its database. This could be crucial when a certain material is not readily available, or a more cost-effective alternative is needed to determine certain characteristics for proper materials to be used for specific type of applications, like prosthetics or orthotic components (see Figure 2.3.47).

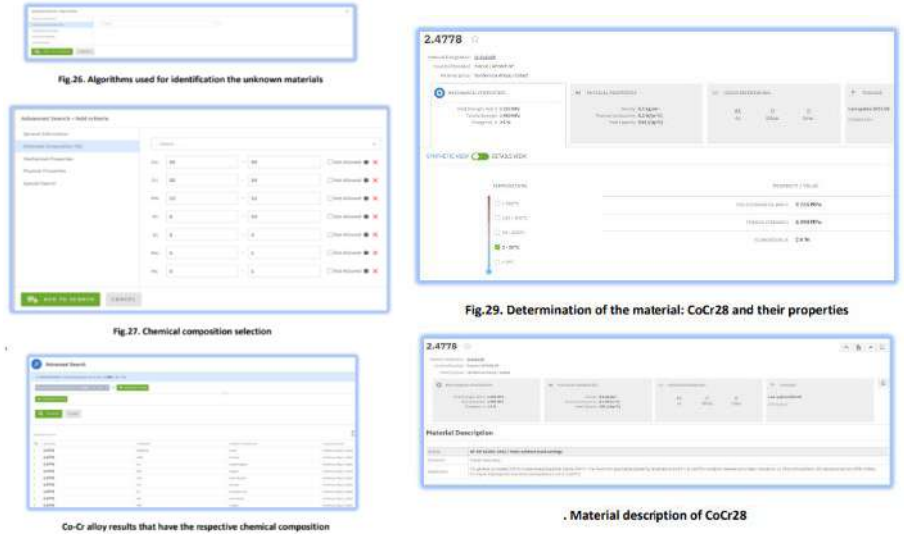


Figure 2.3.47. Identifying of unknown materials by comparing analytical composition data to find matching materials and desired properties

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In the same way, as the provided example, students (users) can play to search in the Total Materia database other type of materials (Total Materia database comprises additional information concerning other types of materials, like polymers or composite materials that are suitable to be used for realizing of different bio-mechatronic components, like orthoses or prostheses, etc. to be made of well-known and used materials (like PLA or ABS or nylon) or from materials that are unknown and could be identified by comparing the reached characteristics experimentally determined to the ones that are provided in the Total Materia database) in the end.

2.3.13. Conclusions about Testing & Materials teaching resources of the e-learning platform

In conclusions, the Testing and Materials virtual laboratory of the e-learning platform provides a comprehensive range of educational resources that are primarily focused on materials that are suitable for 3D printing technologies, including the latest advancements in bio-materials field. This information is provided through dedicated course module and additional lectures. Another significant aspect of the Testing and Materials virtual laboratory of e-learning platform is its detailed explanation of various microscopic analysis techniques. These explanations cover the working principles, settings, and equipment items types, aiding users in familiarizing themselves with these instruments and the importance of evaluations conducted through microscopy and other analyses like X-ray and spectroscopy. Additionally, guiding tutorial is provided on preparing samples for different types of analyses. In the field of mechanical testing, the Testing and Materials virtual laboratory has incorporated an extra lecture that goes deeper into various testing methods such as tensile strength, hardness determination and toughness tests. This content is integrated within the Testing and Materials virtual laboratory of e-learning platform through concise descriptions, photos illustrating procedural steps, and videos of tests that have been conducted, such as on a hand orthosis. Moreover, the Testing and Materials virtual laboratory of e-learning platform includes mechanical testing of diverse material samples to determine their mechanical characteristics to be used for more reliable Computer Aided Engineering (CAE) analyses, moving one step forward from the characteristics found on program libraries or internet catalogues to more realistic characteristics to be used as they have experimentally determined through mechanical testing analyses. This approach ensures one more reliable assessment of results reached in terms of Computer Aided Engineering analyses being performed.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Emphasizing the precision and quality control in manufacturing implants, prostheses, and orthoses, an additional lecture that has been realized by the UPB partner addresses these critical aspects. This complements the information already provided on material characteristics and testing methods. Despite the comprehensive coverage of topics like plastic aesthetics, the virtual nature of the laboratory limits the integration of practical hands-on experience, essential in fields like bio-mechatronics. This challenge has been addressed therefore by using images and videos to explain practical aspects of real made experiments.

The Testing and Materials virtual laboratory of the e-learning platform also supports students in selecting appropriate materials for bio-mechatronic components. This is facilitated by a toolkit module that has been integrated into the Testing and Materials virtual laboratory of the e-learning platform, guiding students to learn how to use Total Materia database, in order to step by step teach students to choose the right material based on the requirements of their bio-mechatronic components, considering factors like mechanical resistance and type of material to be used in this context (plastic, metallic, ceramic).

2.4. 3D printing virtual laboratory room (PUT)

2.4.1. Accessing of 3D printing laboratory virtual laboratory room

3D printing virtual laboratory room which has been assigned to the Poznan University of Technology as one may notice in Figure 2.4.1 can be accessed from the www interface of the EMERALD project (https://project-emerald.eu/?page_id=404) or directly by accessing the next following link: https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-2.95,.1&ss=37

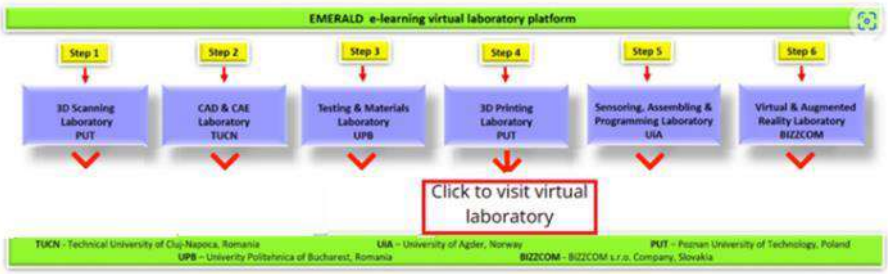


Figure 2.4.1. Accessing of the 3D printing laboratory room from the e-learning platform

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

If the 3D scanning laboratory is accessed first, it is still possible to travel to the other lab, as physically they are in one space (see Figure 2.4.2). The guideline for traveling to the 3D printing lab starting from 3D scanning lab is presented in Figure 2.4.3. Similarly as the 3D scanning virtual laboratory room at PUT, 3D printing laboratory, has been realized using Matterport Pro camera, the captured images undergoing in further processing using Matterport software, allowing the integration of educational materials related to 3D scanning for the bio-mechatronic components that have been developed within the EMERALD project related to this topic in particular.

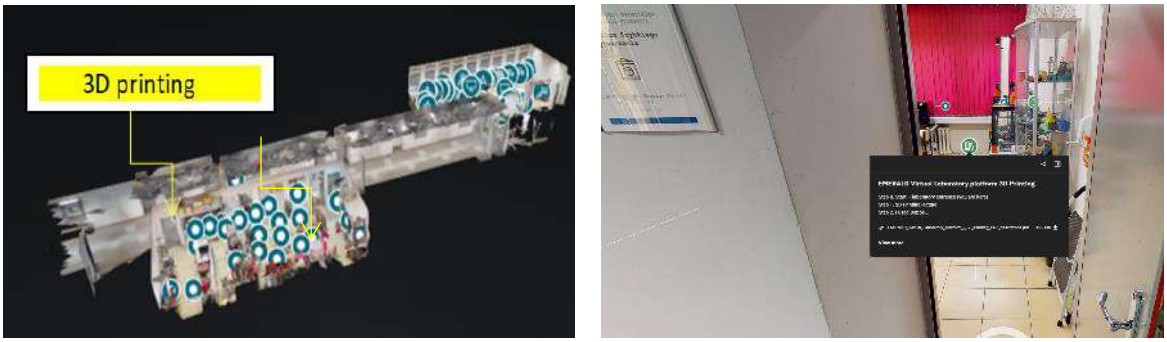


Figure 2.4.2. Main entrance of the 3D printing laboratory of PUT

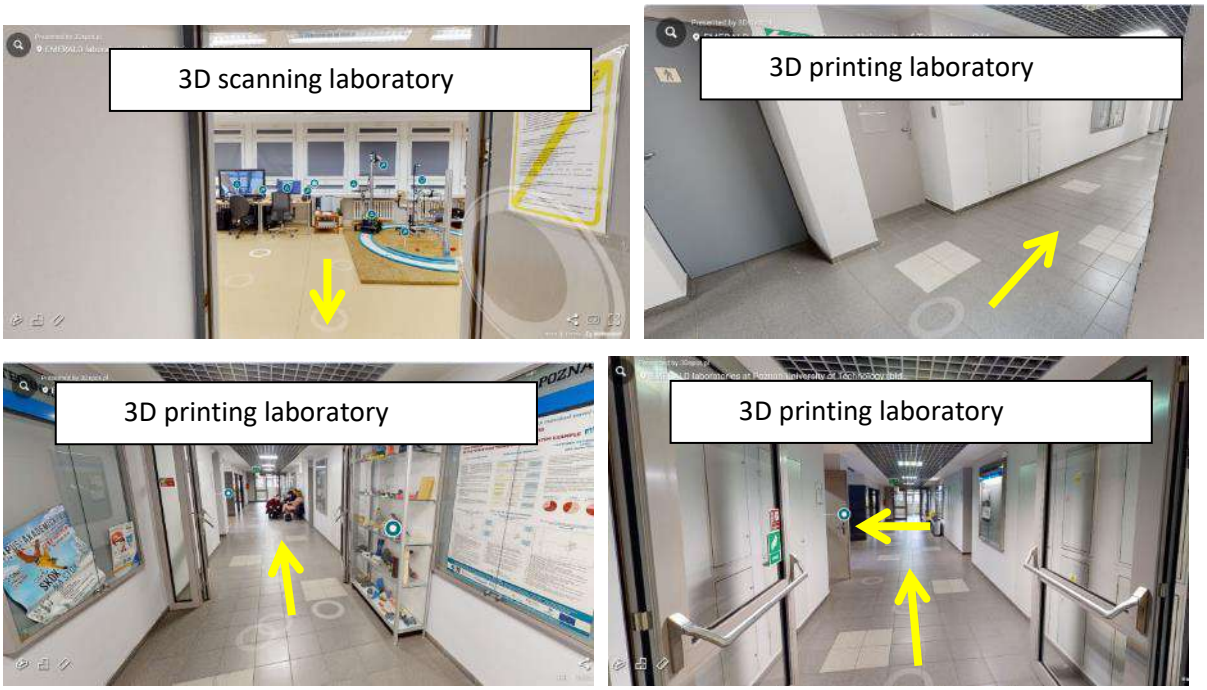


Figure 2.4.3. Reaching to the 3D printing virtual laboratory of PUT

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.4.2. 3D printing teaching resources overview

In this Virtual Laboratory, it is possible to explore 3D printing processes of parts of biomechatronic devices created as case studies of the EMERALD project. The users can get familiarized with 3D printing techniques of polymeric materials – FDM and PolyJet technologies, then see educational videos about how different devices are manufactured. The last step is learning how to create programs for these devices, by use of video tutorial and instruction of installation and use of programs for that purpose.

The course of 3D printing available in that part of PUT virtual laboratory has been divided into 6 main steps (Figure 2.4.4), with multitude of additional information available besides these steps. Users (students) are asked to explore on their own the laboratory and open everything they think could be interesting.

Steps:

Step 0. Start – laboratory entrance

Step 1. 3D Printing course module and lecture

Step 2. Fused Deposition Modelling – wrist hand orthosis – tutorial video

Step 3. Fused Deposition Modelling – bicycle prosthesis gripper – tutorial video

Step 4. Fused Deposition Modelling – ankle foot orthosis – tutorial video

Step 5. PolyJet – mechatronic prosthesis gripper – tutorial video

Step 6. Tutorials on creating programs for 3D printing processes

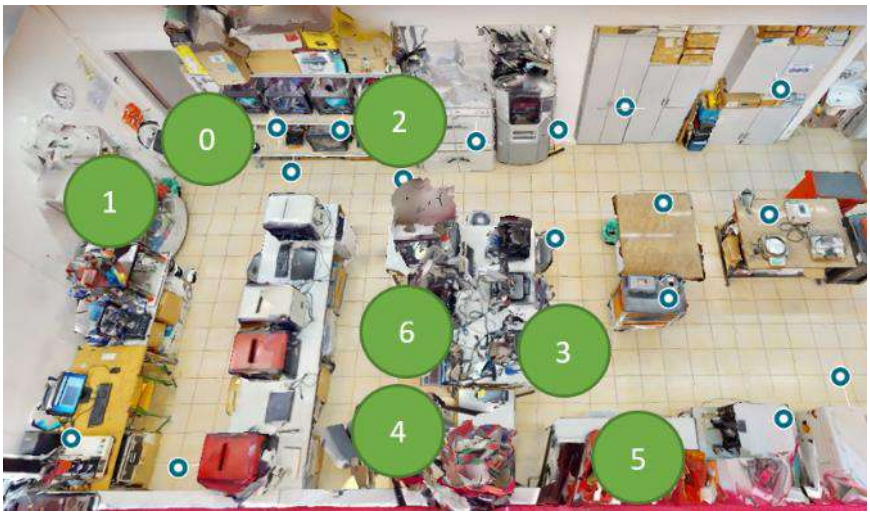
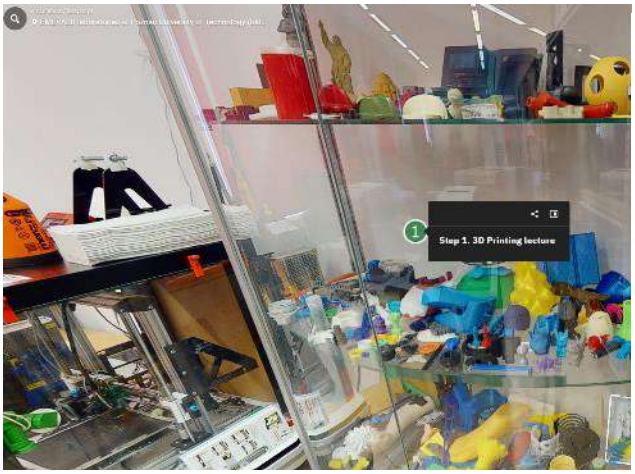


Figure 2.4.4. 3D printing – steps of the course

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.4.3. Step 1 - 3D printing basics – module and lecture

In order to comprise the basics of the 3D printing stage related in the conceiving of the bio-mechatronic systems for people with special needs (amputated arms) first step that has to be followed by the students is related to the foundational course materials that cover the basics of 3D printing. Two of such materials are prepared – O1 course module (document) and a lecture in form of slides. The basics related to the 3D printing course that has been prepared by PUT and TUCN partners of the EMERALD consortium in the frame of O1 provides theoretical fundamental information needed for the students (users) to comprise the working principles of the main 3D printing methods that can be used for producing of bio-mechatronic components, like orthoses, prostheses or robotic arms. The course module that provide the describing of main methods of 3D printing technologies can be accessed like shown in Figure 2.4.5 being possible to be accessed directly on the 3D printing laboratory of the e-learning platform or by downloading it from the next following link: https://project-emerald.eu/wp-content/uploads/2023/03/EMERALD_IO1_module_7_3D-Printing.pdf



EMERALD

The Education, Scholarships, Apprenticeships and Youth Entrepreneurship

EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC MECHATRONIC SYSTEMS

MODULE 7 – 3D PRINTING

Project Title	European network for 3D printing of biomimetic mechatronic systems 21-COP-0019
Output	IO1 - EMERALD e-book for developing of biomimetic mechatronic systems
Module	Module 7 – 3D Printing
Date of Delivery	July 2022
Authors	Filip GÓRSKI, Razvan PACURAR

Figure 2.4.5. Accessing of the EMERALD 3D printing course module on the 3D printing laboratory platform

The document containing 3D printing course module created in O1 is an extensive resource on 3D printing technologies, particularly focusing on their applications in creating biomimetic and prosthetic devices. The summary of the document is as follows:

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

1. Introduction to Additive Manufacturing (AM): The document begins by introducing AM, also known as 3D printing highlighting its revolutionary impact across various industries, especially in medicine. It notes the ability of AM to create intricate structures that were previously impossible with traditional manufacturing methods, opening new possibilities in medical treatments and procedures (see Figure 2.4.6).

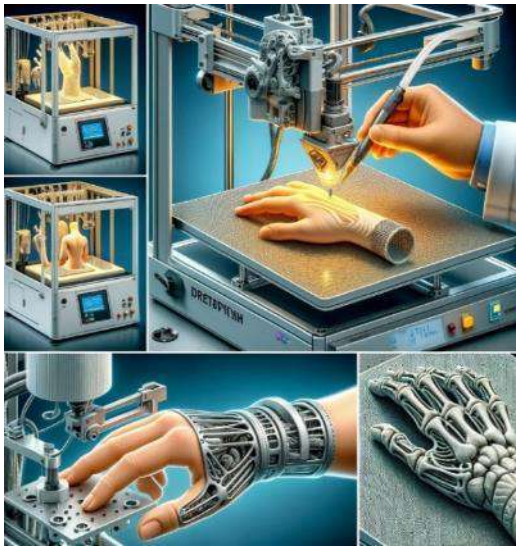


Figure 2.4.6. EMERALD 3D printing course module and lecture – main ideas as depicted by AI

2. 3D Printing in Medicine: The application of 3D printing technologies methods shown in Figure 2.4.7 in medicine includes the creation of prosthetics, implants, surgical tools, and even human tissues and organs. Custom-made patient-specific prosthetics, tailored implants, and the use of 3D printing for surgical planning and simulations are particularly emphasized.

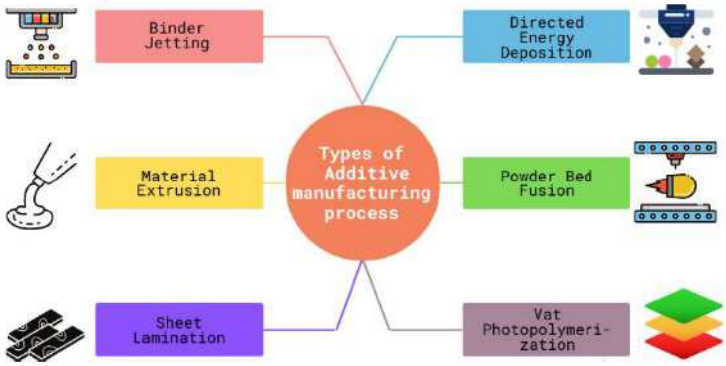


Figure 2.4.7. EMERALD 3D printing course module – technology overview

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

3. Biomechatronics and Prosthetics: AM's role in biomechatronics is explored, particularly in developing advanced prosthetics and exoskeletons. The document highlights the ability of AM to create custom-fit, complex structures, significantly improving the comfort and functionality of prosthetics and exoskeletons.
4. Basics of 3D Printing Technology: The document delves into basic definitions and concepts of AM, covering various aspects like rapid prototyping, rapid manufacturing, and rapid tooling. It also discusses different 3D modeling software, materials used in AM, and post-processing requirements.
5. Review of 3D Printing Technologies: Different 3D printing technologies are reviewed, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and others (see Figure 2.4.8). Each technology is described in detail, including the materials used, process specifics, and their applications in medical device fabrication.

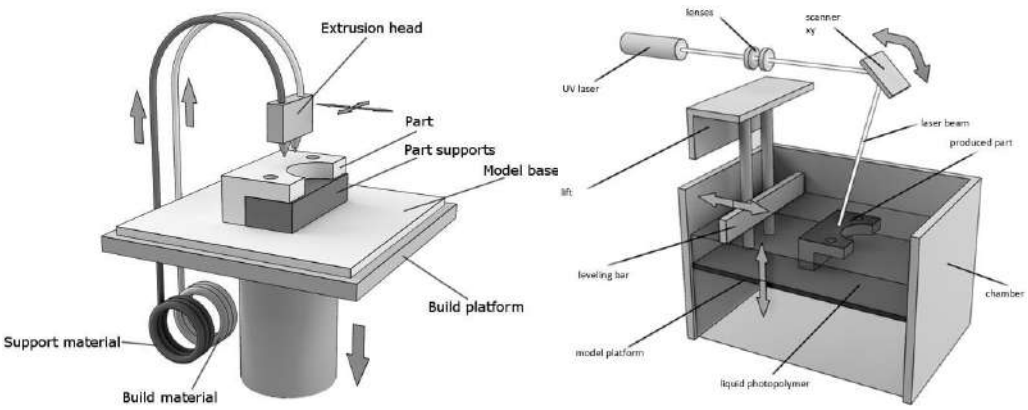


Figure 2.4.8. EMERALD 3D printing course module – technology schemes (FDM, SLA)

6. Preparation for 3D Printing Processes: The module provides insights into preparing 3D printing processes, including selecting data formats, using slicer software, and setting parameters for printing anatomical shapes. It also contains detailed guidelines on how 3D models should be designed and prepared to properly utilize 3D printing processes and their limitations as well.
7. Examples of 3D Printed Biomimetic Devices: Various applications of 3D printing for biomimetic devices are presented, such as artificial joints, heart valves, skin tissues, bones, cartilage, blood vessels, prosthetic feet, and orthoses. Each example illustrates the potential of 3D printing in replicating natural anatomical structures for medical purposes.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

8. Case Study – Therapeutic Wrist Hand Orthosis: A specific case study of a therapeutic wrist hand orthosis is detailed, demonstrating the entire process from design to manufacturing using FDM technology. The study underscores the customization and adaptability of AM in creating patient-specific medical devices. It is related to EMERALD project case study #3 (see Figure 2.4.9). The case study concludes the module.

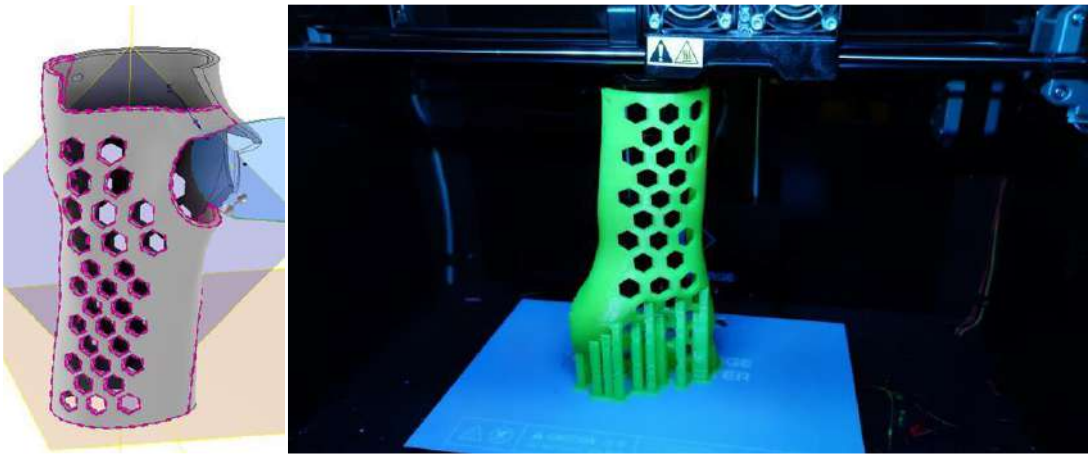


Figure 2.4.9. EMERALD 3D printing course module – case example – wrist orthosis

The second resource available in step 1 of 3D printing laboratory at PUT is lecture by Prof. Filip Górski from Poznan University of Technology. This lecture provides a comprehensive overview of additive manufacturing technologies applicable to the design and production of prostheses. The lecture covers several key aspects:

1. Manufacturing Technologies Overview

It begins with an overview of manufacturing technologies, broadly categorized into subtractive, volumetric, and additive methods. The additive manufacturing (AM) is emphasized as a method where material is applied layer by layer without the need for specific technological equipment.

2. Basics of Additive Manufacturing, classification.

The lecture delves into the fundamental concepts of AM, describing it as a process of creating objects directly from a digital CAD model. This process involves dividing the digital model into layers, and the method of division significantly impacts the process and the final product's properties.

Various AM techniques are discussed, including UV light hardening of liquid polymers, extrusion, sintering, powder printing, and lamination. Each technique has distinct characteristics and applications, with several hybrids combining different processes.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

3. Specific AM Techniques Explored
    - FDM/FFF Technology: Fused Deposition Modeling, a widely used AM technique, is explored in detail. This technique involves building objects layer by layer from a CAD model using thermoplastic polymers.
    - UV Technologies: Technologies like Stereolithography (SLA) and Polyjet are covered, detailing their processes and medical applications such as implants and surgical aids.
    - Sintering Technologies: Selective Laser Sintering (SLS) and other variants are discussed, highlighting their usage in creating complex prosthetic parts and implants.
4. Applications in Prosthetics

The lecture outlines specific applications of AM in prosthetics, such as manufacturing limb prostheses, orthoses, and orthopedic insoles. It highlights the advantages of AM in creating customized, complex shapes that are otherwise difficult to produce.

5. Strengths and Potential, Limitations and Challenges of AM

The lecture emphasizes the strengths of AM, including the ability to produce more complex shapes, the rapid preparation of manufacturing processes, and relatively low costs. The potential for AM to revolutionize manufacturing by enabling independent production of medical products like prostheses is discussed. Despite its advantages, the lecture also addresses the limitations of AM, such as shape and size constraints, the need for post-processing, and the costs associated with machinery and materials.

The lecture presents an overview of industry expectations from AM, particularly in the context of the aviation and defense sectors, highlighting the production of non-standard individualized parts and the potential for increased production profitability.

2.4.4. Steps 2-5 - 3D printing tutorial videos

The steps 2 to 5 require the viewer to watch timelapsed (sped up) videos on how processes of 3D printing of parts of various biomechatronic devices are conducted. The step of program preparation is not yet described in these movies (it is a subject of the last, sixth step). The movies present manufacturing of parts related to particular case studies of EMERALD project. These are the following (see Figure 2.4.10):

1. Wrist hand orthosis (one part of two) – part of the biomechatronic orthosis – VR game controller (case study #3 of EMERALD).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2. End effector (gripper) for bicycle handlebar – part of the sensorized prosthesis (case study #1 of EMERALD).
3. Ankle foot orthosis – part of the sensorized orthoses for therapy gamification (case study #4 of EMERALD).
4. Gripper and worm gear elements – part of the mechatronic actuated hand prosthesis (case study #2 of EMERALD)

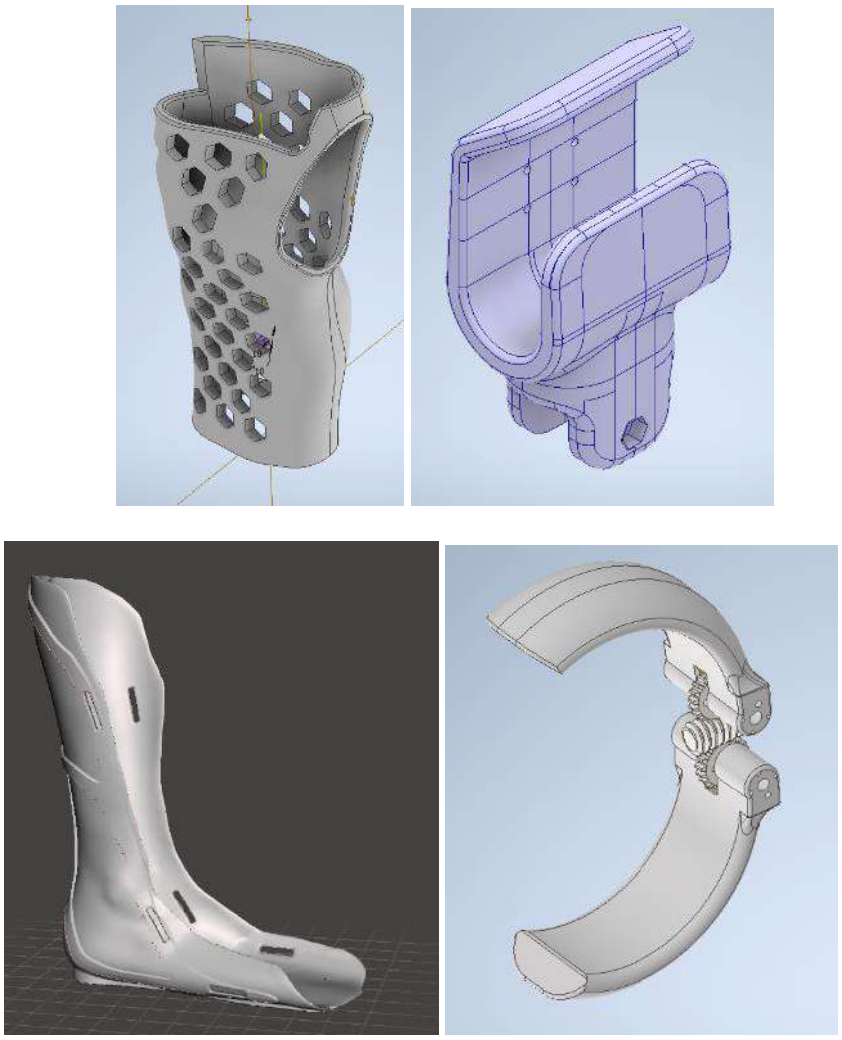


Figure 2.4.10. EMERALD 3D printing tutorials – depiction of parts that are printed in tutorial videos available in the Virtual Platform

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The order of these steps is a result of "typicality" of the depicted processes. No. 1 (step 2) is a very standard process and FDM printer, with a closed chamber, and not many things to settle up. No. 2 (step 3) is similar, but a cheaper printer with open chamber is used, which may cause a bit more problems and limitations in material. For no. 3 (step 4), due to height of the printout, FDM machine with non-typical kinematics – delta type – is used, with open chamber. The no. 4 is a different process – PolyJet, where UV resin is used along with wax-like support structures. The process was selected due to its usefulness in re-creating small details. The PolyJet machine was not in the laboratory when the Virtual Laboratory was created (it's a relatively new purchase), so it cannot be found there, it's only visible in the movie – so that is another additional value for the learners.

By watching the videos, users gradually get familiarized with quirks and specificity of 3D printing of parts of biomechatronic devices for people with special needs, using various polymers and methods of processing. They can get familiar with process course, its length for specific dimensions, materials and processes, post processing activities, as well as they can visually evaluate and compare surface quality of the prints and detail representation, starting with $500 machine (Creality CR-10), ending with a $100 000 one (Stratasys MediJet).

The step no. 2 is accessed by an appropriate link to be found in the room (green no. 2). It contains the YouTube video presenting 3D printing of hand orthosis using FlashForge Creator Pro machine (see Figure 2.4.11).

Figure 2.4.11. EMERALD 3D printing tutorials – step 2

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

As it's an initial video for 3 FDM processes, it presents preparation of the machine (along with material insertion), as well as first layers. Then the process is timelapsed, until the product is removed (see Figure 2.4.12).

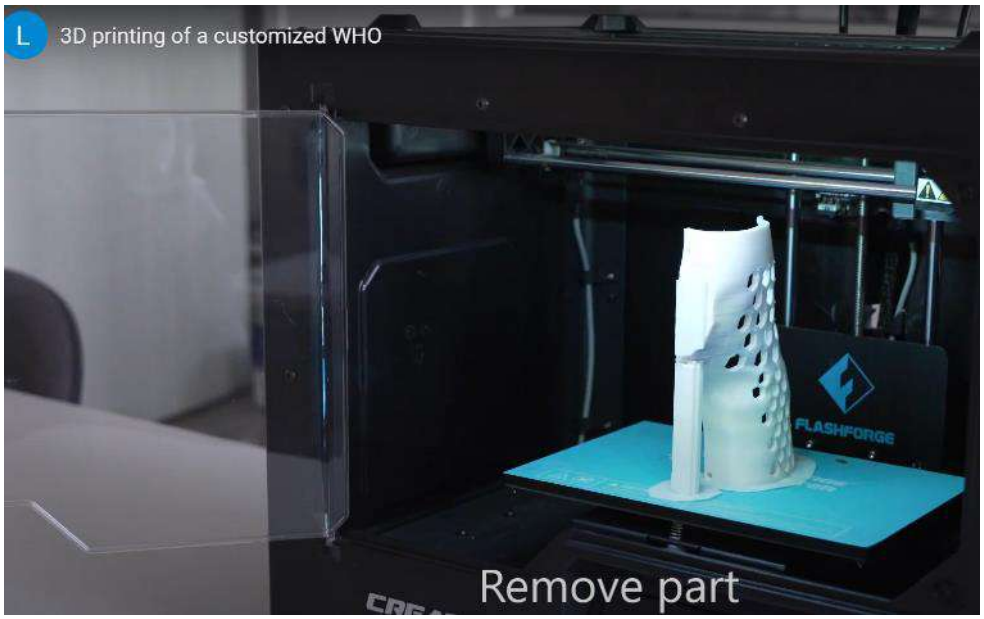


Figure 2.4.12. EMERALD 3D printing tutorials – step 2 – fragment of video

In another place in laboratory – if the student exploring it is careful enough – it can be found a second part, depicting post processing of one half of the hand orthosis (see Figure 2.4.13).

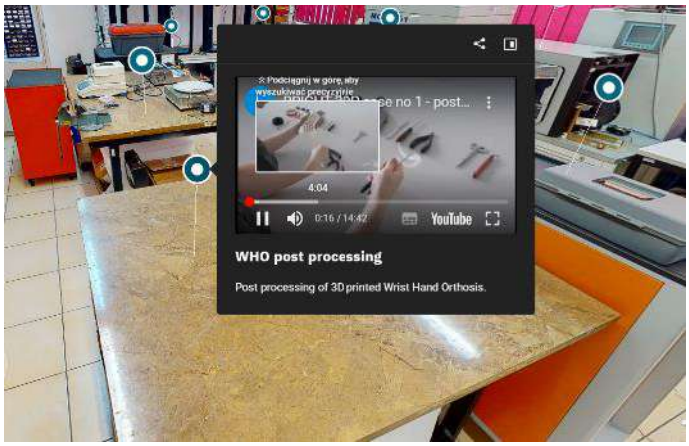


Figure 2.4.13. EMERALD 3D printing tutorials – post processing of hand orthosis

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The second tutorial video can be found by using an appropriate number (3) and it is printing of the bicycle gripper, using PLA material, on an open-chamber, low-cost machine made by Creality (see Figure 2.4.14). In this video, detailed machine presentation is not presented, as it is similar as in the case of other FDM machines. It presents timelapsed print and then removal of the print for visual assessment and preparation of post processing (support removal - not depicted) – see Figure 2.4.15.

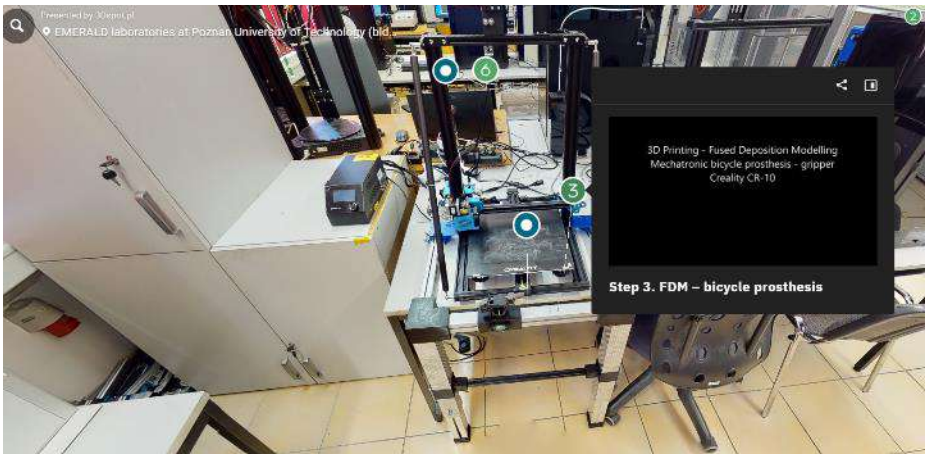


Figure 2.4.14. EMERALD 3D printing tutorials – step 3

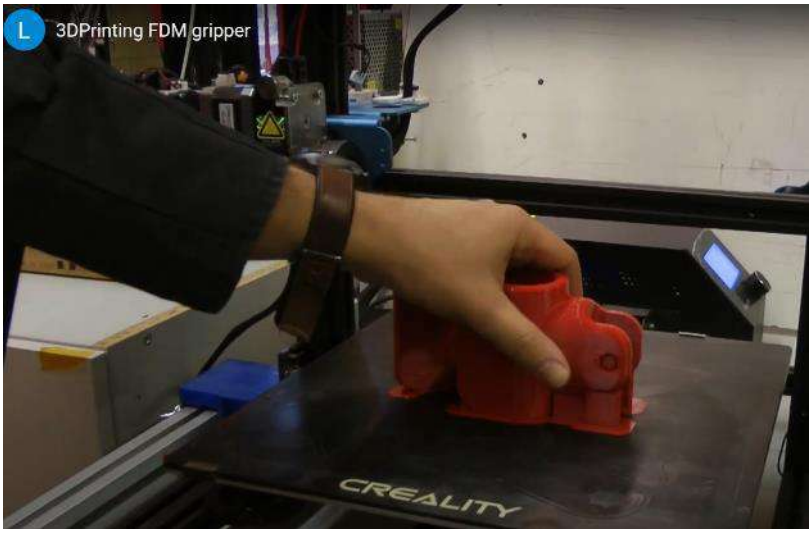


Figure 2.4.15. EMERALD 3D printing tutorials – step 3 – fragment of video

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The third tutorial video can be found by using an appropriate number (4) and it is printing of the ankle foot orthosis, using PET-G material, on an open-chamber, delta-type machine made by FLSun (see Figure 2.4.16). The video presents timelapsed print and then removal of the print for visual assessment and preparation of post processing (support removal - not depicted) (see Figure 2.4.17).

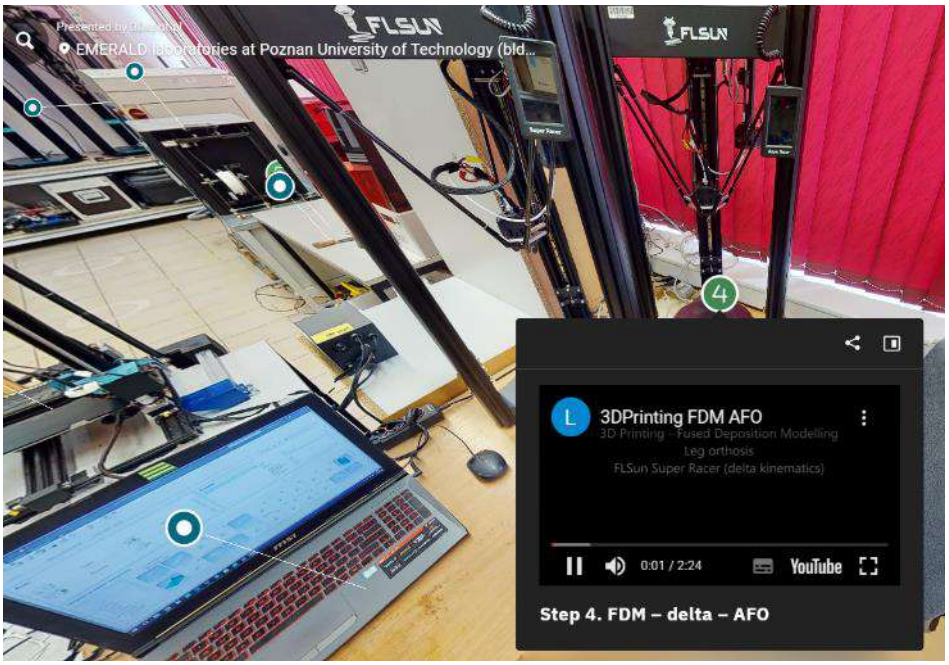


Figure 2.4.16. EMERALD 3D printing tutorials – step 4

Figure 2.4.17. EMERALD 3D printing tutorials – step 4 – fragment of video

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The final tutorial video can be found by using an appropriate number (5) and it is printing of the parts of actuated hand prosthesis, using DraftWhite – UV resin material, using high-quality, expensive professional grade PolyJet device – Stratasys MediJet J5 (see Figure 2.4.18). The video presents timelapsed print and then removal of the print for visual assessment, as well as the post processing procedure (support removal by water jet and cleaning of the parts) (see Figures 2.4.19 -2.4.21).

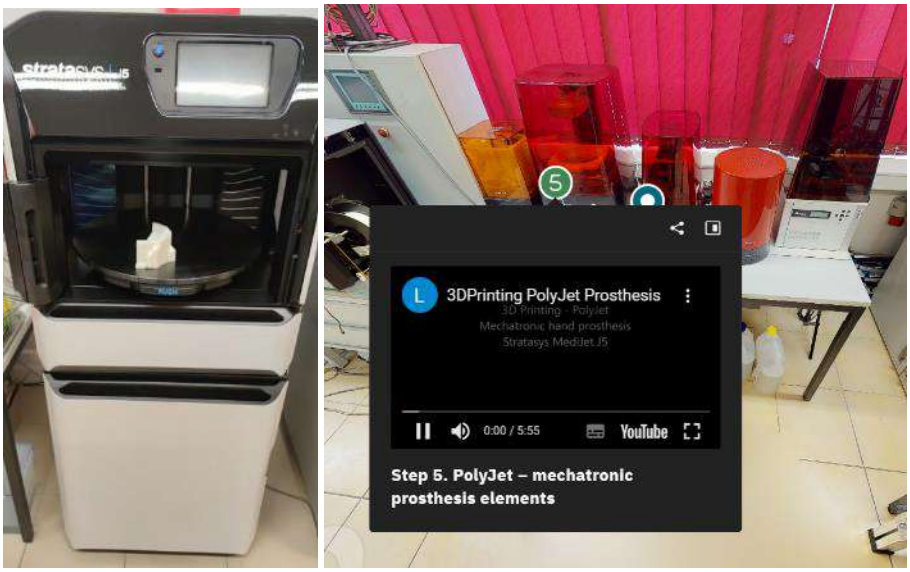


Figure 2.4.18. EMERALD 3D printing tutorials – step 5 – accessing; machine used for the printing (not depicted in Virtual Laboratory)

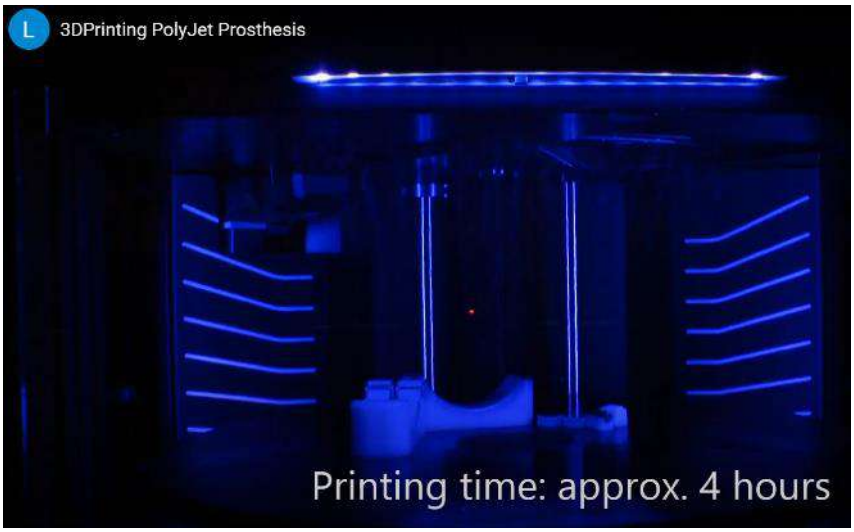


Figure 2.4.19. EMERALD 3D printing tutorials – step 5 – fragment of video – printing

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.4.20. EMERALD 3D printing tutorials – step 5 – fragment of video – post processing

Figure 2.4.21. EMERALD 3D printing tutorials – step 5 – printed parts

After the students get familiarized with the processes course, they can continue with practical work, related to preparing of the programs.

2.4.5. Step 6 – laboratory work

The step 6 can be accessed by an appropriate green marker in the Virtual Lab of 3D printing at Poznan University of Technology. The step contains a compound video, in which three different software solutions are presented and three different programs are prepared, for manufacturing of parts of biomechatronic devices (related to EMERALD case studies) as presented in earlier steps – tutorial videos.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The students are able to learn how these prints were prepared and do it on their own, thanks to links to the software installation, as well as a package of models in STL format, which can be used to exercise various forms of process planning by the students themselves and simulating e.g. times of manufacturing with different settings of processes (such as layer thickness, infill or orientation in the working chamber).

The first part of the tutorial concerns preparation of the ankle foot orthosis model for printing on a delta-type FDM machine, using freeware software Ultimaker Cura (see Figure 2.4.22). The movie presents positioning, selecting parameters and manual support structure preparation, as well as slicing and simulation of process course and length.

Figure 2.4.22. EMERALD 3D printing tutorials – step 6 – first part (CURA)

In the second part, wrist hand orthosis model (case study #3) is prepared for printing on a standard FDM machine, using commercial software Simplify3D (available in trial version for students so they can try themselves) (see Figure 2.4.23). The movie presents the same operations as in the Cura software and assumes printing both parts of the orthosis in the same process.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

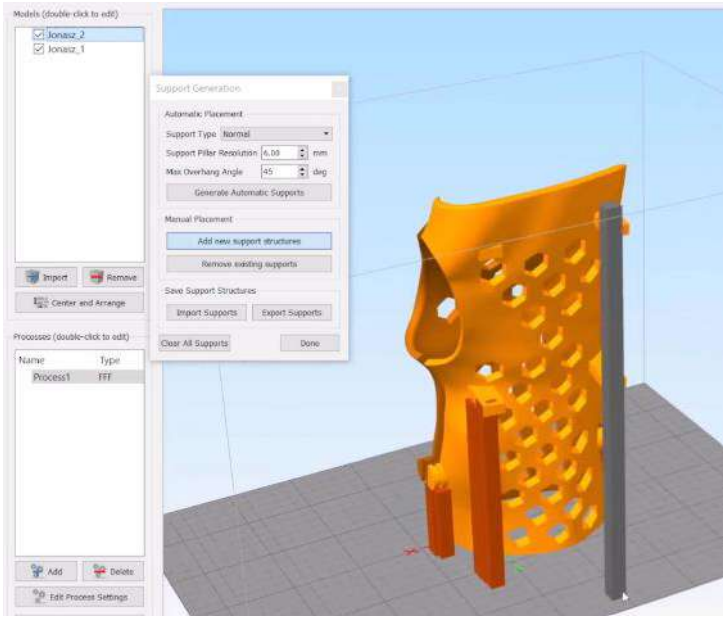


Figure 2.4.23. EMERALD 3D printing tutorials – step 6 – second part (Simplify 3D)

In the third part, parts of actuated mechatronic prosthesis are being prepared for printing on a PolyJet machine, using free software GrabCAD Print. (see Figure 2.4.24) The movie presents the operations of selection of proper position, basic parameters, as well as colors (PolyJet is a multi-color machine, allowing selection of any color of printed parts with standard material configuration).

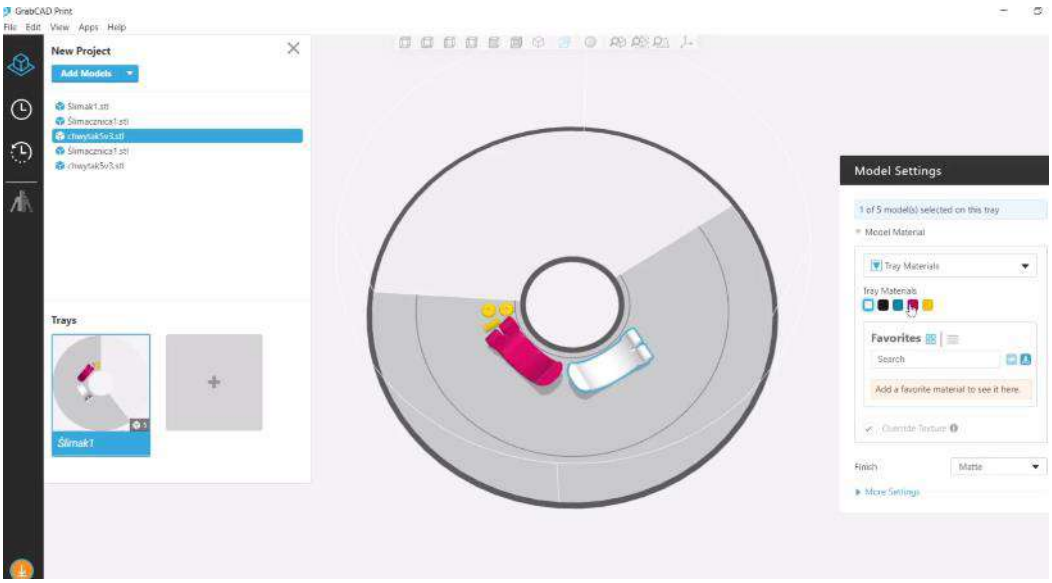


Figure 2.4.24. EMERALD 3D printing tutorials – step 6 – third part (GrabCAD)

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The tutorials are presented in great detail, with comments depicting the main points that the student must pay attention to. After watching the videos, the students are encouraged to install the software and try for themselves. A file with detailed instruction of installation is also available in the same place in the virtual platform.

2.4.6. Additional 3D printing content of the Virtual Lab at PUT

Apart from the steps presented in the main course of the tutorials, related to the main case studies of EMERALD project (biomechatronic individually customized 3D printable devices), the laboratory contains many useful information related to 3D printing and auxiliary processes.

The students exploring the virtual laboratory will find machines of different producers for the FDM /FFF technology. There are also other technologies, e.g. SLA, as well as other processes – post processing tools and a vacuum chamber for Rapid Tooling (Vacuum Casting technology) (see Figures 2.4.25 and 2.4.26).

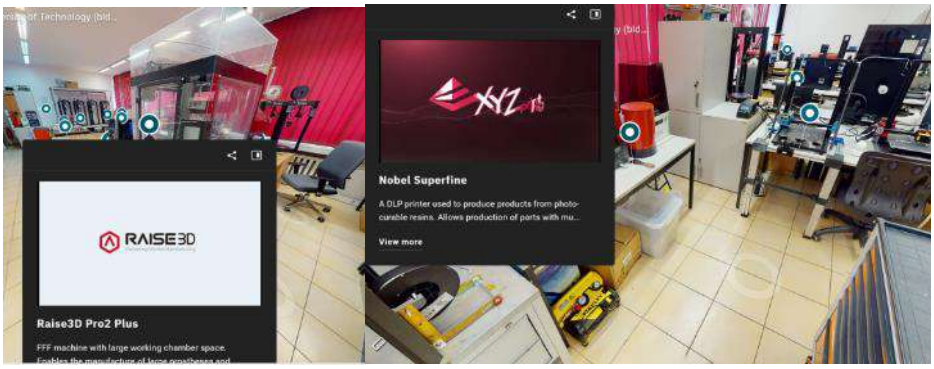


Figure 2.4.25. Additional 3D printing equipment depicted in the virtual laboratory

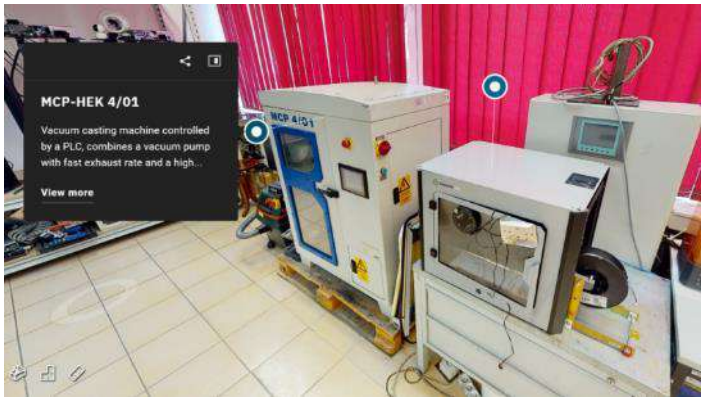


Figure 2.4.26. Vacuum casting technology available in the PUT 3D printing laboratory

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Apart from that, many educational videos are spread at the laboratory. Examples of the teaching content in the VL include (see Figures 2.4.27 - 2.4.31), but are not limited to:

- educational videos of 3D printing of medical parts (uploaded using laboratory's own YouTube channel),
- educational videos of post processing of 3D printed parts,
- educational videos of strength testing and 3D scanning accuracy measurement,
- photographs showing interior of cabinets containing tools and material (helping understand work processes in the laboratory),
- a number of educational videos showing the work of the equipment, by external providers (mostly machine producers)

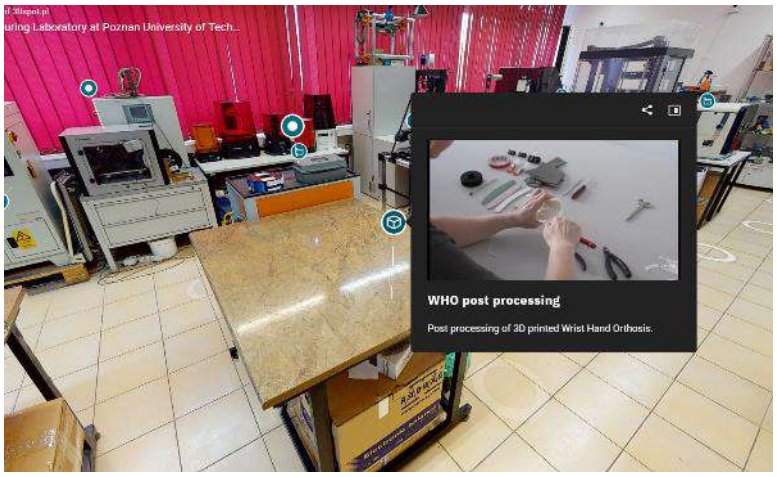


Figure 2.4.27. Educational video of post processing of medical parts

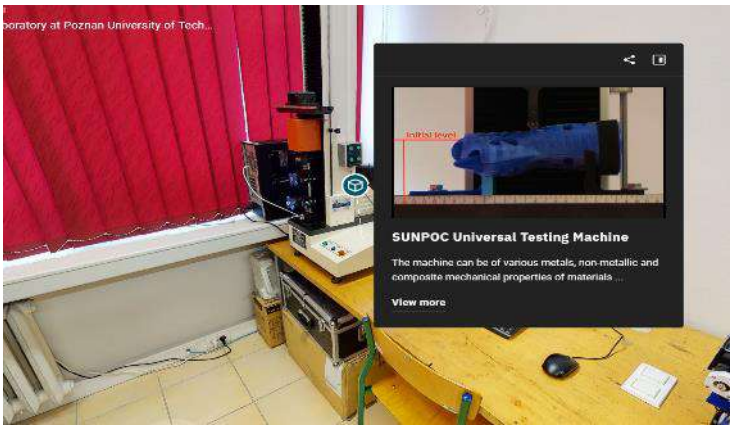


Figure 2.4.28. Educational video of testing of 3D printed medical parts

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

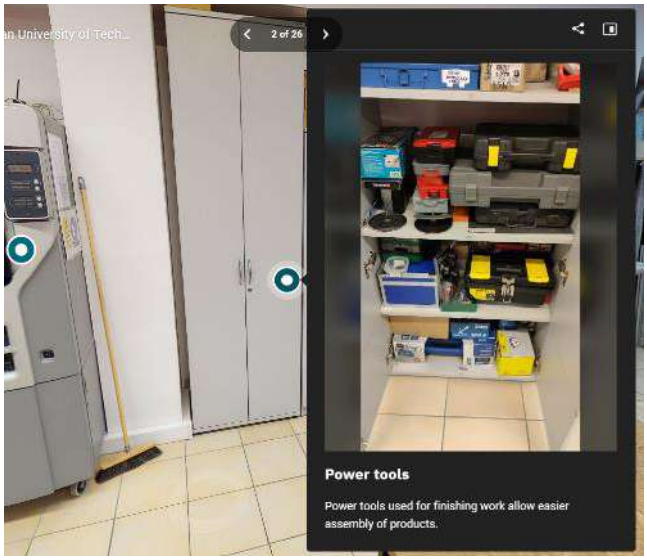


Figure 2.4.29. Photographs of laboratory equipment

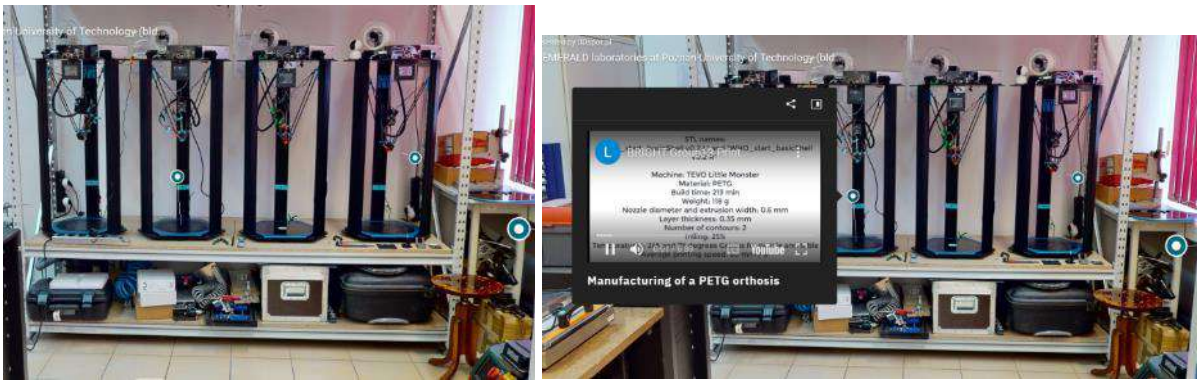


Figure 2.4.30. 3D printing of wrist hand orthosis provided by PUT as it was realized by FFF from PET-G

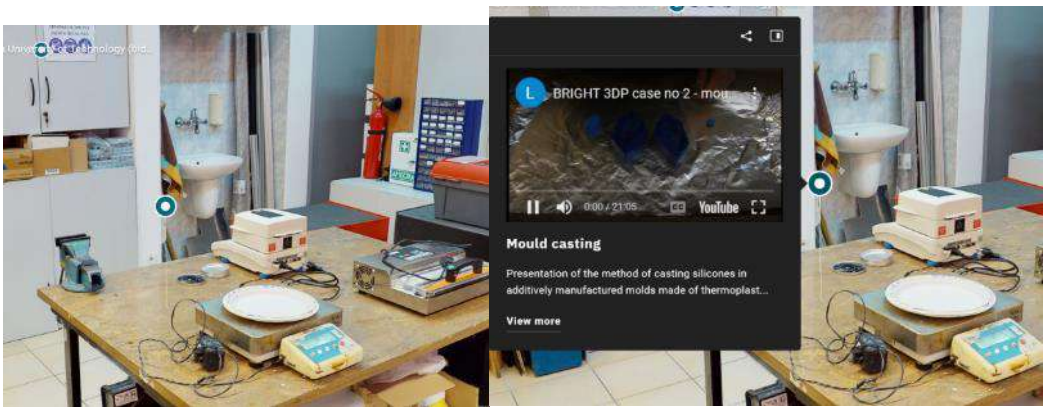


Figure 2.4.31. Vacuum casting application realized at PUT

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

As the last step of work, students are suggested to teleport to the other 3D printing laboratory of the EMERALD platform – the TUCN platform. This is achieved by using a link, floating above a table in the Virtual Laboratory (see Figure 2.4.32).

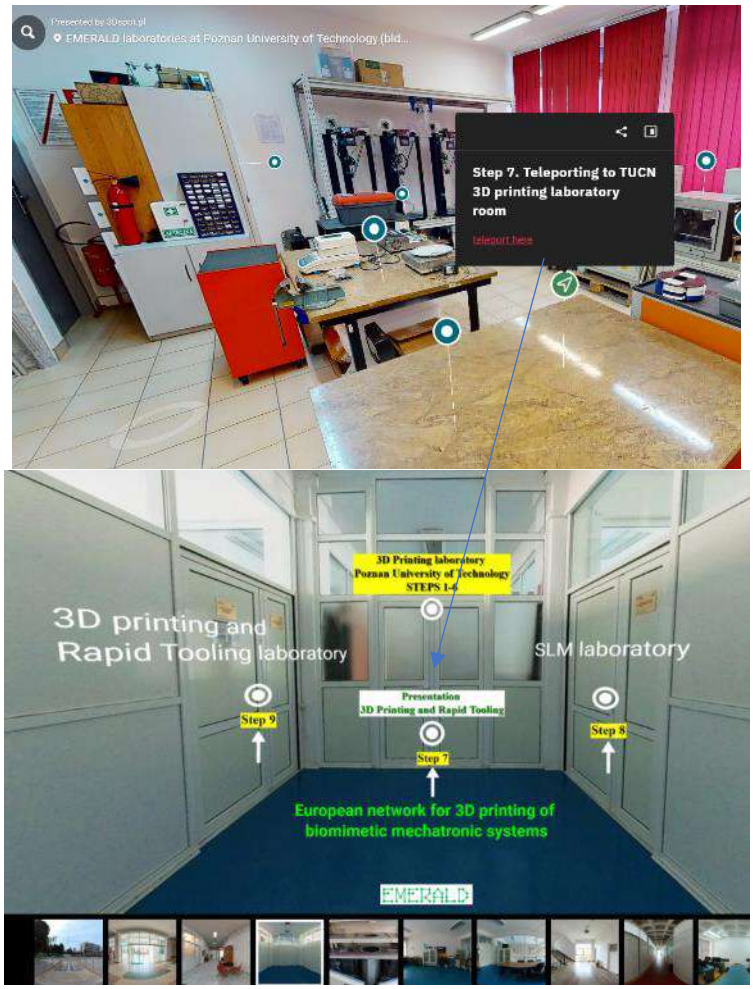


Figure 2.4.32. Teleporting to 3D printing laboratory rooms of TUCN

2.4.7. Additional resources on 3D printing provided by TUCN

Additionally to the existing resources provided by PUT, after students (users) are being teleported into the TUCN 3D printing laboratory room, they are led to access in step 7 presentation that has been prepared by TUCN in the frame of O3 as one main notice in Figure 2.4.32, so as the students (users) can go deeper to understand the processes that are being described in relation with

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

the 3D printing step and the way these technologies can be used for a various range of applications as they have been realized at TUCN using similar types of technologies that have been presented in the PUT 3D printing laboratory room, but also some other types of technologies (like SLS or SLM) that exist in the laboratory of TUCN. In order to access this resource the students (users) are teleported at the main entrance of TUCN, being invited to access the 3D printing laboratory from the main hall of the TUCN building. From here they have the option of continuing the tour with step 7 or to go through steps 1-6 at PUT if they are intending to skip some important steps in the beginning (Figure 2.4.33).

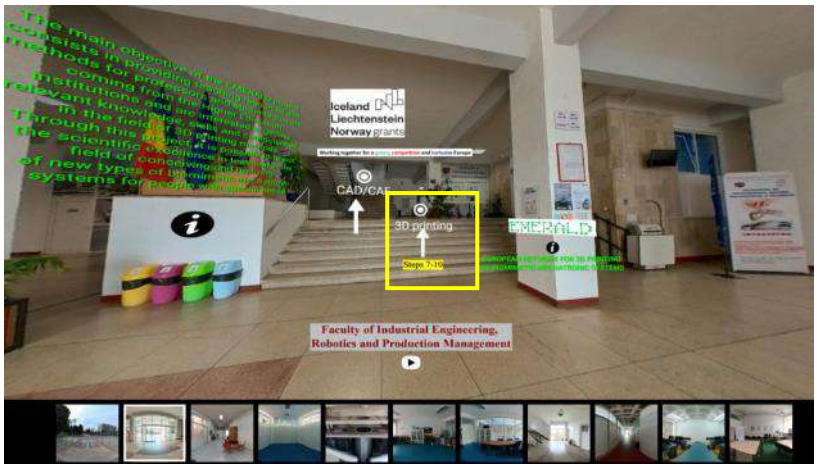


Figure 2.4.33. 3D printing laboratory of TUCN

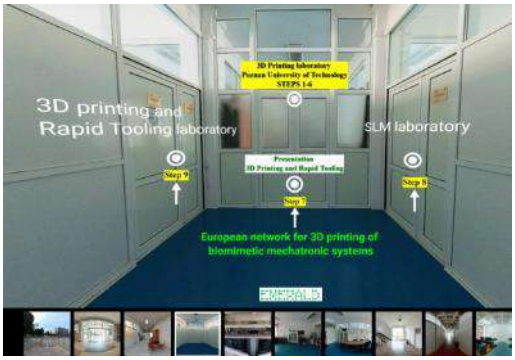


Figure 2.4.34. Accessing the 3D printing presentation of TUCN conceived in the frame of O3

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.4.8. Step 7 - Additional presentation on 3D printing provided by TUCN

The additional presentation can be accessed by the users in step 7, like it is shown in Figure 2.4.34, being possible to be accessed directly on the 3D scanning virtual laboratory of the e-learning platform or by downloading it from the next following link:

https://drive.google.com/file/d/1jE13yyBExK8RI6ug10hKDC9eegH4I-RM/view

The presentation is focused on the key aspects of 3D printing technologies, materials, and their applications in medical domain. 3D printing technologies, also known as additive manufacturing are used to create physical models by successively layering materials until the complete form is realized.

One of the most used of printing method, such as Fused Deposition Modeling (FDM) and / or Fused Filament Fabrication (FFF), which is a classical 3D printing technology that can be used for creating complex shapes and structures with a range of materials from basic plastics like ABS and PLA to advanced composites and bioplastics that are suitable for medical use due to their biocompatibility and mechanical properties is the first technology that is to be mentioned in this context. Materials play a crucial role in these technologies, with the presentation emphasizing a variety of filaments used in FDM, including pure thermoplastics, composites, and bioplastics. These materials are chosen based on their properties, such as durability and flexibility, which are critical for medical applications. The discussion on materials extends to new types of filaments and research areas, exploring innovations like carbon fiber reinforcement and the selection of biobased and biodegradable polymers for more sustainable practices. Applications of these technologies are vast and include the creation of prosthetics, orthopedic implants, and complex tools for surgery (see Figure 2.4.35).

Figure 2.4.35. Artificial hand realized by Fused Filament Fabrication technology

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The versatility of 3D printing allows for personalized medical solutions, as it can create patient-specific models that fit their unique anatomy. The presentation likely showcases examples of 3D-printed prosthetic hands, customized implants, and surgical tools, illustrating the practical benefits of these technologies in improving patient care and advancing medical device manufacturing.

Multi-material 3D printing is highlighted for its ability to create objects with different materials, enhancing functionality and aesthetic. Besides the FDM / FFF technology that has been already presented, technologies such as Stereolithography (SLA), and Digital Light Processing (DLP) are detailed. SLA and DLP are emphasized for their precision in producing complex medical models, prototypes, and functional parts, with materials ranging from standard resins to specialized plastics or biocompatible ceramics (see Figure 2.4.36).

Figure 2.4.36. Applications of multi-material 3D printing methods in medical domain

3D Bioprinting is also a significant technology illustrating the cutting-edge work in printing tissues, vascularized networks, and organs. This segment shows the potential of 3D printing in regenerative medicine, from creating scaffolds for heart valve tissue engineering to bioprinting skin and muscular tissues, which has profound implications for medical research and patient care (see Figure 2.4.37).

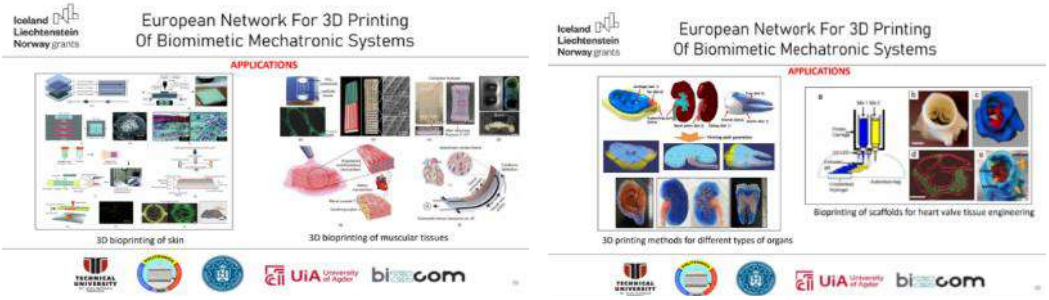


Figure 2.4.37. Applications of 3D Bioprinting technologies in medicine

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In this context the concept of biomimetics in 3D printing is introduced, underscoring the trend of emulating natural processes for innovative solutions in robotics, smart materials, and beyond, marking a convergence of technology and natural science for future advancements (see Figure 2.4.38).

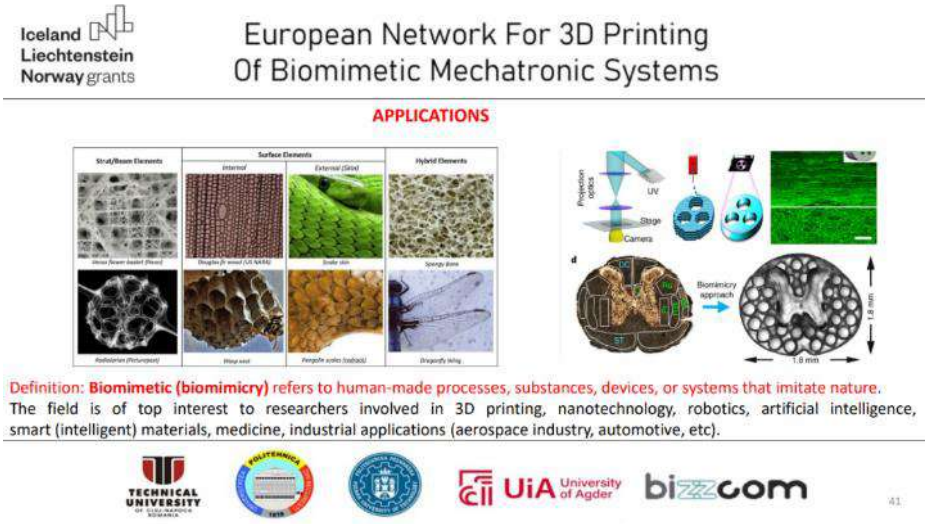


Figure 2.4.38. Biomimetic concept in 3D printing

An interesting category of additive manufacturing technologies consists in 4D printing, which represents an evolution of 3D printing that allows for the creation of objects that can reshape or self-assemble over time when exposed to environmental stimuli, such as water. This cutting-edge technology opens new avenues for biomedical applications, such as water-activated, multi-material devices that respond to bodily changes.

Selective Laser Sintering (SLS), a process that uses a laser to sinter powdered material, typically plastic or metal, to create a solid structure is presented in continuing. The materials and applications sections underscore the versatility of SLS in producing complex and durable items that are applicable in various medical case studies. Selective Laser Melting (SLM) is another featured technology, which, unlike SLS, fully melts the metal powder to create high-density parts. The discussion on SLM materials focuses on the powder used and the grain welding process, illustrating the technology's capability to create intricate metal components for medical use (see Figure 2.4.39).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

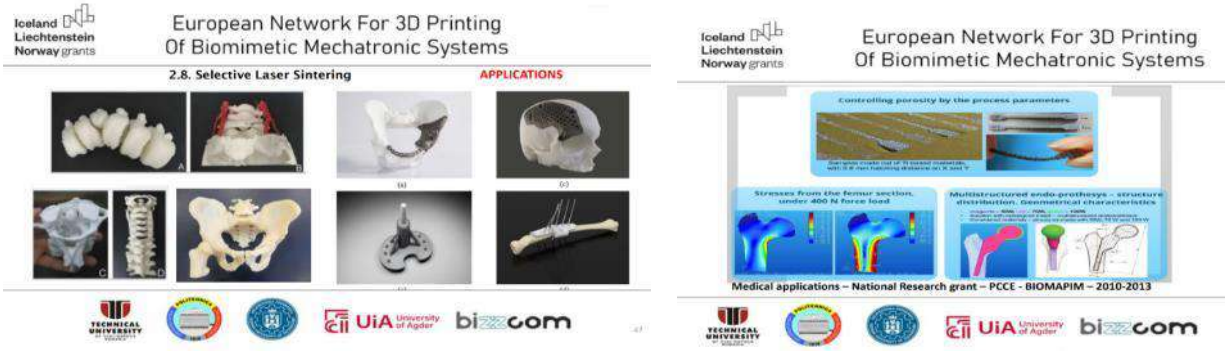


Figure 2.4.39. Applications of SLS and SLM technologies in the medical domain

2.4.9. Steps 8 and 9 – Tour the 3D printing laboratories of TUCN

After visualizing the 3D printing presentation, the students (users) of the e-learning platform are invited to visit and explore the laboratories of 3D printing (TUCN), to watch videos emphasizing the way these technologies are running, to read details about the equipment, items in the laboratories, to see also details of different applications realized at TUCN (see Figure 2.4.40).

Figure 2.4.40. Lab tours of TUCN in which students can explore videos, equipment items, applications

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.4.10. Steps 10 and 11 –3D printing laboratory tutorials realized by TUCN

In the last room of virtual laboratory of 3D printing at TUCN, students (users) can find some tutorials / videos realized by the students of TUCN following the examples that have been provided by PUT concerning 3D printing or additional tutorials that have been prepared at TUCN for preparing files for 3D printing, like shown in Figure 2.4.41. Tutorials and videos can be accessed also directly on the next following links: https://drive.google.com/file/d/1eUiAeck7OEfllAdt-6h5yT1TnycGAWlN/view and https://drive.google.com/drive/folders/18RYe4luK2EO72ZJ_RGAlTX-n8EvEHD_l

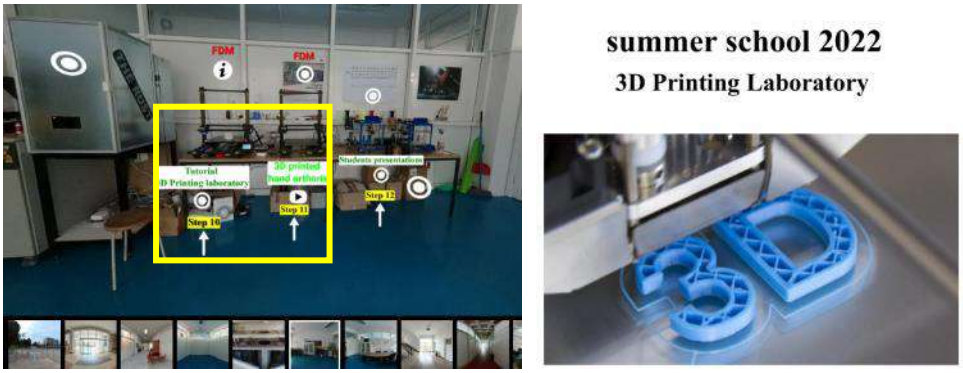


Figure 2.4.41. Tutorials prepared for 3D printing laboratory work with the students

Last but not least, additional videos were prepared with instructions in Cura software program to be used by the students at TUCN. Videos on how students have been working to prepare setup of models and how these were realized by 3D printing have been included in few relevant videos, as they can be seen presented in Figure 2.4.42.

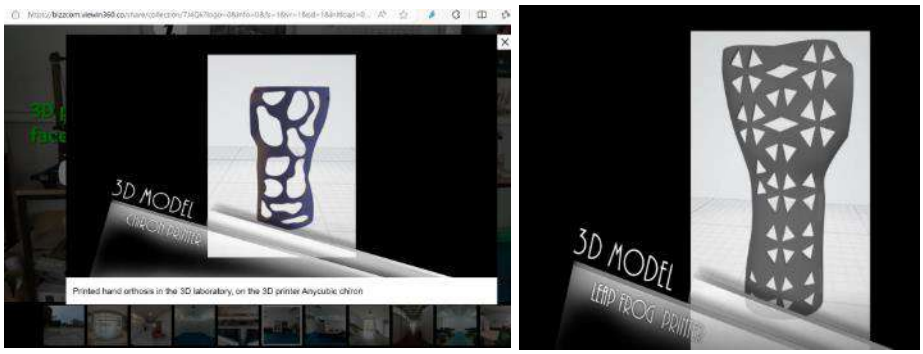


Figure 2.4.42. Models prepared and realized by 3D printing technologies in the laboratory of TUCN

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.4.11. Step 12 – Good practice examples realized by students using 3D printing resources of EMERALD project

Last aspect that has been included in the laboratory of 3D printing is referring to good practice examples on how students have used the resources in processing of 3D printed models – few of the most relevant examples done by the students in this direction is shown in Figure 2.4.43 proving the efficiency, the importance and relevancy of the resources that have been prepared in the e-learning platform for the students. Powerpoint presentations (focused on 3D printing of parts made by students) have been included in the platform like shown in Figure 2.4.44 and 2.4.45), these good practice examples being possible to be accessed on the following link: https://drive.google.com/drive/folders/1Zg7WsYbr9JAsmUziV6wgGR3bgqtuD7g9

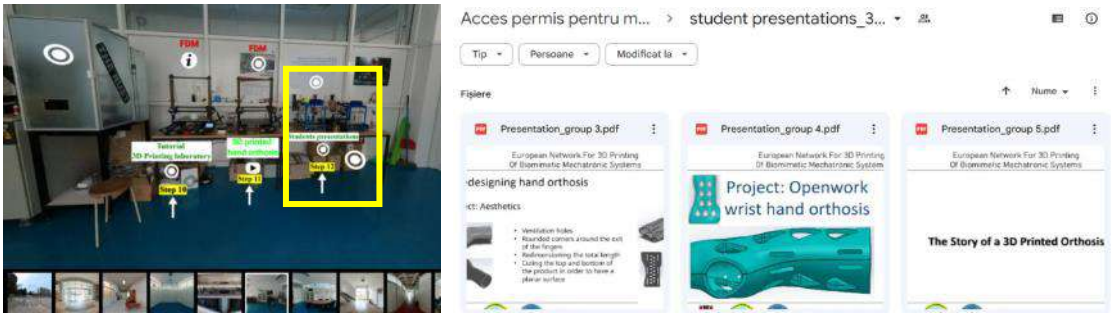


Figure 2.4.43. Good practice examples realized by the students using the EMERALD 3D printing resources of virtual laboratory of the e-learning platform

In Figure 2.4.44 and 2.4.45 are presented few relevant examples extracted from Powerpoint presentations made by the students emphasizing their work done using 3D printing technologies, like FDM printing.

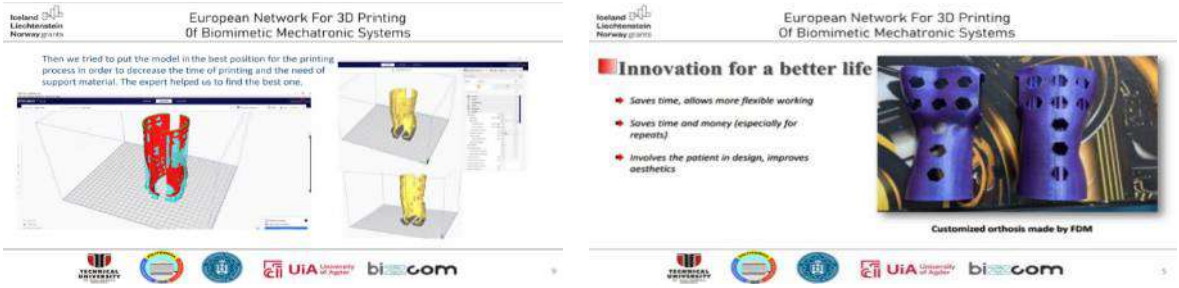


Figure 2.4.44. Good practice examples made by students using e-learning platform 3D printing resources

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.4.45. Good practice examples made by students using e-learning platform 3D printing resources

2.4.12. Conclusions about 3D printing teaching resources of the e-learning platform

The materials contained in the Virtual Platform regarding 3D printing present a unique opportunity for any student to get familiarized with the newest possibilities in 3D printing of parts of biomechatronic devices, using different technologies, processes, parameters and materials, as well as post processing methods. The comprehensive, detailed presentations, tutorial videos and instructions allow the students to get a grip on the technology, its foundations, requirements and use. Great expertise of authors of the materials (coming from Poznan University of Technology and Technical University of Cluj-Napoca, both known for their decades-long expertise in 3D printing processes) brings possibilities to learn a great deal about the 3D printing, both by watching very detailed videos on how to realize the process and by doing work themselves, on a presented set of data of real products, devised for real patient cases – people with special needs, with orthotic and prosthetic equipment designed in the EMERALD case studies. Such a course is unprecedented and unavailable at any other e-learning platform.

2.5. Sensoring, assembly and programming virtual laboratory room (UiA)

2.5.1. Accessing of the sensoring, assembly and programming virtual laboratory room

Sensoring, assembly and programming) virtual laboratory room which has been assigned to the University of Agder (Norway) as one may notice in Figure 2.5.1 can be accessed from the www interface of the EMERALD project (https://project-emerald.eu/?page_id=404) or directly by accessing the next following link:

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

https://bizzcom.viewin360.co/share/collection/7J4Z9?logo=0&info=0&fs=1&vr=1&sd=1&initload=0&thumbs=1

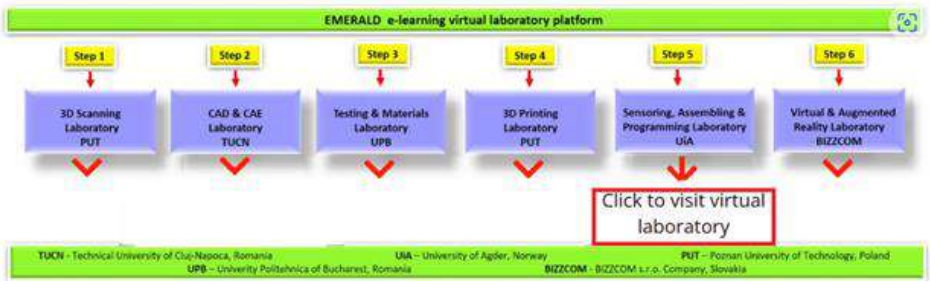


Figure 2.5.1. Accessing of the sensoring, assembly and programming virtual laboratory room from the e-learning platform

The Virtual Laboratory tour begins at the entrance of the UiA main building, as shown in Figure 2.5.2. Upon entering the building through the main corridor, one may access the sensoring, assembly and programming, as shown in Figure 2.5.3.

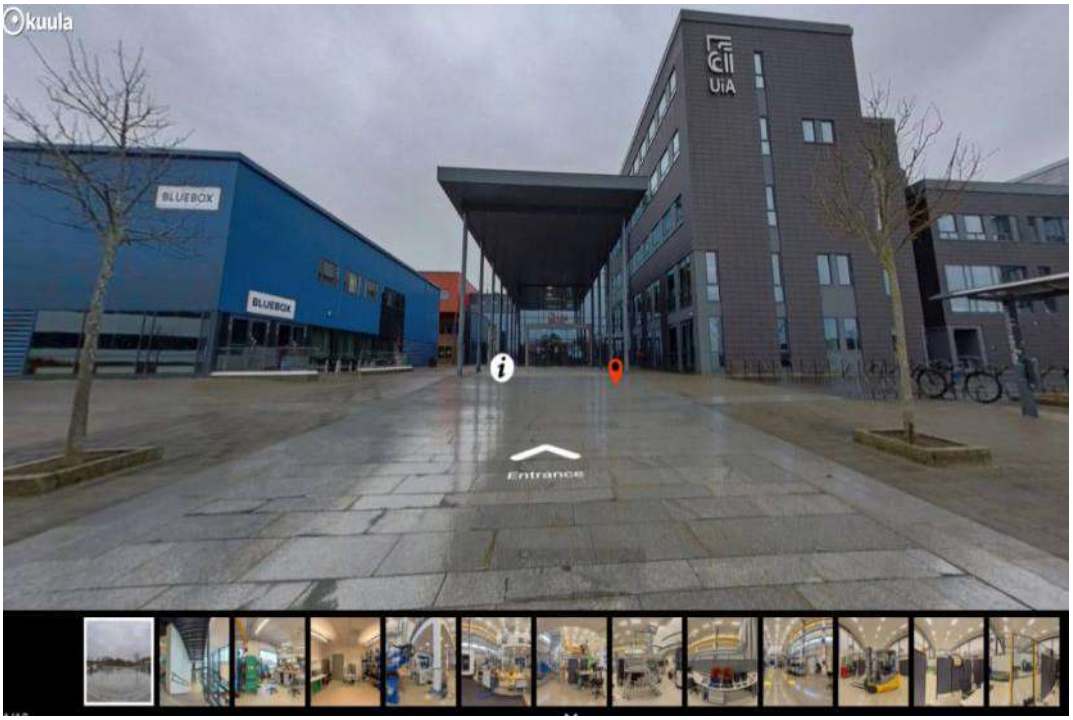


Figure 2.5.2. Entrance of the UiA main building

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

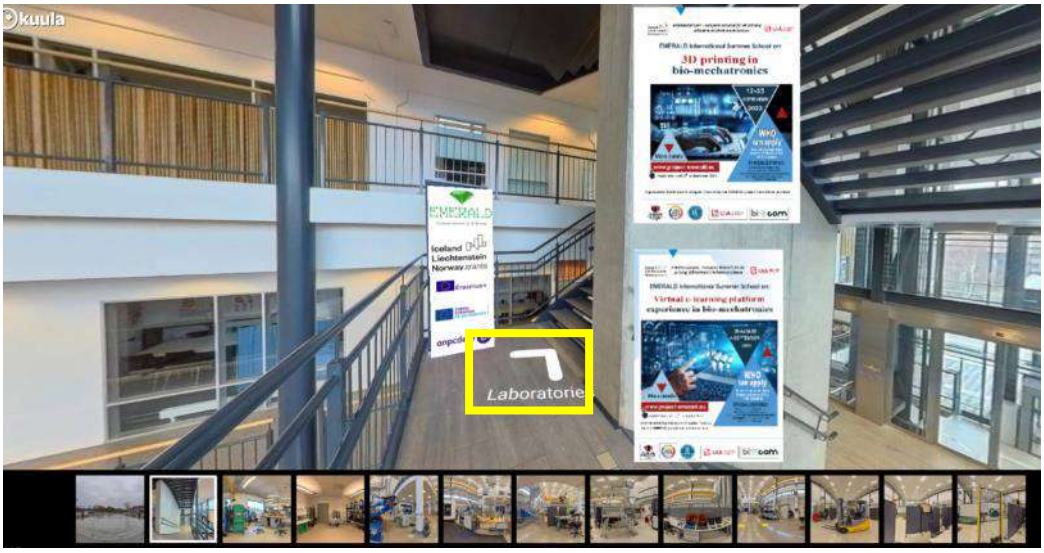


Figure 2.5.3. Access to the sensoring, assembly and programming laboratory (UiA)

The first virtual laboratory to visit at UiA which can be seen in Figure 2.5.4 have been assigned for the sensorics, actuators and for additional aspects related to bio-mechatronic.

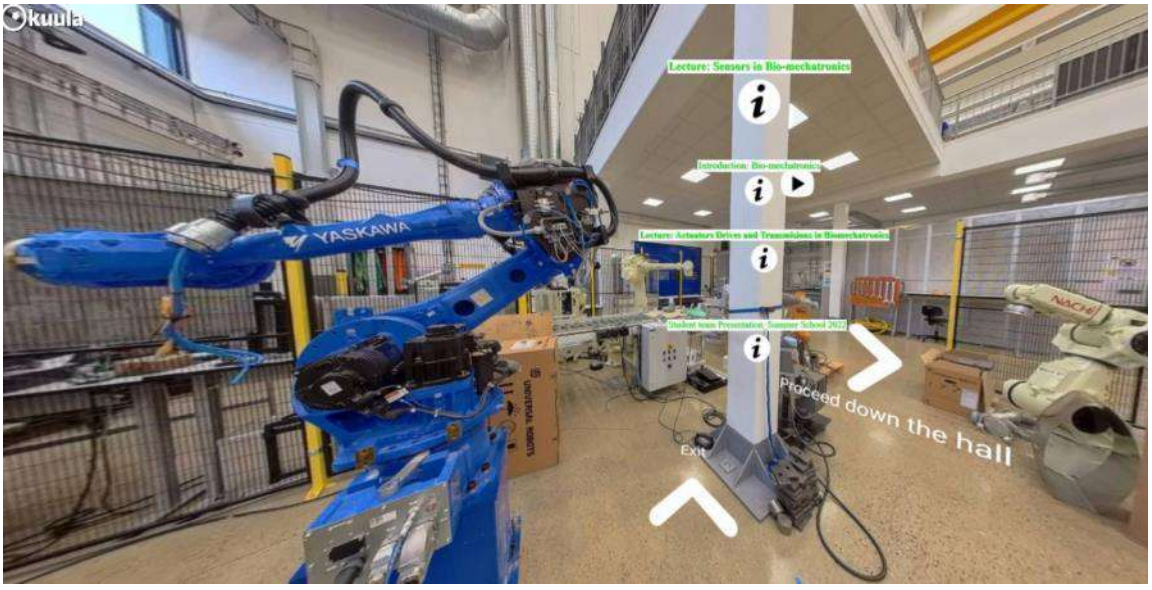


Figure 2.5.4. Virtual laboratory of sensorics, actuators and bio-mechatronics (UiA)

In same way there have been assigned specific laboratories for the Assembling and Programming topic at University of Agder (UiA) as one may notice presented in Figure 2.5.5.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

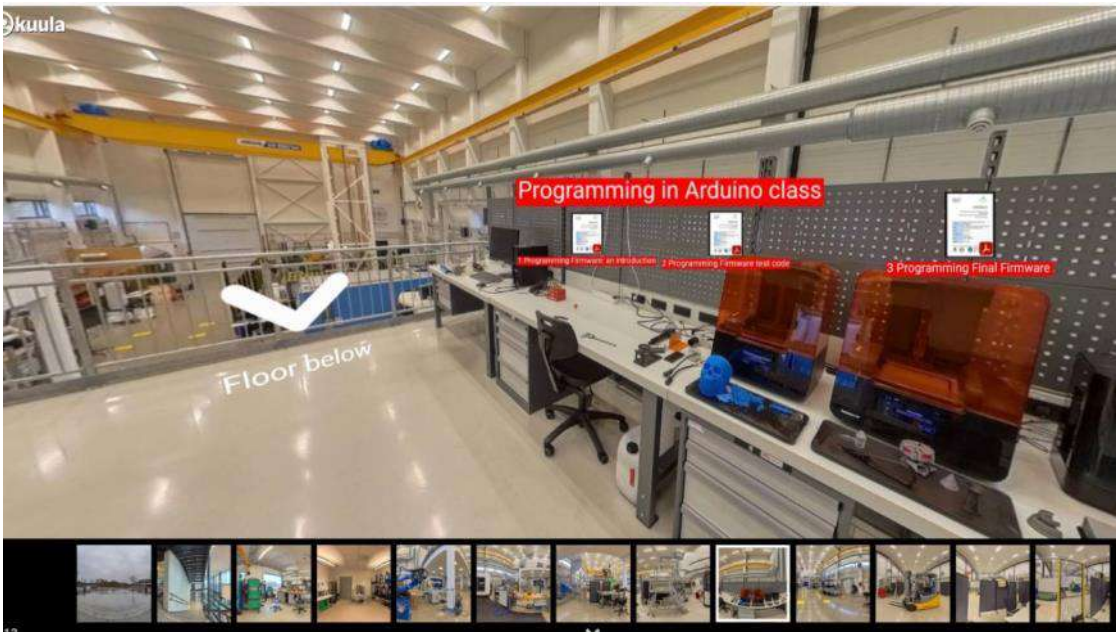


Figure 2.5.5. Assembling and programming virtual laboratories at University of Agder (UiA)

All figures that can be seen in Figures 2.5.4 and 2.5.5 have been realized using Insta 360 camera, the captured images undergoing in further processing using Kuula software, allowing the integration of educational materials related to the sensoring, assembly and programming of the bio-mechatronic components that have been developed within the EMERALD project related to these topics.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.5.2. Structuring of the teaching resources being provided about sensoring, assembly and programming in the e-learning platform

The e-learning virtual laboratory platform dedicated to the sensoring, assembly and programming stage in particular offers an enriched educational experience that is tailored to the bio-mechatronic systems destined for people with special needs (with amputated arms) such as robotic arms, orthoses and prostheses, focusing on the necessary steps that are particularly necessary to be followed after the 3D printing of the component, step that is continuing mainly with the sensoring, assembling and programming of such systems. The main aim of the platform in relation to sensoring, assembling and programming aims to familiarize the users and facilitate their comprehensive learning by providing them first the basics on types of sensors that can be used for such type of systems, followed by the assembling of other important components, like step engines or actuators and ending with the programming steps that are necessary to be realized for such type of systems. In order to comprise easier all these steps, students (users) are invited to go through some lectures / courses on the beginning so they can comprise the terminology and the basics, and to go afterwards to a set of instructional videos or applications or toolkits through which they can easily understand how sensoring, assembling and programming of such bio-mechatronic systems has to be realized in the end.

2.5.3. Step 1 - Sensoring course module

Since sensoring is one of the most important step to be realized for the bio-mechatronic systems, students (users) are invited to go through the Sensoring lecture resources being provided in the EMERALD e-learning virtual laboratory platform on the beginning. Therefore first step to be followed is related to the Sensors and electronics course module that has been produced by the EMERALD consortium in the frame of O1 (by UPB partner), course that can be accessed through the platform, can be visualized or can be downloaded as one may notice in Figure 2.5.6 – see: https://project-emerald.eu/wp-content/uploads/2023/02/EMERALD_IO1_module_5_Sensors-and-Electronics.pdf

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.5.6. Sensors and electronic course module realized by UPB in the frame of O1

The course module on Sensors-and-Electronics provides a comprehensive understanding of various aspects of sensors and electronics that are crucial for biomimetic mechatronic systems. The course module begins with an insightful introduction to measurement systems, which are essential in the case of biomimetic mechatronic systems. The course module then further on underlines the crucial role of measurement systems in extracting valuable information from various processes. It is also emphasized the importance of establishing a material connection, either physical or electromagnetic, between the system and the process being observed. This introductory section sets the stage for understanding the indispensable role of sensors in these systems, showcasing how sensors interact with the process and modify their parameters to provide measurable data.

The next section of the course module provides an extensive analysis of sensors, a cornerstone of measurement systems, classifying the sensors into two broad categories: parametric (passive) and generative (active). In this section there are provided details and are explained differences that there are between parametric sensors, which alter their parameters in response to external stimuli without generating energy, resistive sensors like strain gages, RTDs and capacitive sensors, as shown in Figure 2.5.7.

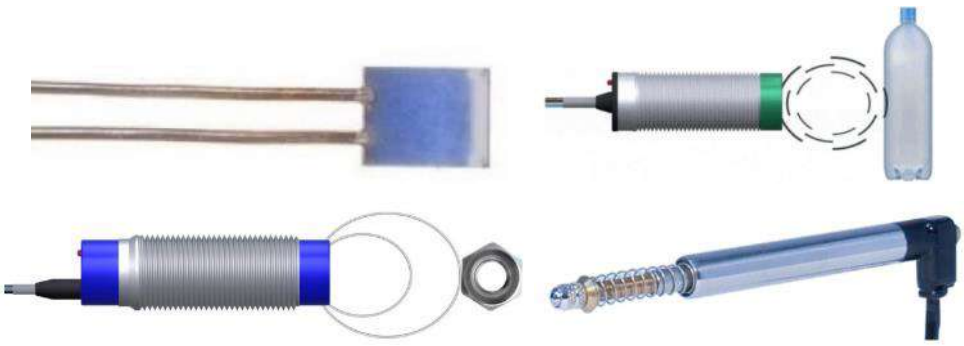


Figure 2.5.7. Different types of sensors that are used for the bio-mechatronic systems

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Generative sensors, which actively generate energy during their interaction with the process, are discussed next. This section is rich in examples, such as thermocouples and various piezoresistive sensors. It covers a range of sensors, including accelerometers, piezoelectric temperature sensors, photodiodes, and photoelectric sensors, with detailed explanations and illustrative figures (see Figure 2.5.8). This part of the course module offers a comprehensive understanding of how these sensors operate and their applications in different scenarios.

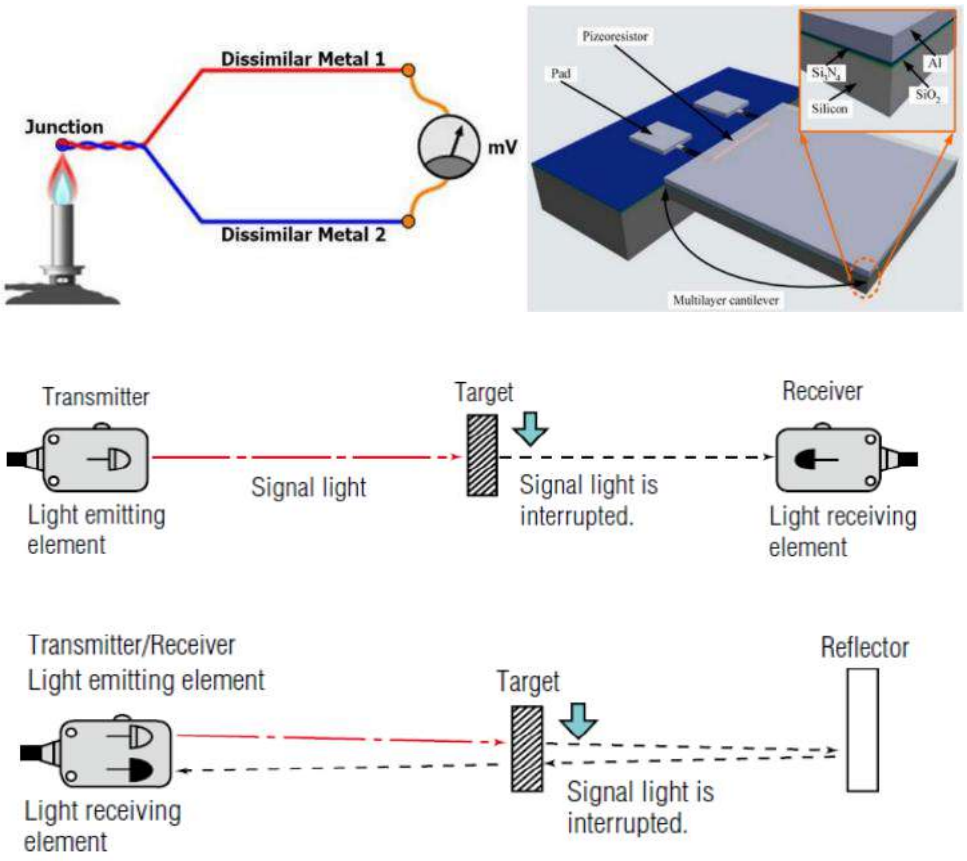


Figure 2.5.8. Generative sensors, piezorezistive sensors and photodetector models

The course module is realizing then the transitions into the critical topic of signal conditioning. This section of the course module is crucial for understanding how to adapt the sensor's output for compatibility with other system components. The course module covers various operations integral to signal conditioning, such as input coupling, filtering, amplification, attenuation, excitation, linearization, and isolation. Each of these operations is carefully explained with the aid of illustrative figures (see Figure 2.5.9), which provide visual insights into their mechanisms and importance.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

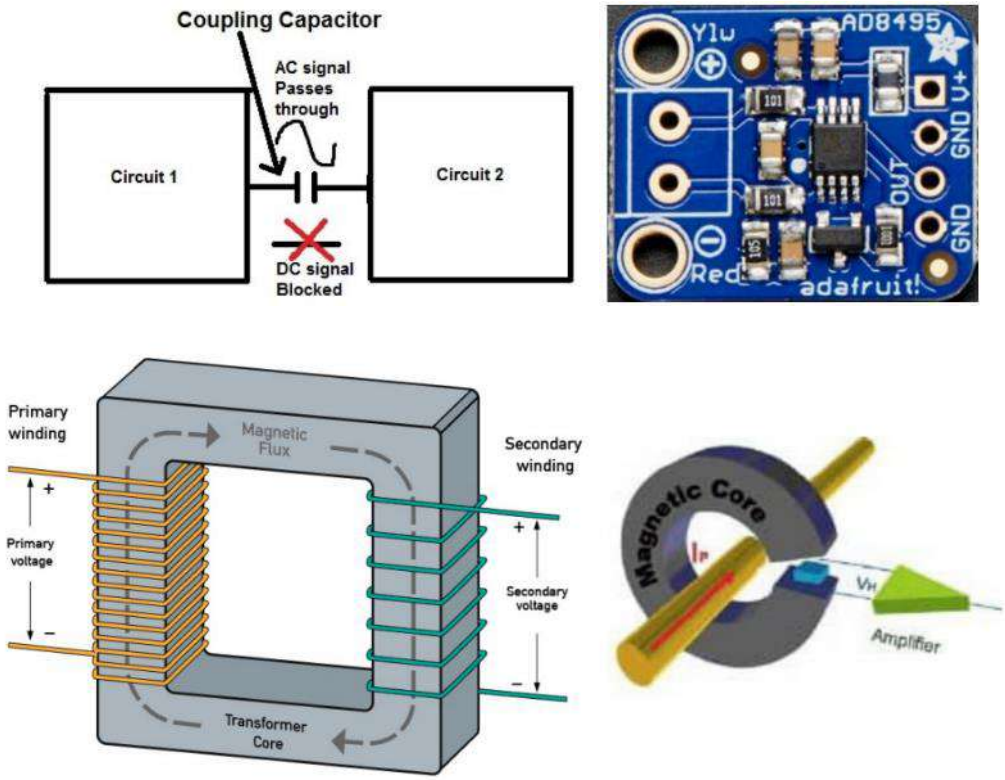


Figure 2.5.9. Other system components that is necessary to be integrated within bio-mechatronic systems

Finally, the course module concludes with a thorough discussion on analog-to-digital converters (ADCs). ADCs are fundamental in converting the analog signals from sensors into a digital format that can be processed by computers. This section of the course module goes deeper into the functionality of ADCs, emphasizing their measurement range, resolution, and scan rate. Figure 2.5.10 visually provides a clear understanding of ADC operations and their significance in measurement systems.

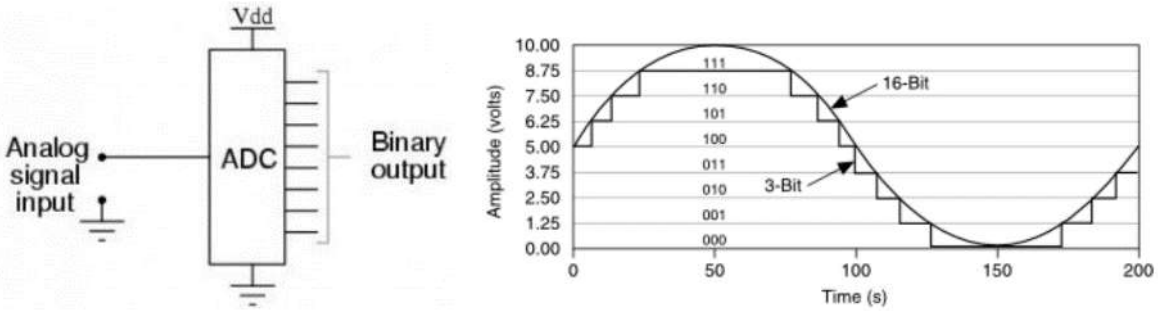


Figure 2.5.10. ADC operations and their significance in the measurement systems

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.5.4. Step 2 - Sensoring lecture additional presentation

In addition to the course module, a video presentation has been prepared by UPB concerning this topic of Sensors and Electronics, in order to provide much deeper insight to this field with applicability in bio-mechatronics. The additional video presentation can be accessed by the students (users) like it is shown in Figure 2.5.11, being possible to be accessed directly on the sensoring, assembly and programming virtual laboratory of the e-learning platform or by downloading it from the next following link:

https://drive.google.com/file/d/14gYebo7OjLtEEbShwcjy_6kIV5ddQ7Dy/view?usp=sharing

Figure 2.5.11. Sensors and electronic video presentation realized by UPB in the frame of O3

Besides the theoretical basics on how to use the sensors and electronics as they have been explained in the course module, in the video as one may notice in Figure 2.5.12 there are provided real practical examples on how to use the sensors and electronics that are needed to be integrated in the structure of bio-mechatronic systems.

Figure 2.5.12. Integrating of sensors and electronics into the structure of bio-mechatronic systems

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.5.5. Steps 3 and 4 - Sensors in Biomechatronics and Actuators Drives additional presentations

In addition, in the frame of O3, 2 course presentations related to Sensors in Biomechatronics and Actuators Drives and Transmissions in Bio-Mechatronics were prepared by the University of Agder (EMERALD partner) being possible to be accessed directly on the sensoring, assembly and programming virtual laboratory of the e-learning platform (see Figure 2.5.13) on the next following links: https://drive.google.com/file/d/1y7xSAzkPsNR5p2MJROkoBemMIx49KQpr/view and https://drive.google.com/file/d/1AyJyPZYGucl8CVr67Ig0ObibM05uSQiK/view

Figure 2.5.13. Sensors and actuators lectures prepared by UiA partner in the frame of O3

Therefore in the introduction section of the first presentation, there is explained that on the dynamic intersection of mechanical and electronic systems, position sensors emerge as indispensable components, particularly in the field of biomechatronics. Biomechatronics, a sub-discipline of mechatronics, focuses on the development of systems that assist or restore functions within the human body. This presentation is exploring the significance of position sensors in biomechatronic systems, highlighting their contributions to precision, control, and safety based on several practical examples that are being provided as one may notice in the examples presented in Figure 2.5.14. Position sensors act as the vigilant eyes of control systems, offering real-time feedback on the location or orientation of mechanical components. This constant stream of information empowers control systems to make instantaneous adjustments, ensuring that various elements within the biomechatronic system maintain their intended positions.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

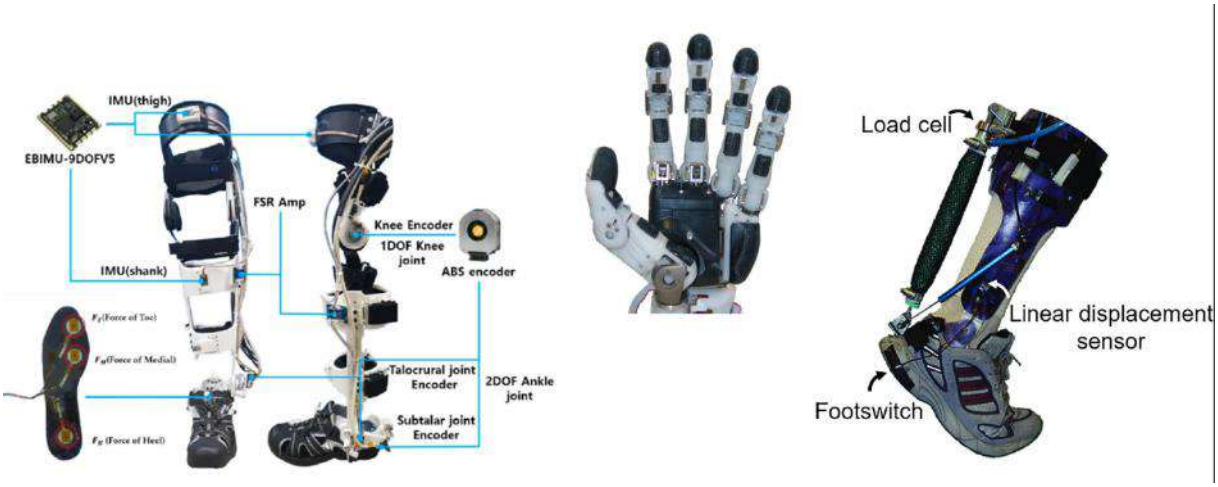


Figure 2.5.14. Practical use of positioning sensors in biomechtronics

Accuracy parameter that is highly important in the field of biomechatronics is highly depending on positioning sensors. These sensors enable meticulous control of movements, a critical factor in the design and functionality of prosthetic limbs, exoskeletons, and other assistive devices as shown in the examples provided in Figure 2.5.15. The accuracy they provide is foundational to the well-being and seamless functionality of users.

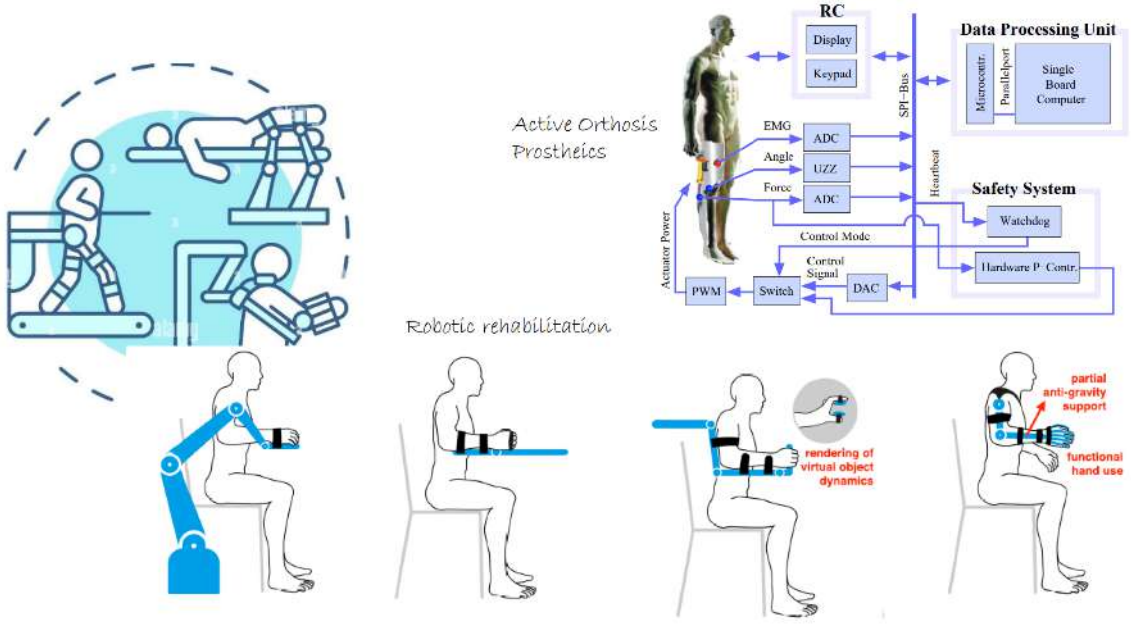


Figure 2.5.15. Robotic rehabilitation and active orthosis/prostheics

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The concept of closed-loop control systems becomes synonymous with the utilization of position sensors. Through a continuous feedback loop, these sensors measure actual positions and feed this information back to the controller. This dynamic process allows the biomechatronic system to adapt and optimize its behavior, ensuring a seamless and precise performance. Position sensors stand at the forefront of technological advancements, particularly in the field of biomechatronics, where the integration of mechanical and electronic systems is aimed at assisting or restoring functions in the human body. This presentation delved into the critical role played by position sensors in biomechatronic systems, highlighting their importance in ensuring precision, control, and safety.

Position sensors also play a dual role in monitoring the health and performance of biomechatronic systems. By continuously tracking the position of moving parts, these sensors enable the early detection of deviations or anomalies. This capability provides valuable data for proactive maintenance and troubleshooting, contributing to the overall reliability of the system.

In the complex interplay between machines and the human body in biomechatronics, position sensors emerge as critical components. Their role in facilitating precise control of prosthetic limbs and exoskeletons is highly important in creating natural and responsive movements. In the field of robotics, stiffness control stands as a crucial concept, allowing robots to dynamically adjust their mechanical stiffness or compliance. This adaptability is crucial for robots to interact with the environment in a controlled and adjustable manner, especially in scenarios where precision, safety, and collaboration with humans are mandatory.

Robots equipped with stiffness control capabilities can exhibit adaptive compliance, a quality particularly valuable in applications where the robot needs to work alongside humans or handle delicate objects. This adaptability is achieved by adjusting the mechanical stiffness of the robot based on real-time task requirements. Central to stiffness control is the use of variable stiffness actuators, mechanisms that enable robots to modulate their stiffness dynamically (see Figure 2.5.16). This flexibility is essential for robots to respond to the dynamic and unpredictable nature of their operating environments. By adjusting stiffness, robots can ensure optimal performance and efficiency across a wide range of tasks. The application of stiffness control extends to various domains, with notable implications in collaborative robotics. For instance, a robot can reduce its stiffness when collaborating with a human to ensure safety during shared tasks. Conversely, it can increase stiffness for tasks demanding precision and stability, showcasing the versatility of stiffness control in diverse scenarios.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

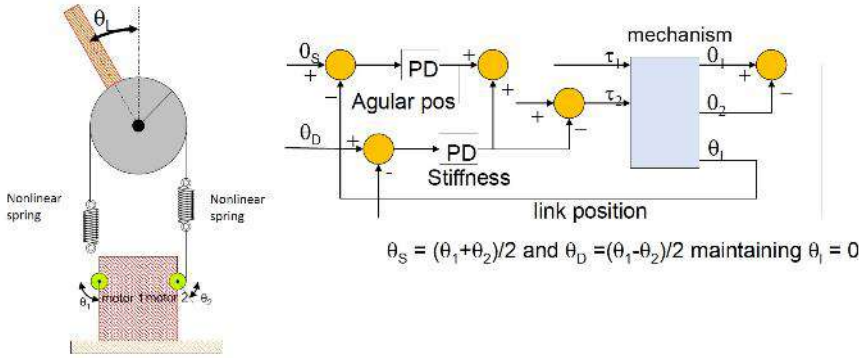


Figure 2.5.16. Use of variable stiffness actuators in the bio-mechatronic systems

In rehabilitation robotics, stiffness control plays a pivotal role in assisting individuals in regaining motor control and strength. By adjusting stiffness, robotic systems can provide tailored support and resistance, facilitating effective rehabilitation protocols. However, the implementation of stiffness control poses challenges. It requires sophisticated control algorithms and the integration of sensors to provide real-time feedback. Striking a balance between compliance and stability is a complex task that necessitates careful consideration in the design and implementation of robotic systems. As an active area of research and development, stiffness control in robotics continues to evolve. Researchers are exploring advanced control algorithms and innovative mechanisms to further enhance the adaptability and versatility of robotic systems. The ongoing development of stiffness control technology holds promise for the continued advancement of robotics in applications ranging from collaborative tasks with humans to rehabilitation and beyond.

Potentiometers, commonly used angular position sensors, operate as voltage dividers. They consist of a resistive element and a wiper that moves along the resistor, producing a variable voltage output (see Figure 2.5.17).

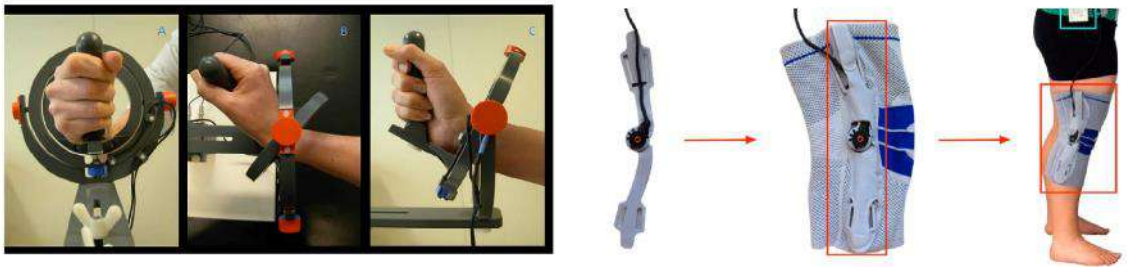


Figure 2.5.17. Potentiometer as an example of measuring linear and angular position

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The measuring range and resolution of potentiometers are determined by the physical size of the resistor and the precision of the wiper movement. These sensors offer a straightforward method for angular position measurement but may have limitations in terms of accuracy and wear over time.

In contrast to potentiometers, LVDTs are linear position sensors that offer high precision and reliability. They operate based on electromagnetic induction and consist of a primary coil and two secondary coils. The displacement of the core induces varying voltages in the secondary windings. LVDTs exhibit a wide measuring range, high resolution, and low hysteresis. Their properties make them ideal for applications requiring accurate linear displacement sensing.

Similar to LVDTs, RVDTs are designed for rotary position measurement. They consist of a primary coil and two secondary coils wound around a toroidal core. RVDTs provide accurate and reliable angular position measurements, making them suitable for applications demanding precision in rotational motion sensing.

Optical encoders employ light-based technology for position sensing. Quadrature encoders, a subtype of optical encoders, generate two square wave signals with a phase difference. This phase information enables not only position determination but also directionality. Phasesensitive demodulators play a crucial role in decoding the signals, providing accurate angular position information.

Force and torque sensors, such as Force Sensitive Resistors (FSRs), Flex Sensors, and Strain Gauges, are crucial for measuring mechanical interactions. FSRs exhibit variable resistance under applied force, and their signal conditioning involves converting the resistance change into a measurable voltage. Flex sensors measure bending, while strain gauges gauge deformation in materials subjected to force or torque.

In biomechatronics, an Inertial Measurement Unit (IMU) as one may notice in Figure 2.5.18 serves as a pivotal sensor system that integrates multiple sensors to measure and relay information on accelerations, angular rates, and, optionally, magnetic fields associated with the human body or biomechanical devices. Comprising accelerometers, gyroscopes, and sometimes magnetometers, IMUs play a crucial role in biomechanical studies, sports science, and the development of wearable devices. Accelerometers within the IMU capture linear motion, offering insights into movements, gait patterns, and the intensity of physical activities. Gyroscopes, measuring rotational rates, provide essential information about joint movements and orientations during various activities.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

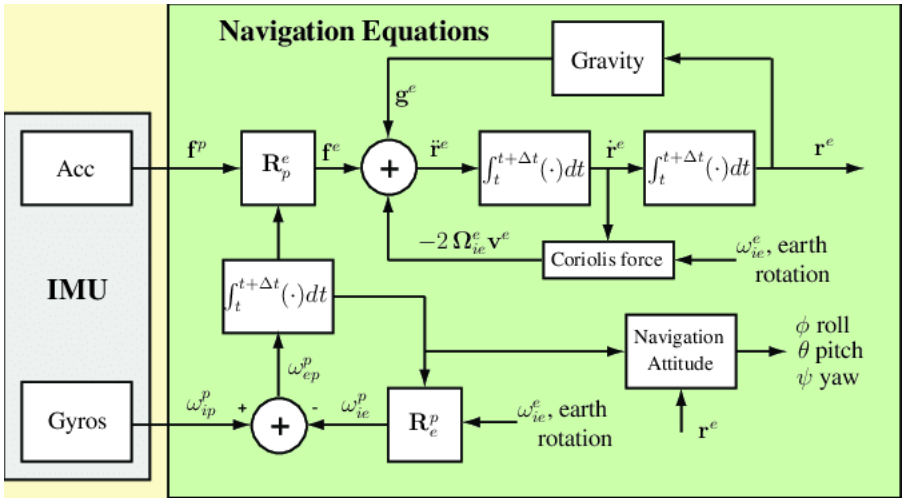


Figure 2.5.18. Navigation of IMU

While IMUs are prevalent in biomechatronics for motion sensing and analysis, Inertial Navigation Systems (INS) are less commonly used directly in this field. INS finds more extensive application in navigation, aerospace, and autonomous vehicles where precise positioning and trajectory information are critical.

Electroencephalography (EEG) is a non-invasive medical test used to measure and record the electrical activity in the brain (see Figure 2.5.19). This neurophysiological monitoring technique involves placing small metal discs or sensors, known as electrodes, on specific locations on the scalp. These electrodes detect and amplify the electrical signals generated by neurons in the brain.

The recorded signals, referred to as electroencephalograms, provide information about the brain's electrical patterns in the form of different types of brain waves, such as delta, theta, alpha, beta, and gamma waves. Each type of wave is associated with different states of consciousness, activities, or specific neurological conditions. EEG is commonly utilized in the diagnosis and monitoring of neurological disorders, including epilepsy, seizure disorders, sleep disorders, and certain brain injuries. It serves as a diagnostic tool that helps healthcare professionals assess brain function, identify abnormalities, and make informed decisions about treatment plans. In addition to its diagnostic applications, EEG is widely used in neuroscience research to study brain function, cognition, and mental states. It offers insights into brain activity patterns during various tasks, emotions, and cognitive processes. EEG is also employed to study event-related potentials (ERPs), which are changes in brain activity time-locked to specific events or stimuli, aiding cognitive neuroscience and psychology research.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

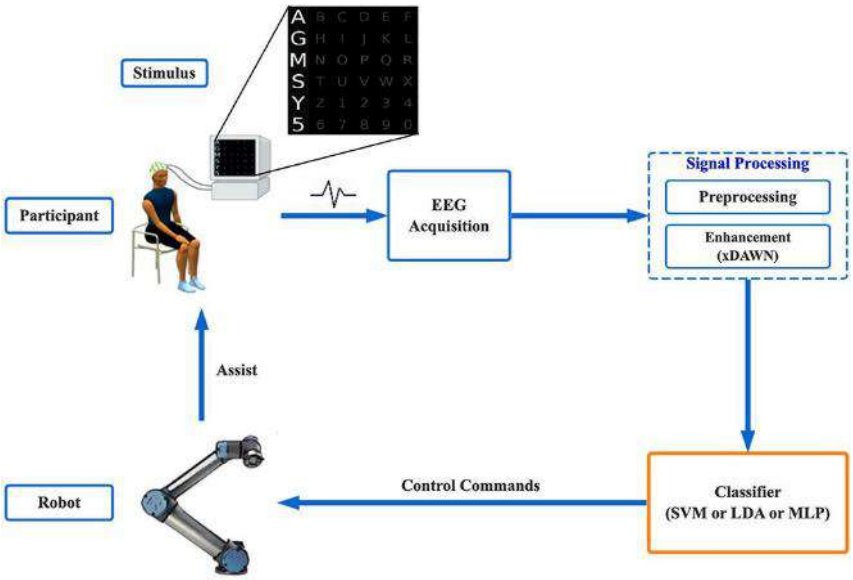


Figure 2.5.19. Electroencephalography (EEG) method used to measure and record the electrical activity in the brain

One of the notable advantages of EEG is its non-invasive nature. It does not require surgery or the insertion of electrodes into the brain, making it a safe and commonly used tool in both clinical and research settings. In biomechatronics research, there may be specific scenarios where an INS or a hybrid system, incorporating inertial navigation principles, is explored. For instance, studies analyzing human movement in complex environments or developing advanced wearable exoskeletons might benefit from the integration of INS technology to enhance the accuracy and robustness of motion tracking. In conclusion, position sensors stand as main components in the foundation of biomechatronics and diverse technological applications. Their role in providing feedback for control systems, ensuring precision, enhancing safety, enabling human-machine interaction, and contributing to efficiency underscores their significance. As technology continues to advance, the integration of position sensors will likely play an increasingly pivotal role in shaping the capabilities and functionalities of biomechatronic systems and beyond.

Concerning the second presentation provided related to the actuators, in the beginning of the lecture it is provided a definition of bio-mechatronics along with the main differences with mechatronics.

Therefore it is explained on the beginning that biomechatronics stands as a dynamic interdisciplinary field at the intersection of biology, mechanics, and electronics, focusing on creating mechatronic systems that seamlessly interact with the human body.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

At the core of these systems lie actuators, drives, and transmissions, essential components that enable precise movement, enhance mobility, and contribute to the overall functionality of biomechatronic devices. Actuators in biomechatronics serve as the driving force behind movements, translating electrical signals into mechanical motion. These devices play a pivotal role in the development of prosthetics, exoskeletons, and other assistive technologies. Electric actuators, such as brushless DC motors, are commonly employed for their efficiency, precision, and ease of control. These actuators empower biomechatronic systems to replicate natural human movements, providing users with enhanced mobility and functionality. Drives in biomechatronics are the mechanisms that transfer power from the actuators to the various components of the system. The choice of drive systems is crucial in achieving smooth and controlled movements. In applications like powered prosthetics or exoskeletons, variable impedance drives are often employed. These drives adapt to the changing dynamics of human movement, offering flexibility and responsiveness. Additionally, the integration of advanced drive systems, such as compliant drives, ensures a more natural and fluid interaction between the biomechatronic device and the user. Transmissions act as the intermediary between the drive system and the moving parts of biomechatronic devices. They play a vital role in adjusting torque, speed, and direction, optimizing the system's performance. In biomechatronics, where precision and adaptability are paramount, various transmission mechanisms are utilized. Harmonic drives, for example, offer high torque-to-weight ratios and compact designs, making them suitable for applications where space is limited, such as in wearable exoskeletons. Continuously variable transmissions (CVTs) provide smooth and seamless adjustments, ensuring that biomechatronic systems can adapt to the diverse needs of users. The synergy of actuators, drives, and transmissions is particularly evident in the development of advanced prosthetics. These components work in harmony to replicate the intricacies of natural limb movement, providing users with a more intuitive and functional experience. In the context of exoskeletons, these technologies enable individuals with mobility impairments to regain strength and perform activities with greater ease. Biomechatronics researchers and engineers continuously strive to enhance the integration of these components, exploring novel materials, control algorithms, and feedback systems to improve the efficiency and user experience of biomechatronic devices. The intersection of biomechanics and mechatronics in this field not only addresses the challenges of human-machine interaction but also opens new possibilities for improving the quality of life for individuals with diverse mobility needs.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Haptic feedback involves the sense of touch in human-computer interaction, providing users with tactile sensations through force, vibration, or motion. In the context of haptic technology, devices equipped with sensors and actuators enable users to feel and interact with virtual or remote environments. This technology is particularly crucial in applications where tactile feedback enhances the user's sense of immersion and control. Haptic feedback finds diverse applications, from gaming controllers that simulate the recoil of a weapon to surgical simulators that replicate the feel of tissues during medical training. In biomechatronics, haptic interfaces play a crucial role in creating more intuitive and realistic interactions between humans and robotic systems (see the examples provided in Figure 2.5.20).

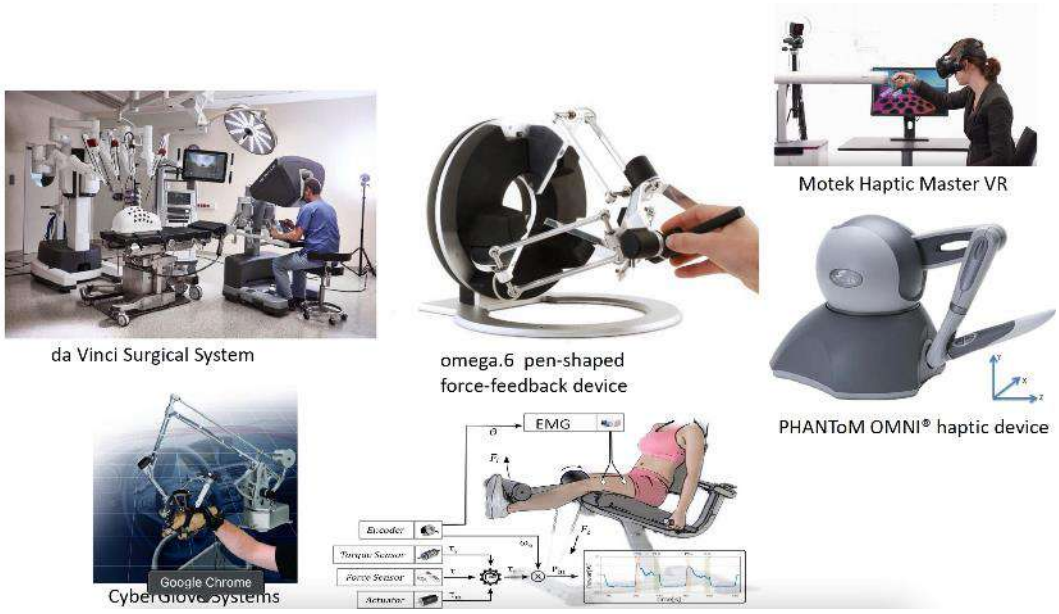


Figure 2.5.20. Examples of haptic technology systems

Telemanipulation involves the remote control of robotic systems by a human operator. This concept extends beyond traditional remote control by incorporating haptic feedback, allowing the operator to feel and perceive the remote environment as if physically present. The integration of telemanipulation in biomechatronics has significant implications for applications in healthcare, surgery, and hazardous environments. In telemanipulation for medical purposes, surgeons can remotely control robotic surgical instruments with haptic feedback, enabling precise and minimally invasive procedures. This technology has the potential to expand the reach of expert medical care to remote locations and enhance surgical capabilities.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The integration of haptic feedback and telemanipulation in biomechatronics holds promise for advancing human-machine interaction in various fields. In prosthetics and exoskeletons, haptic feedback can provide users with a more natural and responsive experience, allowing them to perceive the forces exerted by the device and interacts with their environment more effectively.

In rehabilitation robotics, telemanipulation enables therapists to guide and control robotic devices remotely, providing personalized therapy sessions for patients. Integrating haptic feedback mechanisms, as illustrated in the Arduino with motor example (see Figure 2.5.21), significantly augments the realism of patient interactions in rehabilitation, enabling patients to experience sensations like resistance, force, or textures, thereby enhancing motor control and contributing to more effective rehabilitation outcomes

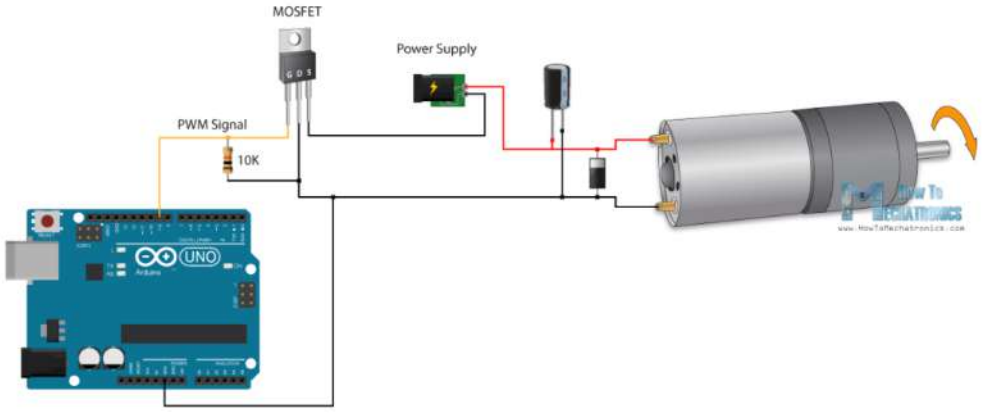


Figure 2.5.21. Arduino with motor

Pulse Width Modulation (PWM) is a technique used to generate analog-like signals using digital devices, like microcontrollers. Arduino boards have several pins that support PWM output. The Arduino can vary the duty cycle of the PWM signal, effectively changing the average voltage supplied to the connected device. In motor control applications, PWM is commonly used to regulate the speed of a motor. By adjusting the duty cycle of the PWM signal, one may control the effective voltage delivered to the motor.

In many applications, particularly those where the mechanical load on the motor remains relatively constant (constant torque), the speed of a DC motor is indeed directly proportional to the applied voltage. By controlling the voltage with PWM it is possible to effectively adjust the speed of the motor while maintaining a constant torque.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

This PWM-based motor control approach (see Figure 2.5.22) is fundamental in various applications, including robotics, automation, and electronics projects. It provides a means to control motor speed dynamically, responding to changing conditions or user inputs.

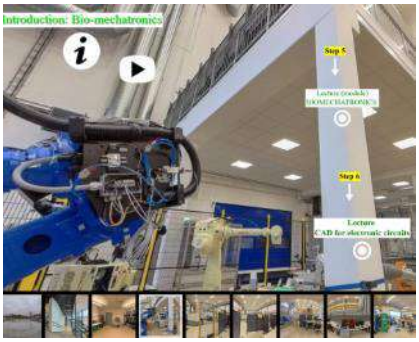
Figure 2.5.22. Example of PWM-based motor

When implementing such a system, it is essential to consider the specifications of the motor, the power requirements, and the characteristics of the load. Moreover, heat dissipation from the motor should be managed to ensure the system's efficiency and reliability. PMSM motors are known for higher efficiency and precise control, making them preferable in high-performance applications like the ones related to the conceiving of biomimetic mechatronic systems.

2.5.6. Steps 5 and 6 – Additional lectures related to Bio-mechatronic systems and CAD for electronic circuits

Since there have been make some references to bio-mechatronics aspects mentioned on the previous chapters, there have been prepared in the frame of O3 few additional courses and presentations like the ones provided in Figure 2.5.23. These resources can be accessed directly on the sensoring, assembly and programming virtual laboratory of the e-learning platform (see Figure 2.5.23) or by downloading them from the next following links:
https://drive.google.com/file/d/1mG9Oj2lA3DMqomHTdFKFRvOB9eKgdxO6/view and
https://drive.google.com/file/d/1yYfoH5KaSUtQJrKoHX0e04fcH0qc2WMr/view

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).



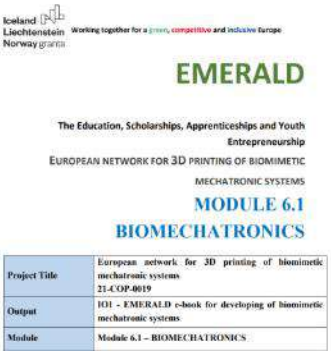


Figure 2.5.23. Bio-Mechatronics course realized by UiA and CAD for electronic circuits realized by PUT

Concerning of Bio-Mechatronics course module, it is underlines for the beginning again the importance of understanding that this term is referring actually to a multidisciplinary field that merges biology, mechanics, and electronics to create technologies that enhance human capabilities. Biomechatronics integrates biological systems, such as the human body and its movements, with mechanical and electronic devices to develop advanced hybrid systems. These systems are widely applied in medical devices, prosthetics, rehabilitation technologies, and in enhancing the performance of able-bodied individuals like athletes and military personnel. The field aims to improve the quality of life for peoples with special needs by developing artificial limbs and prosthetics that enable patients with amputated arms for instance to regain mobility and independence. Moreover, biomechatronic devices assist in surgeries, patient monitoring, and treatment, and have applications in enhancing the abilities of people without disabilities. Notable advances include the use of electromyography (EMG) to control artificial limbs through muscle signals and the development of exoskeletons that assist with movement and weight support for those with mobility impairments. Biomechatronics is continually evolving, with potential future developments in brain-machine interfaces (BMIs) that may allow control of devices through thought and the incorporation of wearable technologies for performance monitoring. Ethical considerations are crucial as the field grows, with the need to ensure responsible use and consideration of potential societal impacts.

In order to comprise as easy as possible these concepts, the Bio-mechatronics course module realized by UiA aims to provide various advancements and applications in biomechatronics, emphasizing the integration of mechanical systems with biological functions.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In this context, the All-in-One Servo Lab (AIOSL) represents a novel framework designed to enhance the teaching of motion control in mechatronics education, combining theoretical knowledge with practical, hands-on experience using cost-effective components, focusing on an elevator model for implementation.

In another example, a novel adaptive sliding mode controller is developed for a two-degree-of-freedom (2-DOF) elastic robotic arm. This controller shows promise in effectively managing uncertainties and disturbances, outperforming traditional controllers in simulation tests. Forward kinematic modeling is advanced through a Radial Basis Function Neural Network (RBFNN), optimized by a Cooperative Search Optimization Algorithm (CSOA). This approach allows the model to learn the kinematic features of a manipulator autonomously, showing superior performance over other models (see Figure 2.5.24).

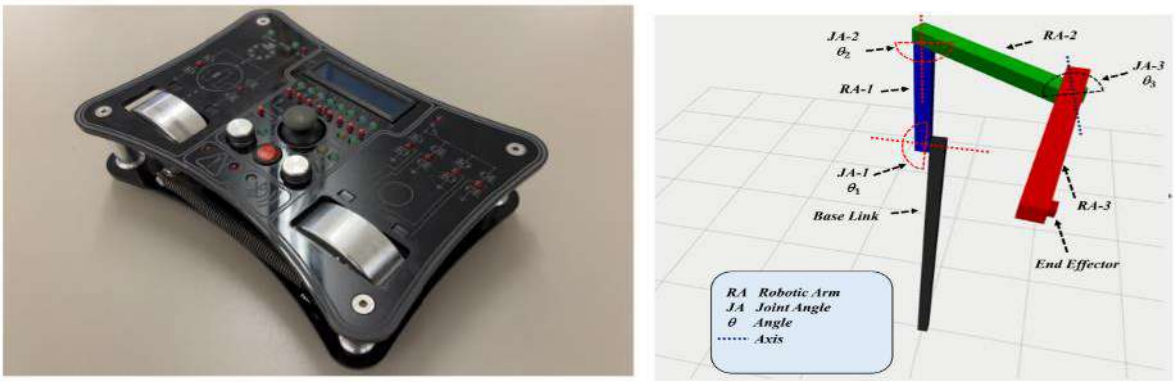


Figure 2.5.24. The all in one servo lab (AIOSL) and Kinematic model of the 3-DOF manipulator

Sensing and actuation technologies for robotic grasping and haptic rendering is one other application in which advancements in sensors, such as touch and optical, and actuators for various types of robotic grippers can be visualized (see Figure 2.5.25). This research serves as a foundation for future developments in robotic interaction and haptic technologies. For paraplegic patients, a mixed reality (MR) enabled framework has been used, allowing proprio and teleoperation of a humanoid robot. The system aims to enable patients to perform unscripted tasks in a realistic environment, enhancing engagement and presence illusion (see Figure 2.5.25).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.5.25. Sensing/actuation technology and haptic technologies used for teleoperation

In continuing, a study on the user experience of a virtual reality (VR) rehabilitation solution is presented, highlighting the feasibility of using VR in physical rehabilitation within a biomechatronics lab and potentially in a home environment (see Figure 2.5.26). Despite some challenges with cybersickness and balance in home setups, VR solutions are deemed practical for enhancing rehabilitation processes.

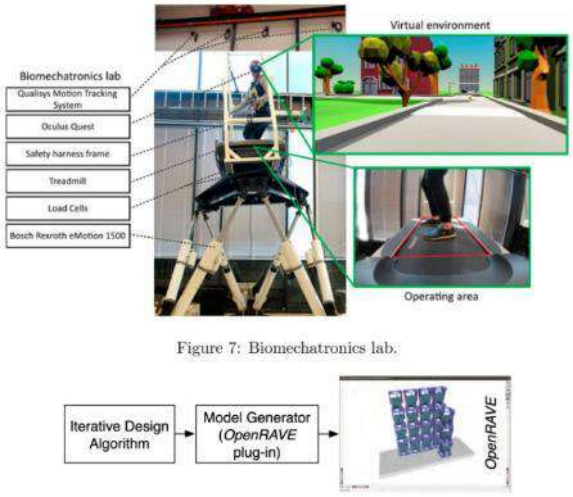


Figure 7: Biomechatronics lab.

Figure 2.5.26. User experience of a virtual reality (VR) rehabilitation solution

The series of studies and developments is ending by emphasizing highlight significant innovations in the field of robotic manipulation and grasp control, with a particular focus on modular and adaptive systems, which aim to improve interaction and functionality of these systems.

OpenMRH is an open-source plugin for OpenRAVE, allowing for the creation of various modular hand models that can be used to develop and test grip or motion planning algorithms efficiently. This tool facilitates dynamic code generation and user input to create models for algorithm validation.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In this context, is introduced the enhanced open-source framework for designing, simulating, and controlling low-cost sensorized modular hands called ModGrasp (see Figure2.5.27). One demonstrative video on the ModGrasp sensorized modular hands can be visualized on a video (see Figure 2.5.28) that is available on-line on the following link: http://youtu.be/2CIYboez9r0

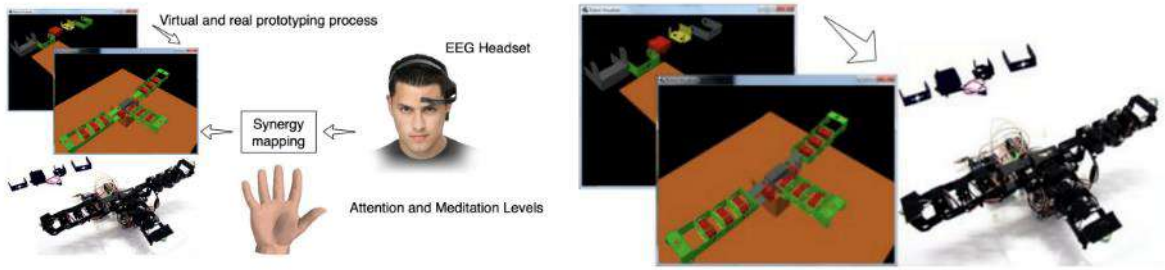


Figure 2.5.27. ModGrasp control architecture and integrating of virtual and physical rapidprototyping framework for the design, simulation and control of low-cost sensorised modular hands.

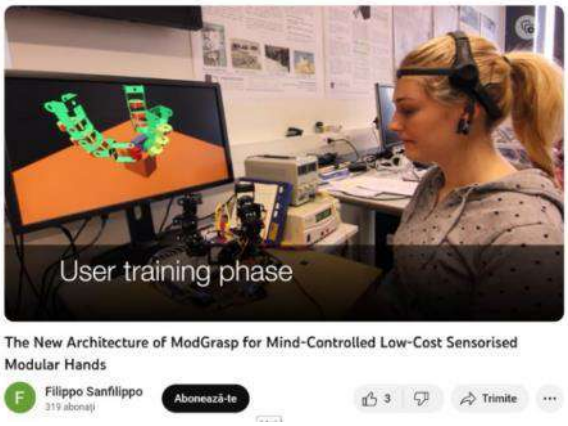


Figure 2.5.28. Demonstrative video on using the ModGrasp sensorized modular hands

The new architecture shown in figure 2.5.28 features the individual controller boards for finger links and a hierarchical software setup enhancing the system's responsiveness and functionality. A compelling application of this framework is a mind-controlled manipulator, which interprets EEG signals for hand operations, showcasing the synergy between human cognitive states and robotic control. ModGrasp was also featured in another study, emphasizing its capabilities in rapid prototyping and versatility in simulating different manipulator configurations. The inclusion of low-cost sensors allows for sophisticated functionalities like torque sensing and collision detection, further augmented by visual feedback through a 3D visualization environment.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In terms of the second presentation related to the "CAD Design of Electronic Circuits for Mechatronic and Medical Purposes" chapter module, this chapter provides an extensive overview of the process and techniques involved in creating electronic circuits for specialized applications. It begins by highlighting the critical role of Printed Circuit Boards (PCBs) in electronic systems and details the specific requirements for PCBs in various industries, especially in medical applications where factors like Electromagnetic Compatibility (EMC), lead-free assembly, and the necessity for low voltages and currents are paramount. The chapter of the course module then goes deeper into the types of PCBs as well as PCB design procedures that is particularly described accompanied by several figures, each illustrating a key aspect of the process. Therefore in the beginning (see Figure 2.5.29) an exemplary scheme of a power supply, demonstrating the initial stage of creating an electrical schematic that outlines the components and their interconnections. This is a critical step in visualizing the circuit before the actual layout design begins. Following this, an example of a board scheme related to a power supply is revealed following the schematic design is translated into an actual PCB layout. This step involves strategically arranging components and determining their connections through paths, a process central to effective PCB design. Importance of thermal management in PCBs is highlighted in continuing showcasing an example of thermal transfer in a PCB. This aspect is crucial, especially in high-power applications, to ensure the reliability and longevity of the electronic components. Then the nuances of PCB routing comparing examples of correct and poor routing are given, emphasizing the importance of layout planning for optimal electrical performance and manufacturability.

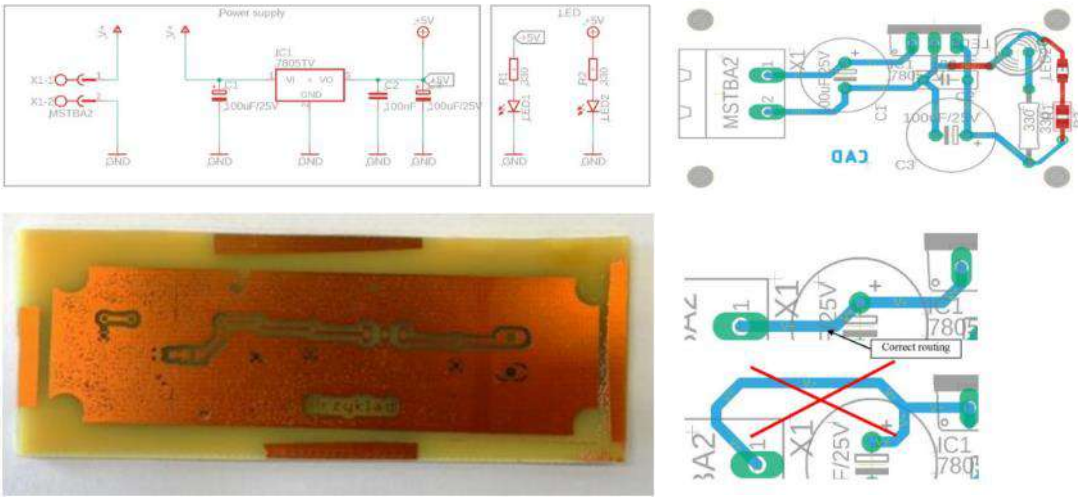


Figure 2.5.29. Exemplary scheme of a power supply and example of thermal transfer in a PCB

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In continuing the course module is focusing on the ground plane, illustrating an example of a ground plane on the bottom layer of a PCB. In this context is underlined the role of the ground plane in providing a voltage reference, shielding from noise, and aiding in heat dissipation. Lastly, there are provided insights into more intricate details of PCB design. In Figure 2.5.30 it is shown an example of signal settings, critical for ensuring the proper functioning of the circuit.

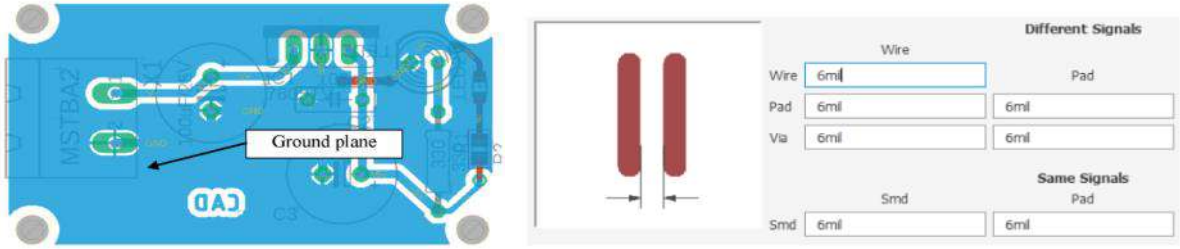


Figure 2.5.30. Ground plane and example of signal settings on a PCB circuit

Overall, the chapter of the course collectively enriches the understanding of the PCB design process, offering visual examples that complement the textual explanations in the module. They provide a clear, practical understanding of each step, from schematic design to layout planning and thermal management, crucial for effective CAD design in electronics.

2.5.7. Step 7 - Assembling case study and application

The Assembling resources being provided in the EMERALD e-learning virtual laboratory platform is continuing with the assembling of the bio-mechatronic system. The Assembly virtual laboratory room of University of Agder can be accessed through the e-learning platform, can be visualized or can be downloaded as one may notice in Figure 2.5.31.

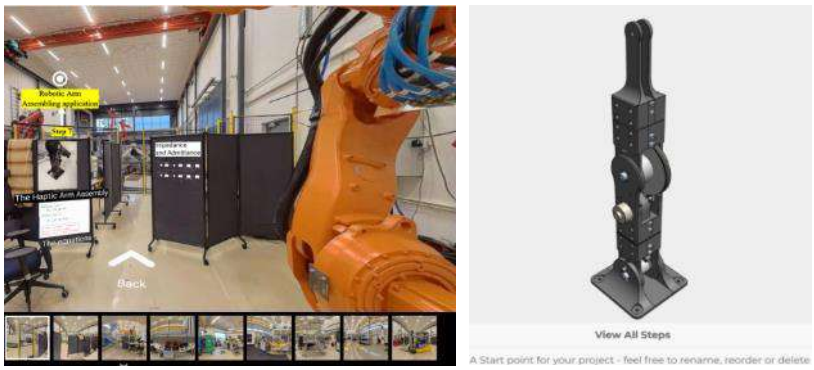


Figure 2.5.31. Assembling application realized and integrated within the Assembling laboratory of UiA

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In the Assembly room there are presented components of one robot griper that has been realized during the International Summer School 2022 edition organized by University of Agder in the frame of the EMERALD project. On the next following link there are provided information on the haptic system that has been realized by the team of University of Agder, based on which the students had the chance to work on in the Assembling, but also Programming domain later on (see: https://github.com/Microttus/elastic_actuator/blob/main/images/DSC_2766.JPG)

Supplementary to this in the frame of O3 one supplementary application has been realized by the University of Agder (UiA) related to the Assembling of the haptic system, as one may notice on the following link: https://instructions.online/?id=3988-mechanical%20assembly and in Figure 2.5.32. On this application that is realized similar to a game, students can see all the 42 steps that are necessary to realize the assembly of this mechatronic system and to comprise easily how such assembling has to be made.

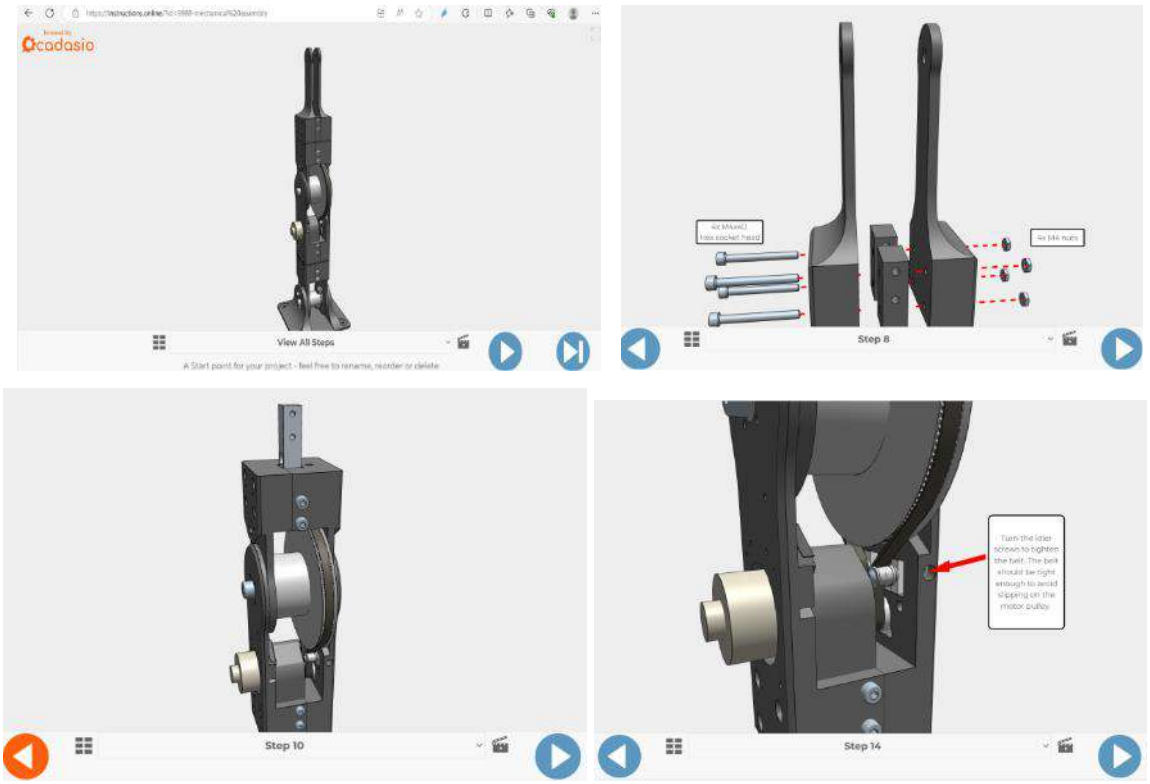


Figure 2.5.32. Robotic arm application realized in the frame of O3

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In addition to this there are two realized presentations that can be accessed through the e-learning platform as one may notice in Figure 2.5.33. These videos can be accessed on the e-learning platform or by accessing the following links: https://www.youtube.com/watch?v=6Vf5faGhciQ and https://www.youtube.com/watch?si=nHkEfITcb-D-KBVI&v=x0tvgowaUfE&feature=youtu.be The presentations that have been realized by the University of Agder (UiA) team are showing the general description about realized haptic system as well as testing of this device after the realized assembling and programming of the motions.

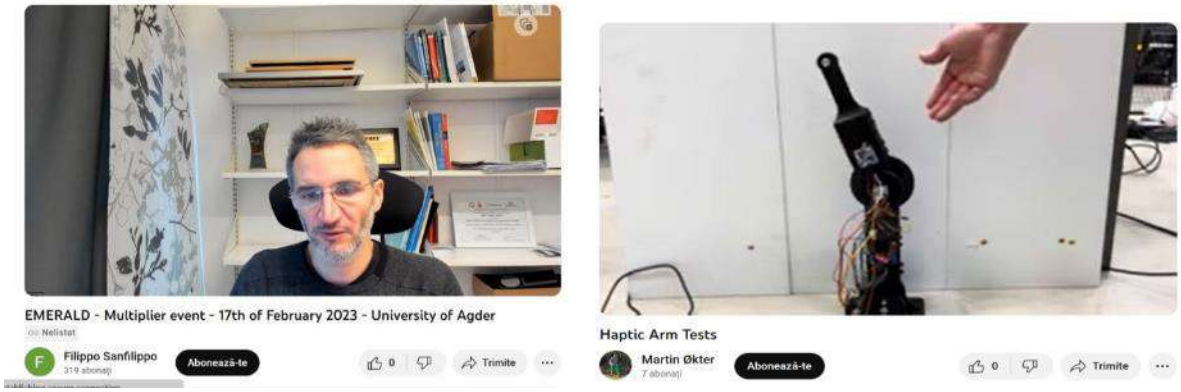


Figure 2.5.33. Presenting of the haptic system assembling concept and testing of haptic device

2.5.8. Step 8 - Programming course module

The Programming resources being provided in the EMERALD e-learning virtual laboratory platform is continuing with the programming of the bio-mechatronic system can be accessed through the Programming virtual laboratory of the e-learning platform, can be visualized or downloaded as one may notice in Figure 2.5.34 or by accessing the next following link: https://project-emerald.eu/wp-content/uploads/2023/02/EMERALD_IO1_module_3_ComputerProgramming.pdf

Figure 2.5.34. Programming course module realized by BIZZCOM

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The course module on basic programming is focused on one, very popular programming language – Python. Python's popularity can be attributed to several factors. Its ease of learning and use is a major contributor, making it an excellent choice for beginners and experts alike. Python's versatility allows it to be used in various domains such as web development, data analysis, artificial intelligence, and scientific computing. The language's strong community support and extensive libraries and frameworks further enhance its appeal. Python's readability and simplicity, combined with its powerful capabilities, have made it one of the fastest-growing programming languages in recent years.

Python, one of the most popular programming languages in the world, designed to be used in a range of applications, including data science, software and web development, automation, and generally getting stuff done. The course module on programming module – serves as an introductory guide to Python for individuals with some programming experience. It begins by outlining the structure of the Python class, which includes a mix of written materials and practical coding exercises. The course is designed to gradually introduce Python, starting with fundamental concepts such as strings and lists. As learners progress, they tackle more complex programming tasks, including working with text files, processes, and HTTP connections. The course is structured to accommodate learners who are familiar with basic programming concepts like variables and if statements, without requiring extensive prior expertise in programming. In the course module, there is a plethora of practical examples and detailed pieces of code, so that the learner is able to gradually progress through the steps of learning the language. An essential part of the course is setting up Python on the learner's machine. The document provides clear instructions for installing Python, which is a free and open-source language, available for all operating systems. The emphasis is on two key abilities: running existing Python programs and using the Python interpreter interactively. This dual capability is fundamental for following the lecture videos and successfully completing the exercises.

Python's nature as a dynamic, interpreted language is highlighted. The language's design eschews explicit type declarations for variables and functions in the source code, which contributes to its simplicity and adaptability. Python's runtime type tracking ensures that the code behaves as expected, even without compile-time type checking (see Figure 2.5.35).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

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

Figure 2.5.35. Python course module – example code for demonstrating Python's dynamic nature

The course module explains that Python source files, using the ".py" extension, are referred to as "modules." Running these modules is straightforward, typically using a command line argument. The document suggests consulting official documentation for various command-line options available for running Python programs. Python's built-in string class, "str," is highlighted for its utility and ease of use. String literals in Python can be enclosed in either single or double quotes, with the former being more common. The course module discusses much deeper the flexibility of Python strings, including their ability to span multiple lines and include backslash escapes.

The built-in list type in Python, called "list," is introduced. Lists in Python are flexible and can be manipulated using standard functions like 'len()'. Elements within lists are accessed using square brackets, and list literals are created using square brackets. An example of Python code performing a sum operation is provided like shown in Figure 2.5.36, demonstrating the practical application of Python's syntax and functions.

The course module on Computer Programming therefore provides a comprehensive introduction to Python, focusing on its fundamental aspects and practical applications. The popularity of Python is rooted in its ease of use, versatility, and strong community support, making it a preferred choice in various fields of software development.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

```
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']
```

Figure 2.5.36. Python course module – example code - lists

2.5.9. Step 9 – Brain computer interface additional lecture and presentation

In addition to this, one lecture on Brain Computer Interfaces has been realized by TUCN in the frame of O3, being integrated within the Sensoring, Assembly and Programming virtual laboratory of the e-learning platform as one may notice in Figure 2.5.37, this course being able to be accessed and downloaded also from the next following link:

https://drive.google.com/file/d/1Sxoby1XZVAiBupaV6gBuEpPyDJAJJ7QC/view

Figure 2.5.37. Brain control interface realized by TUCN in the frame of O3

In the introduction section of this course there are provided some basic definition in relation to Brain control interface terminology. It is important in this context in the beginning to understand that neurons are the fundamental units of the nervous system, acting as its basic computational components.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

They transmit and process information within the brain and body, functioning as the brain's workforce. Despite diverse shapes and sizes, neurons share common components: the cell body (soma), dendrites for signal reception, and axons for signal transmission. Myelinated axons, featuring a fatty insulating substance called myelin, facilitate rapid electrical signal transmission through saltatory conduction (see Figure 2.5.38). Nodes of Ranvier, gaps in the myelin sheath, play a vital role in efficient nerve impulse conduction. Axon terminals, branching into synaptic end bulbs, transmit signals to target cells at specialized synapses via synaptic vesicles containing chemical messengers.

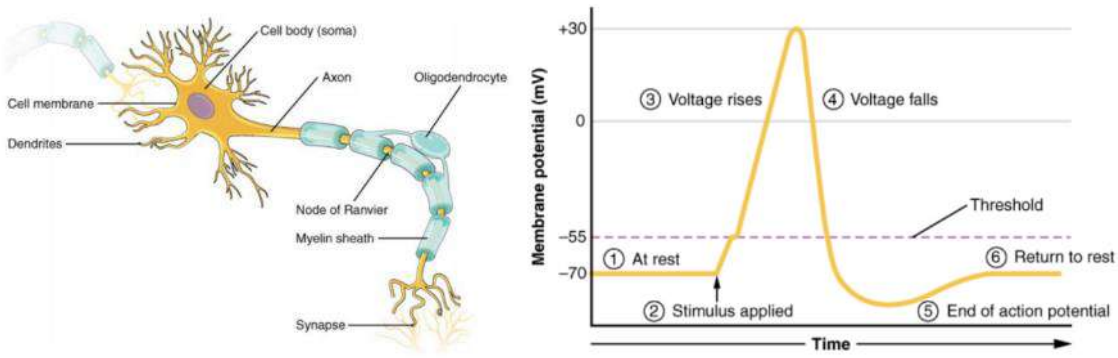


Figure 2.5.38. Structure of a typical neuron and Graphical representation of the neuronal action potential

Neurons communicate through synapses, specialized connections facilitating information transfer. Action potentials trigger the release of neurotransmitters from the presynaptic neuron into the synaptic cleft. Synapses can be excitatory, promoting depolarization and enhancing the postsynaptic neuron's activity, or inhibitory, inducing hyperpolarization and reducing firing rates. The balance of these signals determines whether a neuron fires an action potential, a fundamental aspect of neural computation. Synaptic plasticity, a key concept in neuroscience, involves the brain's adaptive capacity to change the strength of synaptic connections. Long-Term Potentiation (LTP) strengthens synapses, contributing to learning and memory, while Long-Term Depression (LTD) weakens synapses, aiding in synaptic pruning and maintaining neural circuit balance. These forms of plasticity enable the brain to adapt, learn, and optimize connections.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Electroencephalography (EEG) is a non-invasive neuroimaging technique that measures the brain's electrical activity by recording voltage fluctuations resulting from synchronized neuron activity. EEG signals, categorized into delta, theta, alpha, beta, gamma, and mu bands, reflect various mental states and cognitive processes. Fourier analysis decomposes complex EEG waveforms into frequency components, aiding in the identification of active frequency ranges during tasks or neurological conditions. While Fourier analysis provides frequency information, time-frequency analysis techniques, like the Short-Time Fourier Transform (STFT), capture how frequencies evolve over time allowing for studying transient brain events. Fourier-transformed EEG features are used for event detection, emotion recognition, sleep staging, and diagnosing neurological disorders. Additionally, Fourier analysis helps filter and reduce noise in EEG signals, enhancing data quality.

Hjorth parameters, devised by Björn Hjorth, are mathematical descriptors utilized in EEG signal processing to assess time-domain characteristics such as complexity, mobility, and activity. Comprising Hjorth Activity (D0), Mobility (D1), and Complexity (D2), these parameters offer insights into neural dynamics. D0 measures overall signal power, D1 gauges the frequency of signal changes, and D2 quantifies signal unpredictability. These parameters aid in summarizing and interpreting EEG signals concisely. Additionally, their application provides valuable information about brain activity, cognitive states, and neurological conditions. In contrast, the Adaptive Autoregressive Model (AAR) serves as a time-series modeling tool in EEG signal processing, adapting its parameters over time to capture non-stationary signal characteristics. It proves beneficial for real-time applications, event-related potential analysis, and detecting shifts in EEG signal dynamics. Bayesian filtering, another approach in EEG signal processing, combines probabilistic modeling and Bayesian statistics to estimate and update the hidden state of neural activity over time. Particularly useful in BCIs and neurofeedback systems, Bayesian filtering allows real-time tracking of changing cognitive states and adaptive feedback based on EEG data, enhancing various applications in neuroscience.

In EEG signal processing, the referencing method is chosen based on research or clinical goals and data characteristics. Common methods include bipolar referencing, Laplacian referencing, and Common Average Referencing (CAR). Bipolar referencing computes voltage differences between adjacent electrodes to minimize common noise, providing enhanced spatial specificity. Laplacian referencing, or current source density, highlights local voltage changes and reduces volume conduction effects, but it is sensitive to noisy measurements.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

CAR calculates the average voltage across all electrodes to remove common noise, making it easy to implement but reducing spatial resolution. Principal Component Analysis (PCA) is employed for dimensionality reduction, artifact removal, and feature extraction in high-dimensional EEG data. PCA-derived features aid tasks such as cognitive state classification and event detection. Additionally, Common Spatial Patterns (CSP) is a technique for feature extraction and spatial filtering, beneficial in tasks like motor imagery classification for brain-computer interfaces and the classification of cognitive states in EEG data. CSP identifies spatial filters that maximize the separation between classes in labeled training data, making it effective but subject specific. Other spatial filtering techniques, such as Independent Component Analysis and Source Localization, can also be considered based on specific requirements.

Linear Discriminant Analysis (LDA) is a technique in EEG signal processing, serving feature extraction and dimensionality reduction purposes, particularly beneficial for applications like brain-computer interfaces, neurofeedback, and cognitive neuroscience (see Figure 2.5.39). LDA aims to maximize class separability in high-dimensional and noisy EEG data, helping remove irrelevant features for improved classification accuracy and reduced computational load. Quadratic Discriminant Analysis (QDA), a counterpart to LDA, focuses on classification and dimensionality reduction in the presence of non-linear relationships and varying covariance matrices among classes. Nearest Neighbor (NN) and k-Nearest Neighbor (k-NN) are non-parametric techniques vital for classification and regression in high-dimensional EEG data, offering simplicity and flexibility. While these parameters are used for capturing non-linear relationships the NN and k-NN face challenges in computational costs and scaling, highlighting the importance of parameter tuning in case of setting up of these parameters.

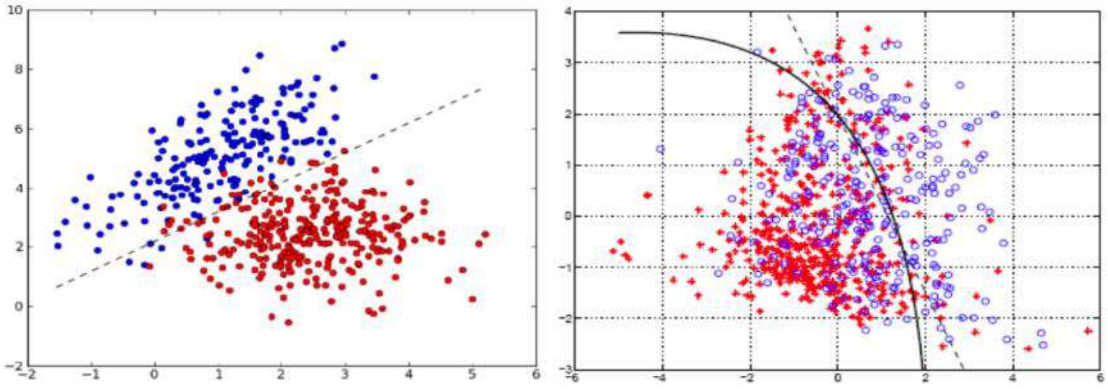


Figure 2.5.39. LDA and QDA techniques for EEG signal processing

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Nearest Neighbor (NN) and k-Nearest Neighbor (k-NN) are classification and regression techniques used in EEG signal processing for tasks like emotion recognition, mental state classification, and brain-computer interfaces. These non-parametric methods classify data based on proximity, with k-NN using majority voting among the k closest neighbors. Their flexibility makes them suitable for high-dimensional EEG data. Complementing these techniques, a confusion matrix offers a detailed assessment of a classification model's performance in EEG applications. It evaluates accuracy, precision, recall, and other metrics for each cognitive state, aiding in refining algorithms and feature selection. Metrics like the F1-score derived from the confusion matrix provide deeper insights into model strengths and weaknesses. Additionally, the Receiver Operating Characteristic (ROC) curve is crucial for visualizing model performance in distinguishing between different cognitive states, illustrating the sensitivity-specificity trade-off at various thresholds. The area under the ROC curve quantifies the overall efficacy of the classification model in EEG signal processing (see Figure 2.5.40).

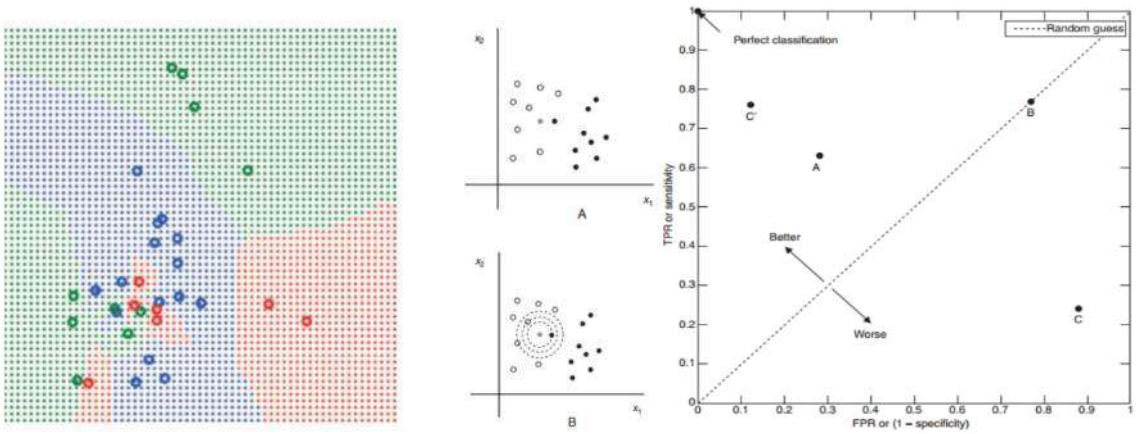


Figure 2.5.40. Decision space of k-NN and example of a ROC diagram

Brain-Computer Interfaces (BCIs) come in two main flavors: Invasive and Noninvasive. Invasive BCIs require surgical implantation of electrodes directly into the brain tissue, enabling high-resolution neural recording and bidirectional communication with external devices. Common electrode types include microelectrode arrays, Utah arrays, and Electro-corticography grids, each with specific applications and challenges such as infection risks and ethical concerns.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Noninvasive BCIs, on the other hand, use external sensors like EEG, fNIRS, fMRI, and MEG to record brain signals without surgery. While more accessible, they face challenges like signal quality and are used in applications such as assistive technology, rehabilitation, research, and gaming. Various sensorimotor paradigms, like SMR and P300, as well as SSVEP, motor imagery, imagined speech, emotion recognition, and hybrid paradigms, shape BCI applications catering to diverse needs, each with unique strengths and limitations. There are also some semi-invasive methods on the role. Ongoing research aims to enhance signal quality, decoding algorithms, and application breadth in both invasive and noninvasive BCIs way.

In addition to the provided lecture, so as the students (users) can understand much better the differences in between Noninvasive, Invasive and Semi-Invasive methods, as well as the applicability of these methods in bio-mechatronics domain an additional presentation has been prepared by the TUCN in the frame of O3, focusing on the practical side of Brain Computer Interfaces methods. The presentation can be accessed on the VR/AR laboratory of the e-learning platform as one may notice in Figure 2.5.41 or can be accessed and downloaded from the next following link: https://drive.google.com/file/d/1b5RHyWa3ZoNRFZPfCNwHc9DE0NTae9ey/view.

Figure 2.5.41. Brain computer interfaces applications additional presentation

The presentation on Brain-Computer Interfaces (BCIs) is exemplifying the three types of Brain-Computer Interfaces (BCIs) there have been mentioned in the course module, like: invasive, semi-invasive, and non-invasive.

Differences are explained also through definitions, but also in a visualized way, accompanied by explanations concerning the main differences between all these methods and applicative ways. (see figure 2.5.42)

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.5.42. Invasive, Semi-invasive and non-invasive Brain-Computer Interfaces (BCIs) methods

Therefore, as one may notice in Figure d, invasive Brain-Computer Interfaces (BCIs) methods involve recording or stimulating neurons directly inside the brain, offering precise control but posing risks such as infection and damage to brain circuits. Semi-invasive Brain-Computer Interfaces (BCIs) methods, while are quite similar, involve interaction with the surface of the brain. Non-invasive

Brain-Computer Interfaces (BCIs), on the other hand, use techniques that do not penetrate the skin or skull, like EEG, which makes them safer but generally less precise than invasive methods.

In terms of BCI applications, their use is encountered in various fields, like using Brain-Computer Interfaces (BCIs) methods for rehabilitation, which can enhance a patient's engagement with their rehabilitation equipment. These interfaces have been particularly effective used also in animal and human studies utilizing methods such as EEG, imagery, etc. The significant advancements in Brain-Computer Interfaces (BCIs) methods demonstrate their potential in improving human interaction with technology, especially in case of patients with physical disabilities or neurological disorders (see Figure 2.5.43).

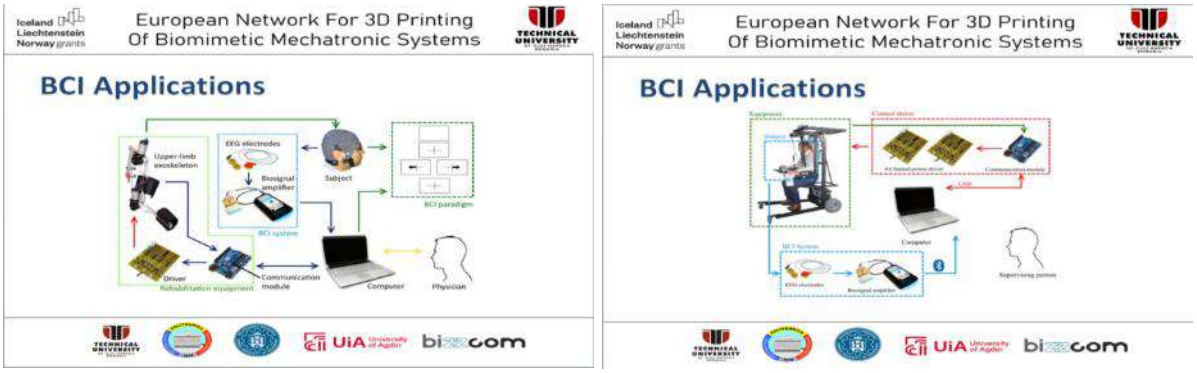


Figure 2.5.43. Examples of BCI applications

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.5.10. Step 10 – Computer programming laboratory instructions

Using information the students can find about computer Programming and Brain Computer Interfaces course modules and presentations, they can continue on accessing the instruction materials / tutorials that have been prepared and integrated in the Programming laboratory of UiA as one may notice in Figure 2.5.44 directly on the programming laboratory room of University of Agder of the EMERALD e-learning virtual platform or by accessing and downloading them from the following links: https://drive.google.com/file/d/1sy-jKQ4Qkt5qZhrZo2VGkXAih7nc1LHJ/view;

https://drive.google.com/file/d/1thWzVKr1Y9ge1XowcYatPYuEZHvHgEwc/view

https://drive.google.com/file/d/1ntwkwNEDSRTJbZ_i0A2eISnN9YZQS16i/view

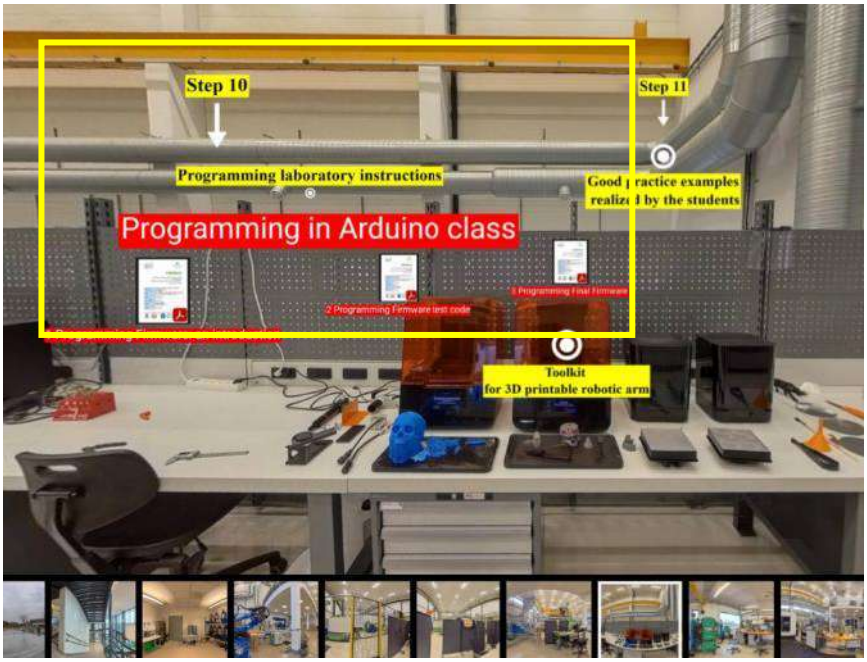


Figure 2.5.44. Laboratory tutorials prepared for programming in Arduino to be realized for the robotic arm

The first laboratory instruction file on "Programming Firmware: An Introduction" offers a practical understanding of firmware and its role in hardware devices, along with a practical guide on using the Arduino Integrated Development Environment (IDE) for programming ESP-based boards (see Figure 2.5.45).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

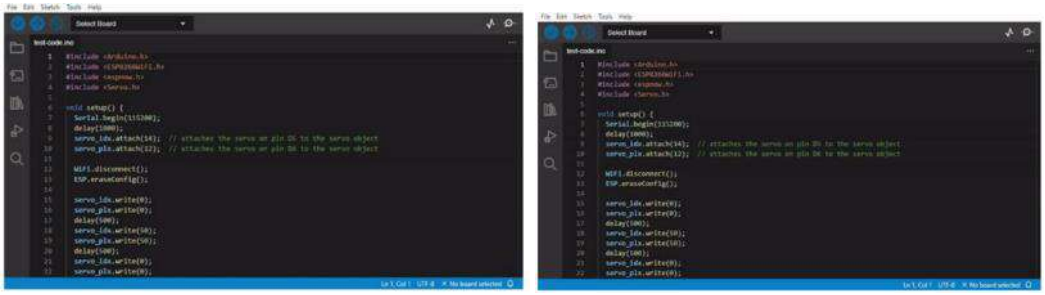


Figure 2.5.45. Practical guide on how to use the Arduino Integrated Development Environment (IDE) for programming ESP-based boards

Firmware is defined as a specific type of software embedded within hardware devices. It is essential for dictating how the device communicates with other computer hardware components. Stored typically in the device's read-only memory, firmware is often the initial software to activate upon powering up a device. Its responsibilities include booting up the device, managing system resources, and providing an interface for applications to interact with the hardware. This section lays the groundwork for understanding the integral role firmware plays in the functionality of electronic devices. Specific attention is given to the Arduino IDE 2.0, selected for its simplicity and accessibility, making it an ideal choice for beginners in firmware programming. The guide then meticulously explains the setup process for ESP-based boards within this IDE. This setup involves inserting specific URLs into the IDE to access the hardware list for ESP boards, a critical step for programming ESP32 and ESP8266 boards. The instructions detail navigating through the IDE's interface to add board manager URLs and installing the necessary board managers, thereby preparing the environment for uploading firmware codes to ESP boards.

The second laboratory instruction file on „Programming Firmware test code" provides a detailed tutorial on programming firmware, specifically focusing on writing and uploading a test code to a D1 mini microcontroller using the Arduino Integrated Development Environment (IDE). This process is crucial for verifying the functionality of the device, ensuring that all components are working as expected. The tutorial begins by setting up the environment to program the D1 mini ESP8266 board. It involves identifying and selecting the correct COM port in the IDE, which the device is connected to via a USB micro connector. This step is essential as it determines how the IDE communicates with the microcontroller. The IDE interface allows the user to select the specific board model, in this case, the "LOLIN(WEMOS) D1 R2 & mini," and the appropriate COM port marked "(USB)" for establishing a successful connection (see Figure 2.5.46).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

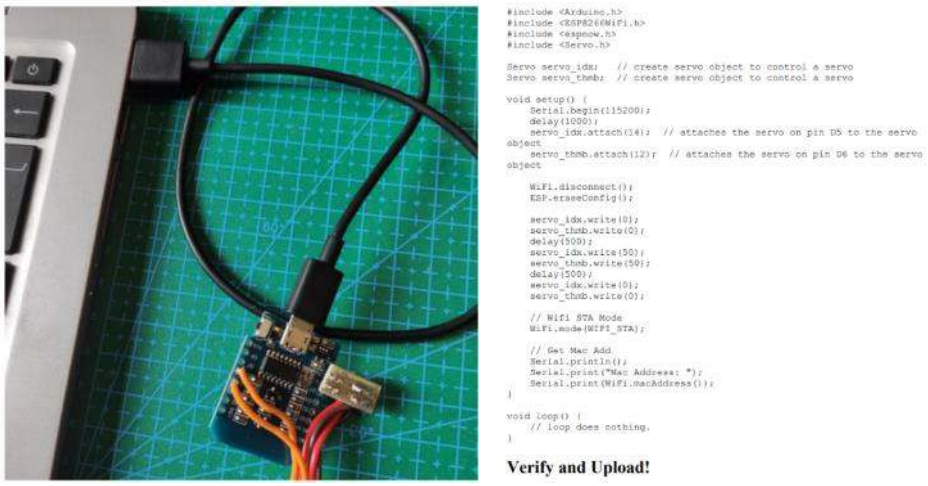


Figure 2.5.46. Programming firmware, writing and uploading a test code to a D1 mini microcontroller

The core of the guide is the test code provided to move the servomotors of the device. The code, written in the Arduino programming language, includes instructions to control the servo motors attached to specific pins on the microcontroller. This code begins with setting up the serial communication and attaching the servos to their respective pins. It then performs a series of write operations to move the servos, testing their range and responsiveness (see Figure 2.5.46). The code also includes instructions for disconnecting from Wi-Fi and erasing previous configurations, ensuring a clean start for the test.

After writing the code, the laboratory instruction document guides the user through the process of verifying and uploading the sketch to the microcontroller as shown in Figure 2.5.47.

This step is crucial to ensure the code is free from errors and compatible with the board. Upon successful upload, indicated by a flashing blue LED on the board, the servos are activated, confirming the proper functionality of the microcontroller and the correctness of the code.

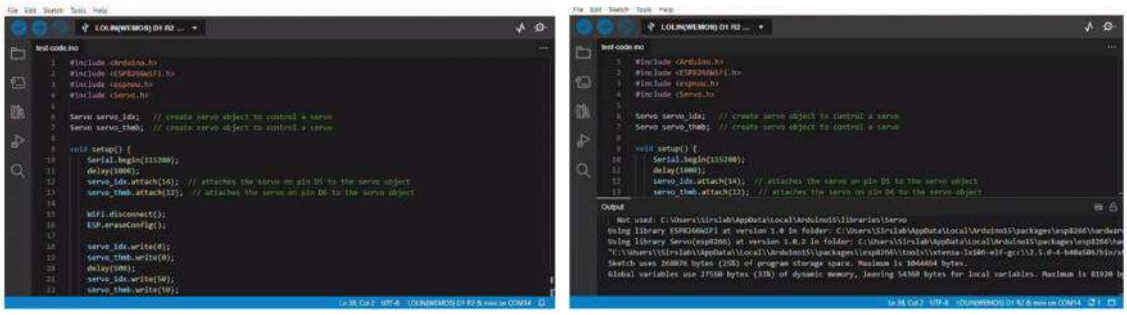


Figure 2.5.47. Verifying and uploading the sketch to the microcontroller

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The third laboratory instruction document entitled „How to get MAC addressed of the boards" was focused on the leveraging the esp-now protocol for device interconnectivity. This has been involving a detailed process of configuring ESP8266 and ESP32 microcontrollers, which are integral for establishing robust network communications (see Figure 2.5.48).

```
#include <Arduino.h>
#include <ESP8266WiFi.h>

void setup() {
Serial.begin(115200);
WiFi.disconnect();
ESP.eraseConfig();

// Wifi STA Mode
WiFi.mode(WIFI_STA);

// Get Mac Add
Serial.println();
Serial.print("Mac Address: ");
Serial.print(WiFi.macAddress());
}


void loop() {
// the loop does nothing
}
```

```
#include <Arduino.h>
#include <WiFi.h>

void setup() {
Serial.begin(115200);

// Set device as a Wi-Fi Station
WiFi.mode(WIFI_STA);
```

Figure 2.5.48. ESP8266 and ESP32 microcontrollers configuration

As one may notice in Figure 2.5.48, the first step in this process consists in the acquisition of MAC addresses of the microcontrollers, a critical component for setting up devices using esp-now. This enables the boards to recognize each other's "ID" and establish a connection.

For the D1 mini boards equipped with ESP8266 microcontrollers, the laboratory document shows how can be successfully uploaded specific codes to obtain their MAC addresses. This involves initiating serial communication, setting the Wi-Fi mode to station, and then retrieving and printing the MAC address. The code is designed to be simple yet effective, ensuring that the MAC address is accurately displayed on the serial monitor of the IDE. A similar process is followed for dongle boards based on ESP32 microcontrollers, with slight variations in the code to accommodate the different hardware (see Figure 2.5.49).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

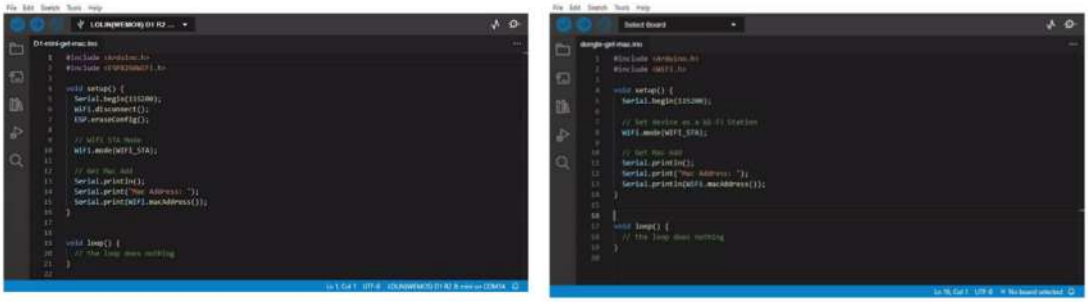


Figure 2.5.49. Reaching out the MAC addresses of hardware components

In continuing it is shown how developing firmware for ESP32 devices has to be set up, enabling them to function as dongles. This involves reading serial data from a connected device and transmitting it wirelessly to an ESP8266 device using the ESP-NOW protocol. The firmware is designed to efficiently map raw force sensed values to a range of 0-255 and then transmit this data to the ESP8266 device and with other similar additional programming tasks as they are provided in the laboratory instructions, final test of the robotic arm should be easy to be performed using dongle to one of our USB ports and battery-power for the thimble microcontroller with the servomotors attached.

In the end of this tutorial an animation video has been added so anyone who is using the tutorials and the instructions can see how wiring of cables must to be done and how final test can be performed with the user typing the characters “AA” and “zz” to the serial port with an effect seen of the thimbles moving to reach this positional command. (see Figure 2.5.50). The video animation can be seen also by accessing the next following link that has been provided in the laboratory manual: https://simplethimble.readthedocs.io/en/latest/_images/firmware-final-test.gif

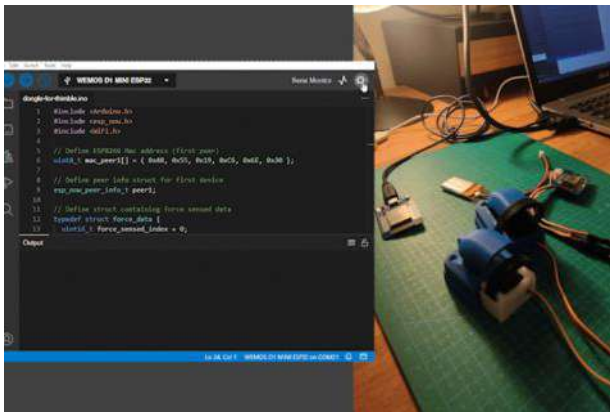


Figure 2.5.50. Video animation for testing of the programming realized

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.5.11. Step 11 – Computer programming good practice examples realized by the students

As one last step, in the laboratory of programming from University of Agder (UiA) on the e-learning platform there have been provided a series of good practice examples of work realized by the students using the teaching resources that they have found in the Sensoring, Assembling and Programming rooms of University of Agder (as one may notice in Figure 2.5.51), all these presentations being able to be accessed also on the next following link: https://drive.google.com/file/d/1hJKWcTMY_wLf6xAVmML2mWfQKcABcxhw/view

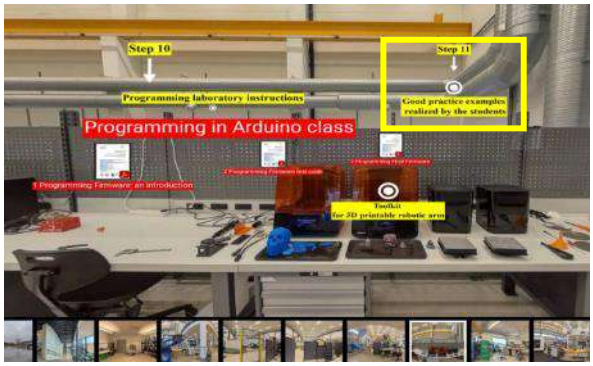


Figure 2.5.51. Good practice examples realized by the students in terms of assembling and programming

In order to emphasize much clearly parts of the results realized by the students in terms of programming, in Figure 2.5.52 there have been presented few examples undertaken from Powerpoint presentations that the students have realized during the EMERALD summer school events organized at University of Agder in the frame of the EMERALD project, proving the efficiency of the providing resources they have been using for realizing such nice achievements.

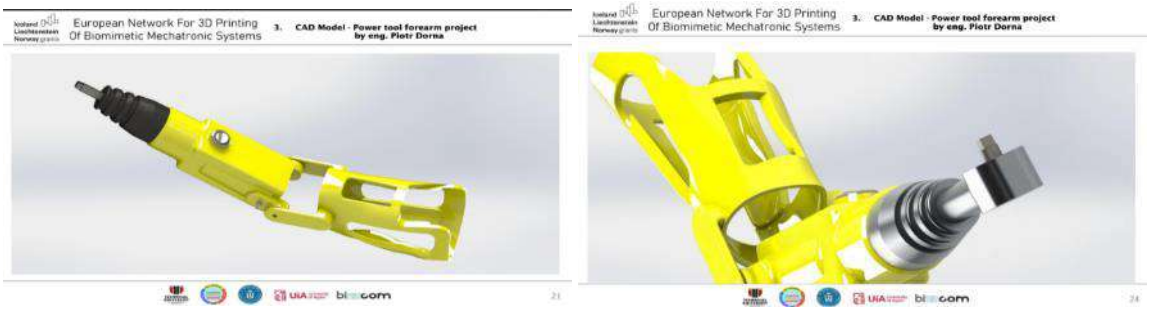


Figure 2.5.52. Good practice examples of programming realized by the students using the EMERALD teaching resources of the e-learning platform

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.5.12. Conclusions about sensoring, assembly and programming teaching resources of the e-learning platform

The e-learning virtual laboratory room of the e-learning platform that has been assigned for sensoring, assembly, and programming, significantly enriches the educational journey in the field of bio-mechatronics by guiding the users and by stimulating them to create and work with devices like robotic arms, orthoses, and prostheses, especially for those with amputated arms. The primary goal of this laboratory is to make students (users) familiar with the entire process, starting with the basics of sensor types suitable for such systems, followed by the assembly of key components like step motors or actuators, and concluding with the necessary programming steps. To ensure a comprehensive understanding, the laboratory of Programming initially offers lectures and courses to familiarize students with fundamental terminology and concepts. This foundational knowledge is then reinforced through a series of instructional videos, applications, or toolkits, which guide users through the practical aspects of sensoring, assembling, and programming bio-mechatronic systems.

2.6. VR / AR laboratory room (BIZZCOM)

2.6.1. Accessing of VR /AR laboratory room

VR /AR laboratory room which has been assigned to the BIZZCOM (Slovakia) as one may notice in Figure 2.6.1 can be accessed from the www interface of the EMERALD project (https://project-emerald.eu/?page_id=404) or directly by accessing the next following link: https://bizzcom.viewin360.co/share/collection/7J4Qv?logo=0&info=0&fs=1&vr=1&sd=1&initload=0&thumbs=1

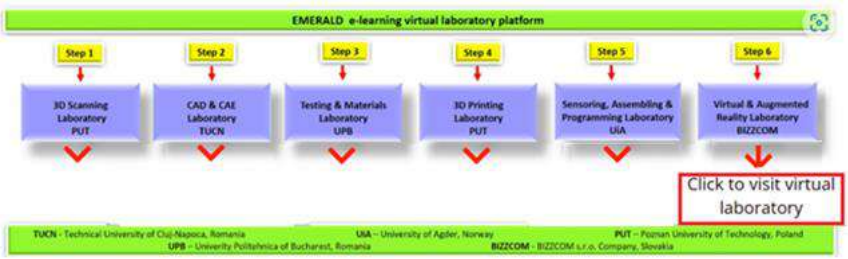


Figure 2.6.1. Accessing of the VR / AR laboratory room from the e-learning platform

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The Virtual Laboratory tour begins at the entrance of the Bizzcom main building, as shown in Figure 2.6.2. Upon entering the building through the main corridor, the users are led to the engineering (training) room as shown in Figure 2.6.3.

Figure 2.6.2. Entrance of the BIZZCOM main building

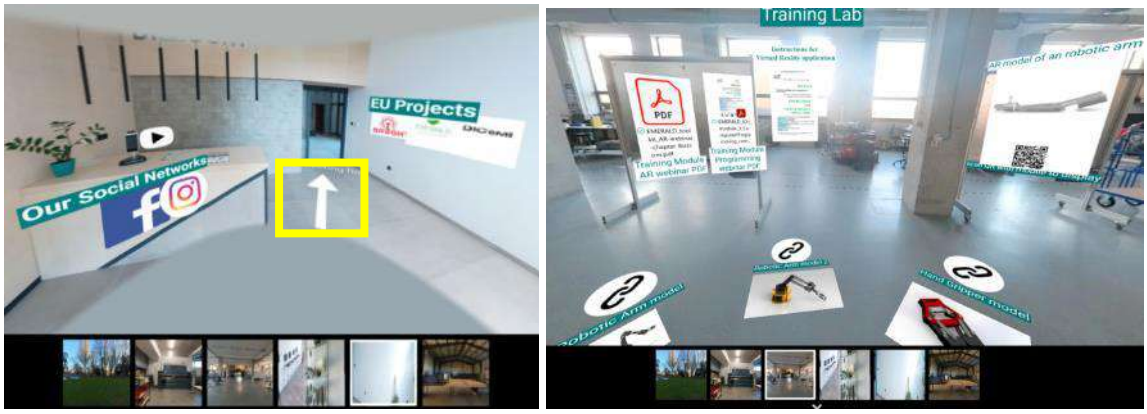


Figure 2.6.3. Access to the engineering / training laboratory (Bizzcom)

The first virtual laboratory to visit at BIZZCOM which can be seen in Figure 2.6.3 has been assigned for the AR training in principle. Room presented in Figure 2.6.4 has been assigned for training in VR. In this room there are provided some basics about VR, teaching resources being completed with the ones that can be found at PUT 3D scanning laboratory due to the multiple existing facilities. Beside these two rooms, there are 2 more that can be visited like: Assembling / Construction Halls, but these are just for seeing some of the existing facilities of this company (like a tour).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

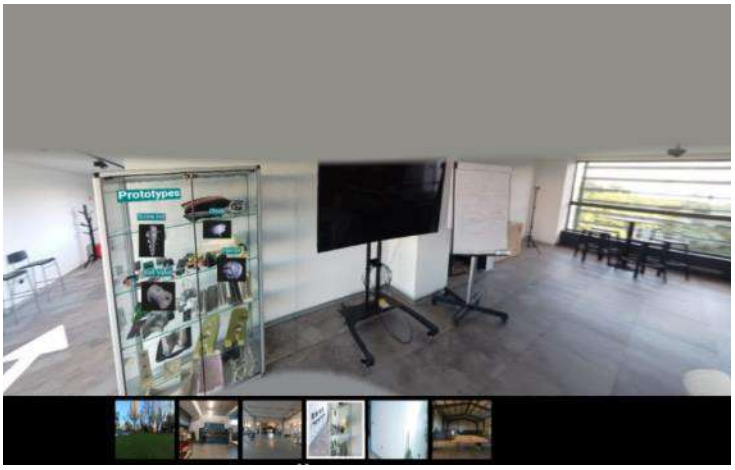


Figure 2.6.4. Training laboratory in VR (Bizzcom)

All figures that can be seen in Figures 2.6.3 and 2.6.4 have been realized using Insta 360 camera, the captured images undergoing in further processing using Kuula software, allowing the integration of educational materials related to the VR / AR of the bio-mechatronic components that have been developed within the EMERALD project related to these topics.

2.6.2. Structuring of the teaching resources being provided about VR /AR in the e-learning platform

The e-learning virtual laboratory platform dedicated to the VR /AR stage in particular offers an enriched educational experience that is tailored to the design of bio-mechatronic systems destined for people with special needs (with amputated arms) such as robotic arms, orthoses and prostheses, focusing on the necessary steps that are particularly necessary to be followed in the field of VR/AR domain. Similar like in the case of the other virtual laboratory rooms of the e-learning platform, the VR / AR laboratory comprises a series of courses, lectures, laboratory toolkits and applications that have been realized on the EMERALD project during its period of implementation and during the organized events (international summer schools and staff for training events). In terms of VR / AR laboratory, BIZZCOM has been assigned as main responsible institution of coordinating this virtual laboratory room in particular, this institution being responsible in hosting of the staff for training event in Bucany, but the provided resources have been produced also by PUT partner who have one dedicated laboratory for VR and rest of contributions has come through the applications that have been developed by the other partners of the EMERALD consortium during the organized events.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.6.3. Step 1 - VR / AR course module

The VR / AR lecture resource being provided in the EMERALD e-learning virtual laboratory platform is leading first to the VR /AR course module that has been produced by the EMERALD consortium in the frame of O1 (by PUT partner), course that can be accessed through the platform, can be visualized or can be downloaded as one may notice in Figure 2.6.5 – see: https://project-emerald.eu/wp-content/uploads/2023/02/EMERALD_IO1_module_4_VR.pdf

Figure 2.6.5. VR / AR course module on the VR /AR laboratory of the e-learning platform

The course starts by providing introduction and additional information about the integrating and use of extended reality (XR) technologies in the biomedical field. In providing a foundational understanding of XR, in the beginning there are needed to be clarified few of the most important key concepts of XR, such as:

- Virtual Reality (VR): This technology creates a completely artificial digital environment that users can experience and interact with as if it were real.
- Augmented Reality (AR): AR overlays digital content on the user's view of the real world, enhancing one's perception with additional information.
- Mixed Reality (MR): MR merges real and virtual worlds to produce new environments where physical and digital objects coexist and interact in real-time.

In case of VR, there are three fundamental characteristics to be considered like the: immersion, interaction, and imagination, which together define the user experience (see Figure 2.6.6). Immersion is achieved through sensory stimuli replacement, interaction is the reciprocal influence between user and digital world, and imagination fills in the gaps left by technology's imperfection.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The course module presents VR as distinct from other forms of human-computer interaction due to its realistic 3D graphics, intuitive user interaction, and the immersion of users within the digital scene.

Figure 2.6.6. Main basis of VR fundamentals and immersion of users with digital scene

In terms of augmented reality (AR) as compared with VR, an important distinguishing have to be made, noting that AR users are not immersed but have the real world enhanced with virtual elements that interact with and permanently affix to their real-world view. Mixed reality (MR) in completion is presented as a blend of VR and AR, with the unique characteristic that digital objects in MR are not necessarily fixed in space relative to the real world (see Figure 2.6.7).

Figure 2.6.7. AR and MR characteristics

In continuing it is important to understand fundamental and basic things about the equipment and software programs that are associated to XR systems, such as VR helmets, motion controllers, immersive gloves, and the various types of AR/MR devices, including smart glasses, optical helmets, and handheld devices (see few examples being provided in Figure 2.6.8).

Figure 2.6.8. VR helmets, VR controllers and Mixed Reality devices

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In terms of hardware systems, these are often a combination of high-output computers, head-mounted displays, input systems like gloves or handsets, and tracking systems. The software, meanwhile, includes applications and platforms that drive these devices, create immersive content, and enable user interaction. From the software point of view, VR applications are built using 3D engines, which are comprehensive programming tools that provide the infrastructure necessary for creating interactive digital environments. These engines facilitate the representation of 3D geometry, object manipulation, scene structuring, and the dynamic interaction of objects within the application as one may notice in the example provided in Figure 2.6.9.

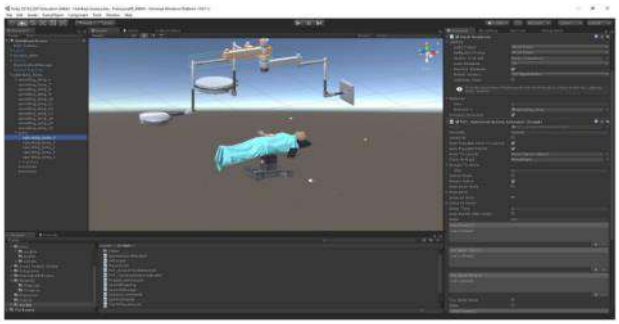


Figure 2.6.9. Example of a VR application realized using a dedicated software for VR called Unity

Applications of XR technologies are varied and have made significant impacts in fields such as engineering, education, entertainment and also in medicine for patient care and therapy. Building of an application starts by defining simulations, distinguishing between "hard" and "soft" simulations, with XR often falling into the former category due to its reliance on physical laws to create realistic environments. In concordance with the requirements and categorization of educational XR applications, these are categorized in three levels based on the complexity. These range from general knowledge of processes or objects (Level 1) to procedural knowledge (Level 2) and practical skills (Level 3) (figure 2.6.10). In conceiving of the design process for VR/AR/MR applications, there are some critical steps and phases like identification, justification and knowledge acquisition that have to be taken into consideration in close correlation with the type of the application as Figure 2.6.10 suggests.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

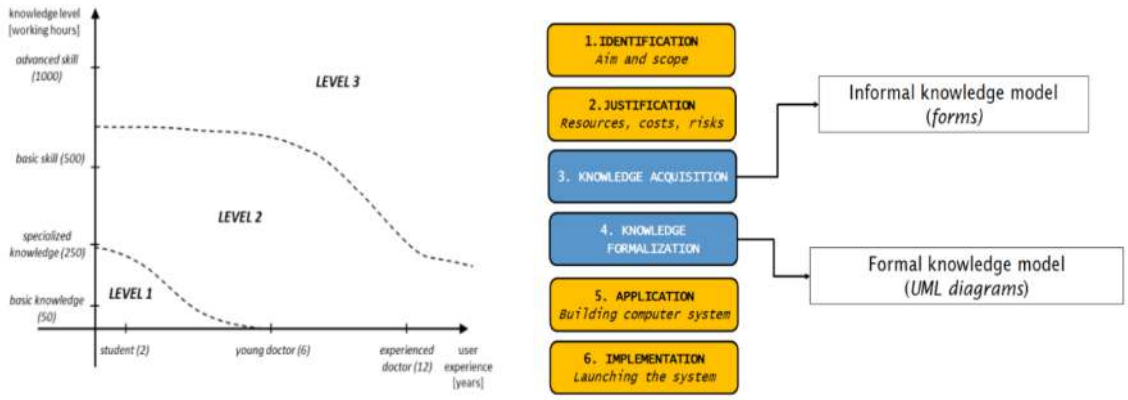


Figure 2.6.10. Levels of complexity and steps for conceiving a VR/AR/MR application

Each step that is necessary to be considered in case of designing of a VR/AR/MR application like shown in Figure 2.6.11 are explained based on some practical case studies that are revealed in the course.

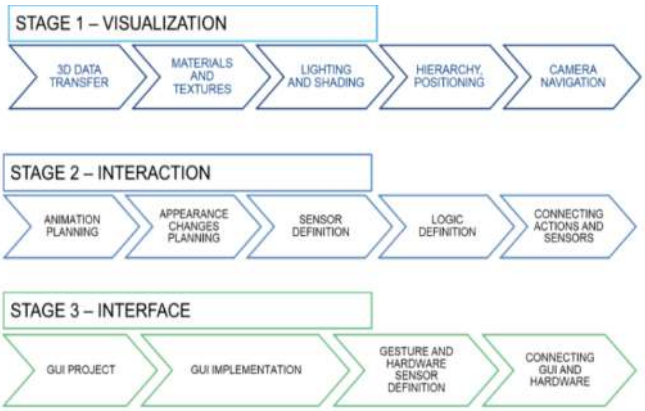


Figure 2.6.11. Stages necessary to be considered for realizing of a VR/AR/MR application

As case studies that are included as base example in the course, a wheelchair configurator as a tool for customizing wheelchair design, offering an immersive experience that helps consultants and customers visualize the product in various configurations is being presented. Also one example on how VR therapy was used to treat acrophobia (fear of heights) by gradually exposing patients to height in a controlled and safe virtual environment is also provided as good practice examples of using VR in relation to medical field, like shown in Figure 2.6.12.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

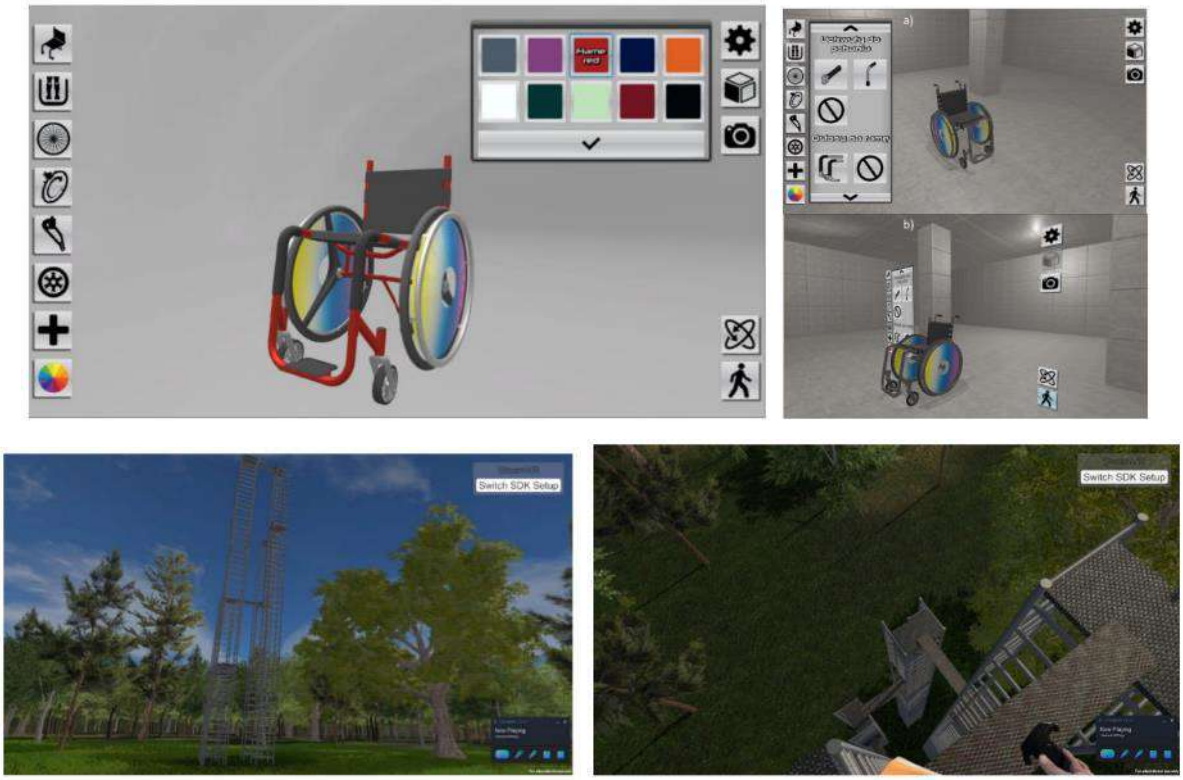


Figure 2.6.12. Good practice examples of using VR for medical applications

In conclusion of the course module there are emphasized the educational benefits of XR applications in biomedical engineering, mentioning their role in medical training and the design of medical devices and environments for several case studies and patients. Beside providing comprehensive understanding of the potential and implementation of XR technologies in the biomedical domain, students (users) are encouraged to further explore and develop applications for this exciting interdisciplinary field with high impact in the medical and educational sector.

2.6.4. Step 2 - AR programming laboratory module and applications

In addition to the VR / AR course module, the AR programming laboratory module of toolkit realized in the frame of O2 by the BIZZCOM partner has been integrated within in the EMERALD e-learning virtual laboratory platform as one can notice in Figure 2.6.13 this toolkit module being able to be accessed and downloaded from the next following link: https://drive.google.com/file/d/1kZhRc5pURCod-9oHYXQcC-tvrOzd6DbR/view

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.13. AR toolkit realized by BIZZCOM in the frame of O2

The EMERALD e-toolkit module on AR applications provides a comprehensive guide to creating AR models, starting from initial 3D object acquisition to final publication on the web, encompassing detailed steps in modeling, animating, and optimizing for AR applications (see Figure 2.6.14).

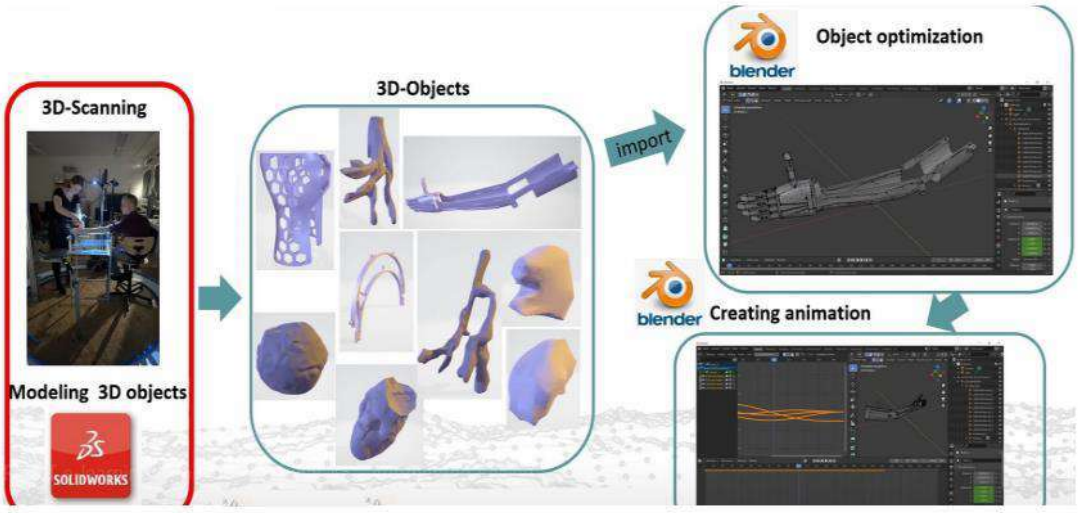


Figure 2.6.14. Main steps of creating of an AR application – overview of the process

In the creating process of an AR application, initially it is necessary to acquire of 3D models, which can be done either through 3D scanning or modeling realized by a CAD software (like SolidWorks) (figure 2.6.15).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

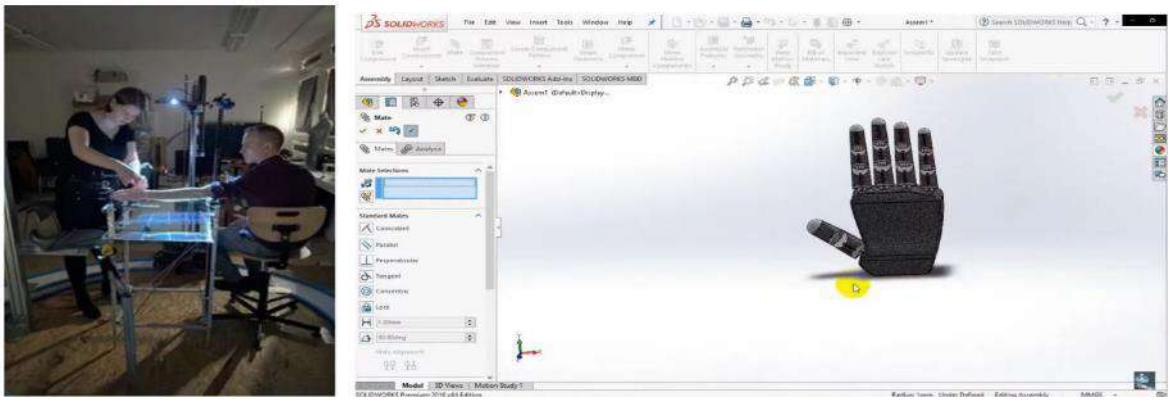


Figure 2.6.15. 3D scanning or 3D part realized by modeling in CAD software

After obtaining of these 3D models, the process continues with optimization and animation, steps that are crucial for the effective use of models in AR. For realizing of this, Blender software is a dedicated software program that can be used to create AR applications. Once the 3D model is ready, the first step consists in uploading the model in Blender for optimization. Specifying the materials or other specifications of the component, such as changing the color palette and understanding the different axes for manipulation are important steps in creating the AR application (see figure 2.6.16).

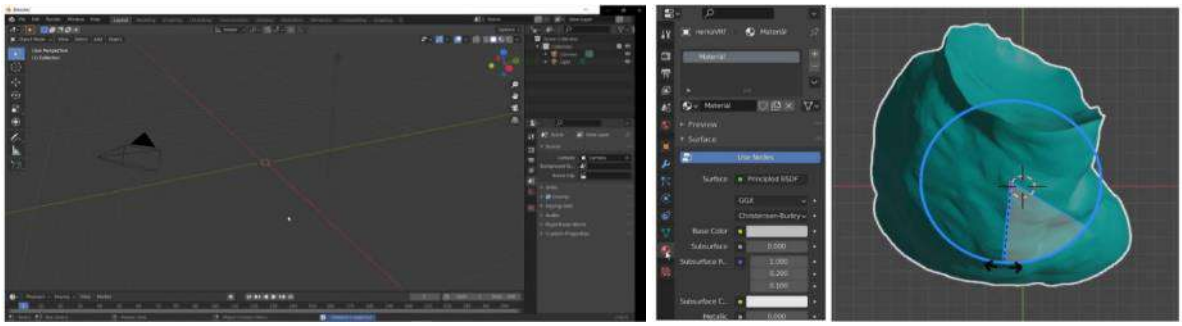


Figure 2.6.16. Importing the model, assigning materials / colors and manipulating of parts in Blender

Creating animations in Blender involves setting a timeline and manipulating the object through various axes. This is followed by fixing the model position at different frames (like at 100, 160, and 200) and making adjustments as needed. If a specific frame is not satisfactory, it can be deleted and replaced with a new one, allowing for detailed customization of the animation. Once the animations are created, they must be saved and exported in suitable formats for different platforms: Glb file for Android or USDZ format for iOS. The USDZ format can be converted using an online core value converter to ensure the cross-platform compatibility (see Figure 2.6.17).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

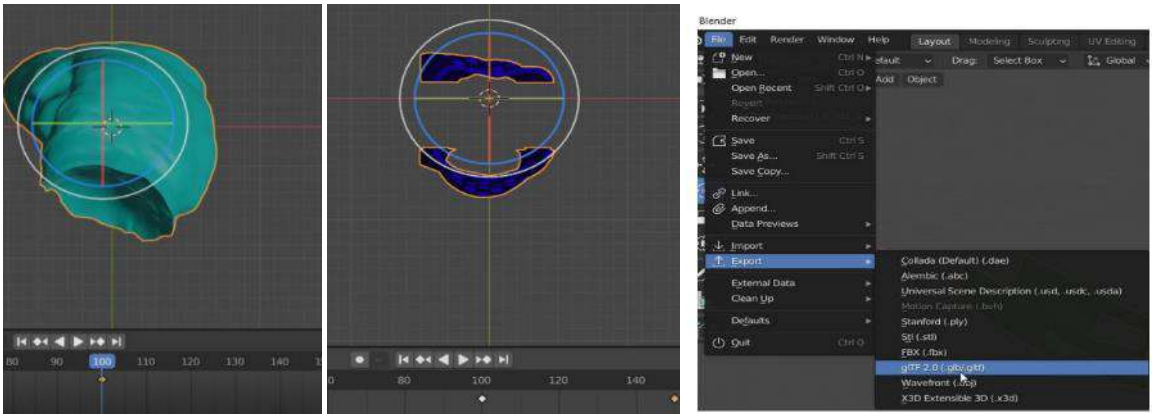


Figure 2.6.17. Steps for creating and saving of the realized animation in Blender

For displaying AR models, using a web interface like WEB APP – 3D Viewer, which creates previews of the 3D models using HTML code is necessary. Resources such as www.modelviewer.dev are recommended for documentation and examples, and an editor on the same site allows for testing and refining the code. Finally, the code needs to be published, which can be done either on a personal web server or through a code sandbox like www.codesandbox.io. This step is crucial for making the AR models accessible and interactive on web platforms, allowing users to click, rotate, and interact with the models on both Android and iOS devices (see Figure 2.6.18).

Following the guide that has been provided on the creating of AR models, starting from initial 3D models acquired either through 3D scanning or through 3D modeling using dedicated CAD software programs, like SolidWorks and continuing with final publication on the web, it is possible to create other similar applications like the one provided in the toolkit following basically the same steps that have been explained and following the details that have been suggested.

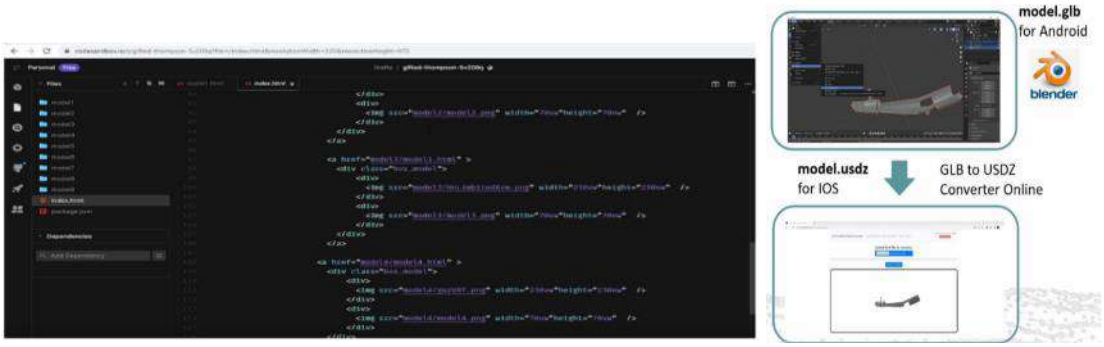


Figure 2.6.18. Generating the necessary code for AR application for Android and iOS

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.6.5. Step 3 - AR programming laboratory module and applications

In continuing, as base support for the toolkit module that has been created in the frame of O2, an additional presentation has been created by BIZZCOM in the frame of O3 in which there have been provided few supplementary details on AR related to several other examples that there have been realized and included in this presentation. The presentation can be accessed directly on the AR / VR laboratory of e-learning platform as one may notice in figure 2.6.19 or by visualizing and downloading it from the next following link:

https://docs.google.com/presentation/d/1pEFhJp4DR_23f3FU5D2eUne-L9bKERxX/edit?usp=sharing&ouid=106989522759795910234&rtpof=true&sd=true

Figure 2.6.19. AR presentation realized by BIZZCOM in the frame of O3.

Besides presenting the basics related to the conceiving of AR applications, the presentation goes much in deeper on providing details on the codes that are needed to be generated for the AR applications, but also on the web applications, providing important details on the steps that are needed to be followed for realizing it on 3D viewer application (including QR code generating) as one may notice in Figure 2.6.20.

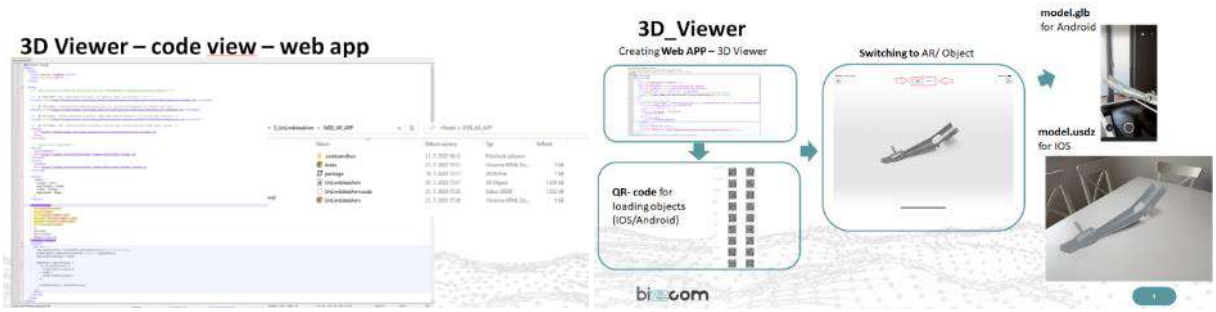


Figure 2.6.20. Creating the web application codes and the other necessary steps to generate QR codes

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

One video with emphasizing the viewing of an application created by BIZZCOM using one tablet, as well as other examples of AR applications which have been generated in the frame of O3 and have been included in the VR /AR laboratory of the e-learning virtual platform of EMERALD project (concerning medical applications) are also provided in the presentation, as one may notice in figure 2.6.21.

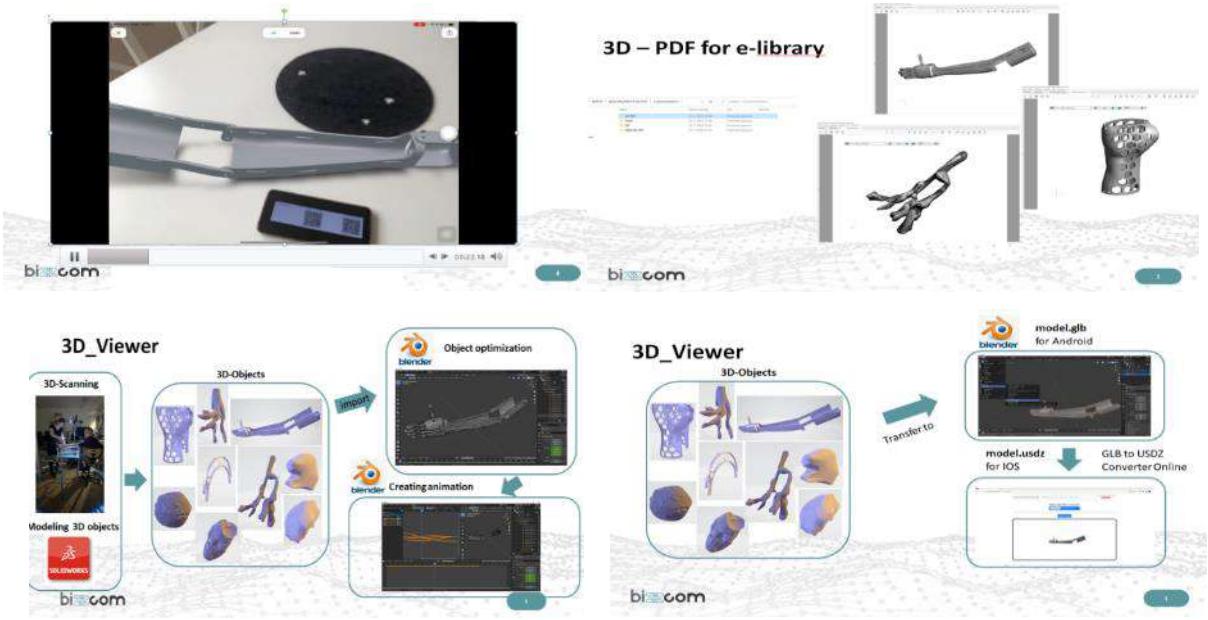


Figure 2.6.21. Video animation and applications in AR realized by BIZZCOM in the frame of O3

2.6.6. Step 4 – AR library of the models

In addition to the entire provided resources one library containing AR applications that have been developed for medical applications have been integrated into VR /AR laboratory of the e-learning platform as one may notice on Figure 2.6.22.

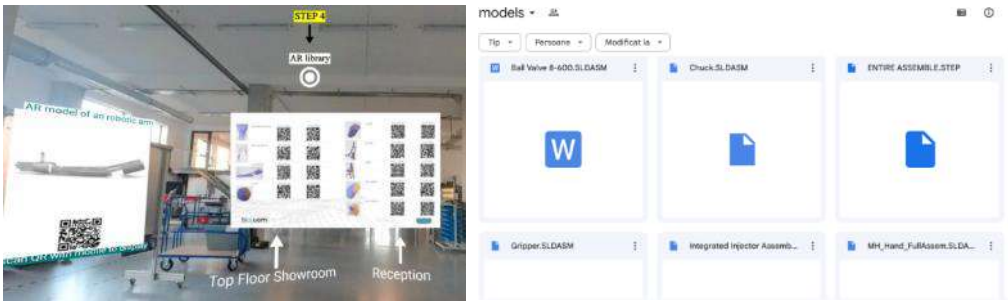


Figure 2.6.22. AR applications and AR library of the models realized by BIZZCOM

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The examples provided in Figure 2.6.23 can be accessed on the following link: https://drive.google.com/drive/folders/1C5EHSuNk1OvT2K1eAXS-lgxpRo83rSke as, can be seen as they are given in the VR /AR laboratory of the e-learning platform or can be scanned directly from this document using the provided QR codes to visualize them on a tablet.

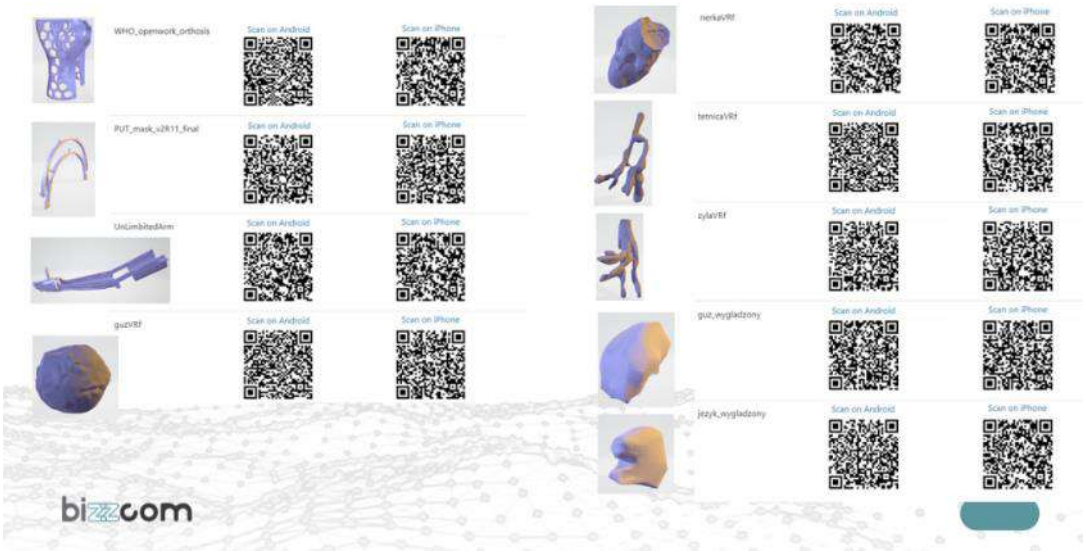


Figure 2.6.23. Examples of AR applications created following the instructions provided by BIZZCOM

2.6.7. Step 5 - Additional resources related to the creating of Virtual laboratories

In addition to the AR application toolkit and presentations, one seminar that provides one complete set with instructions has been created by BIZZCOM in the frame of O3 on how to process 360 photos to create VR images accompanied by teaching resources using Kuula software. This software program has been used by the majority of the EMERALD consortium partners to create a platform based on the 360 photos with the virtual laboratories that were used in the e-learning platform that has been created in the frame of O3 in the end. The seminar on how to use Kuula software on processing the 360 photos, adding teaching resources can be accessed directly on the VR /AR laboratory of the e-learning platform as one may notice in Figure 2.6.24, or can be accessed and downloaded from the next following link:

https://drive.google.com/file/d/1GNKuLBO4-c5yXGOzwMfSHjCT2ykJA5gN/view?usp=sharing

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.24. Training Seminar for working with Kuula in the frame of O3

As it has been mentioned seminar created by BIZZCOM provides a comprehensive guide on creating immersive and interactive virtual tours, offering step-by-step instructions on using the Kuula software various features to build a compelling virtual experience of the created tours.

The process begins with uploading photos to the platform, emphasizing the importance of organizing and naming the files descriptively for ease of identification. Users then navigate to the Create Tour section to start building their tour, adding photos either by dragging and dropping or selecting from their local drive, which then appear as a grid of thumbnails as one may notice in Figure 2.6.25. Once the photos are uploaded, users can begin building the tour by grouping images into a coherent sequence. The key to making the tour engaging and interactive lies in the creation of 'hotspot connections.' These hotspots are clickable icons that link various scenes in the tour, allowing seamless navigation for viewers.

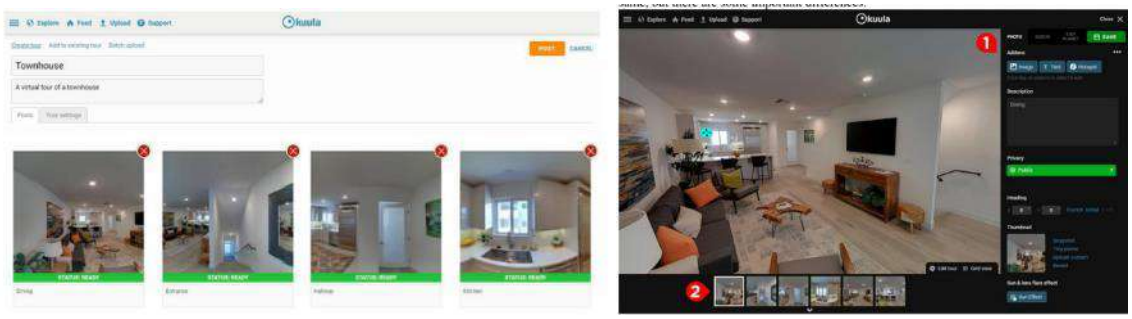


Figure 2.6.25. Uploading and editing the photos by adding hotspots in Kuula software

In continuing the users can provide additional information about specific elements in the scene, like links to external websites or multimedia content.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The customization of these hotspots is crucial, as it enhances the tour's interactivity by allowing changes in their appearance, behavior, and functionality. Further on to create animated transitions between images in a tour, in Kuula software are offered various options like crossfade, walk-in, radial fade, and others, each creating a unique visual effect. Users can choose the type of transition that best fits the style of their tour. Additionally Kuula software is offering access to Dashboard, which is instrumental in creating waypoints. Waypoints are significant points within the tour where users can add external content such as PDFs or videos. This feature adds depth to the virtual tour by incorporating additional informational resources.

The final step in the process is sharing the tour. Kuula provides various sharing options, including the ability to customize the tour with features like auto-rotate, auto-play, and custom branding before sharing. Users can share the tour through email, instant messaging, or by embedding it on a website (see figure 2.6.26).

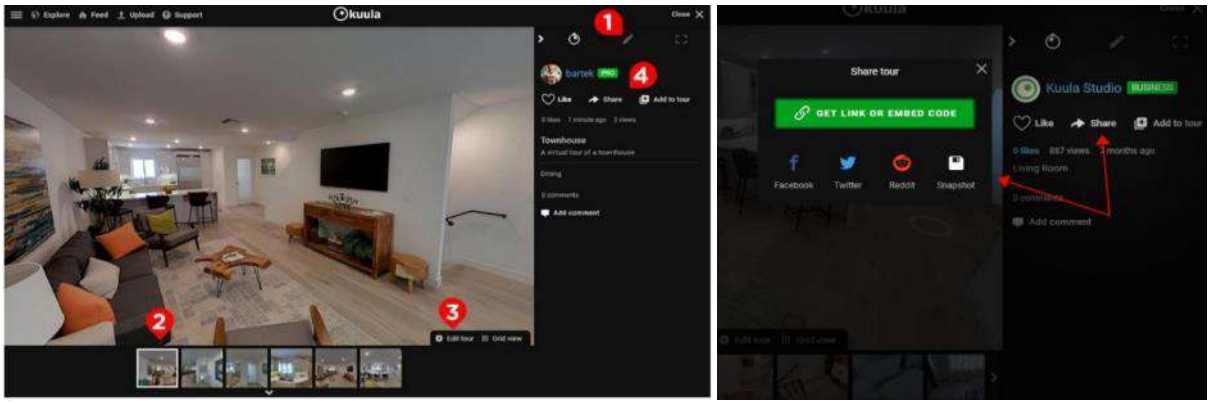


Figure 2.6.26. Customizing of the virtual tour and sharing the tour / embedding the tour on a website

2.6.8. Step 6 - Introduction to VR applications lecture

In continuing an additional VR application lecture providing basic introduction in VR, but focused on a different type of software called Matlab/SIMULINK has been created in the frame of O3 jointly by TUCN and BIZZCOM partners as can be seen in Figure 2.6.27, this educational source being able to be accessed and downloaded on the next following link of the EMERALD Google drive: https://drive.google.com/file/d/143UBeJhGWMnSZSh3rRmLd16KbspF8Dkr/view

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.27. Instructions for VR application realized by TUCN and BIZZCOM

The instructions provided about the basic introduction in VR is focused on the creating of a virtual reality simulation of a robotic arm, primarily using SolidWorks and MATLAB software programs. The project starts with designing the robotic arm in SolidWorks, focusing on the steps that are involved concerning the individually modeling of each component of the robot, excluding minor parts that don't significantly impact the robot's dynamics to simplify the process and reduce computational load. These components include the base, shoulder, arms, flange, and end effector (see figure 2.6.28). Special attention was given on maintaining the dimensions of the real robot and strategically placing individual coordinate systems at the centers of the couplings to streamline subsequent calculations.

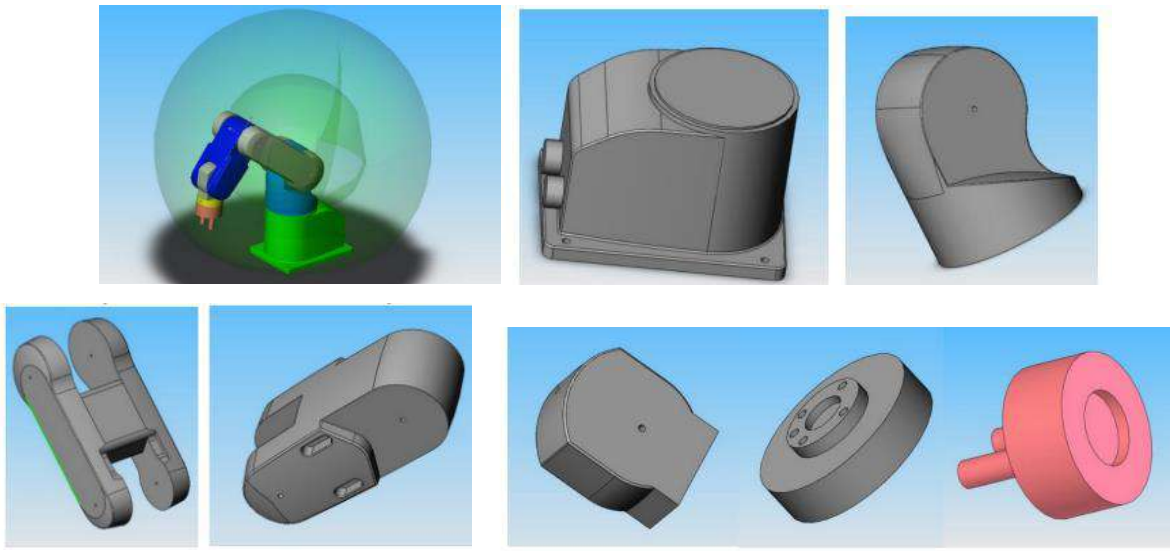


Figure 2.6.28. CAD modeling of the components of a robotic arm using SolidWorks program

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

After the individual components are modeled, they are assembled into a single file in SolidWorks. This assembly process is meticulous, with each part added sequentially, starting with the base. During assembly, rotation couplings crucial to the robot's operation are created based on the relationships between the elements' surfaces. The robot's coordinate system is centered at the base to simplify later calculations. The entire assembly is then optimized for virtual assembly, ensuring that all components are initially positioned vertically for ease of subsequent steps. The next crucial step involves exporting this CAD model into the Matlab/SIMULINK environment for dynamic simulation. All these steps are presented in figure 2.6.29.

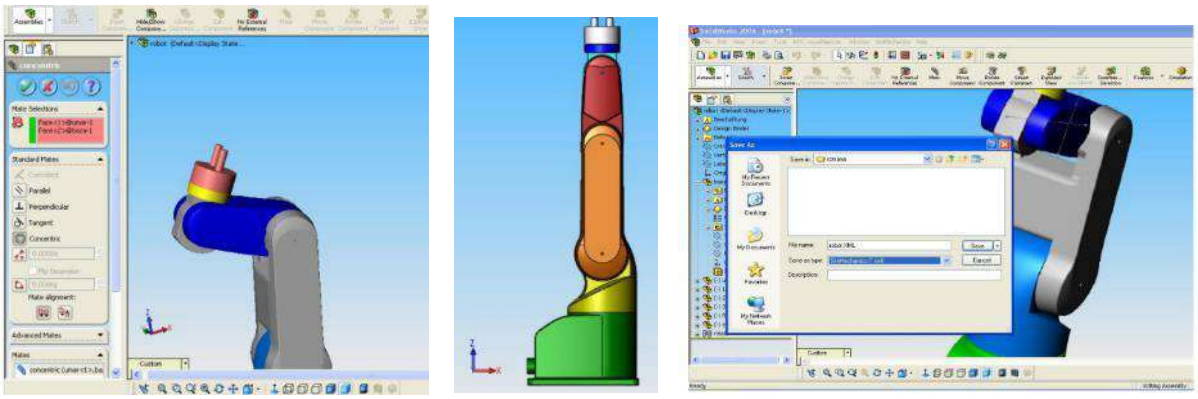


Figure 2.6.29. CAD model of the assembled robot in SolidWorks and exporting of the file to Matlab/Simulink

Saving of the file in Matlab/Simulink is done by saving the geometric model in a special ".xml" format. This step is essential for transferring the detailed design from SolidWorks into a format understandable by Matlab, which will be used for further simulation and analysis.

Once imported in Matlab, each element of the robot and its couplings are associated with specific objects in the Simulink workspace. This association is vital for accurately simulating the robot's structure and movements. Environmental factors affecting the simulation are also considered at this stage like shown in figure 2.6.30. The first step in Matlab involves checking and adjusting the gravitational force's value and orientation, an essential aspect of accurate simulation.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

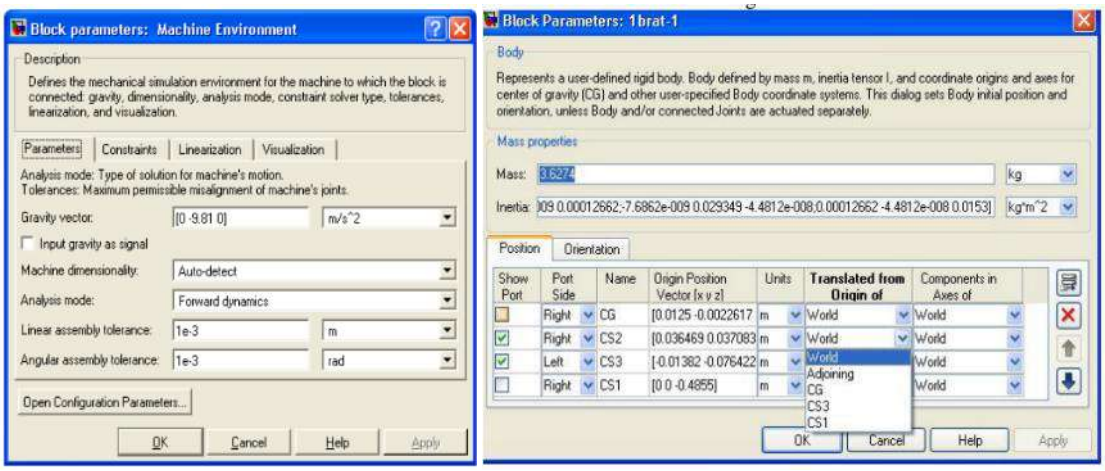


Figure 2.6.30. Adjusting of parameters , orientation and environmental seetings necessary for simulation

In continuing it is necessary to create the SimMechanics model using Matlab's Virtual Reality Toolbox module. This involves setting appropriate units of measurement and image quality to ensure clarity in the VR environment. The model is then exported from SolidWorks in ".wrl" format, after which it undergoes further modifications in a VR editor called VRealm Builder. Here, transformation points are created for each robot element, and these elements are carefully moved into their respective transformation points (see Figure 2.6.31).

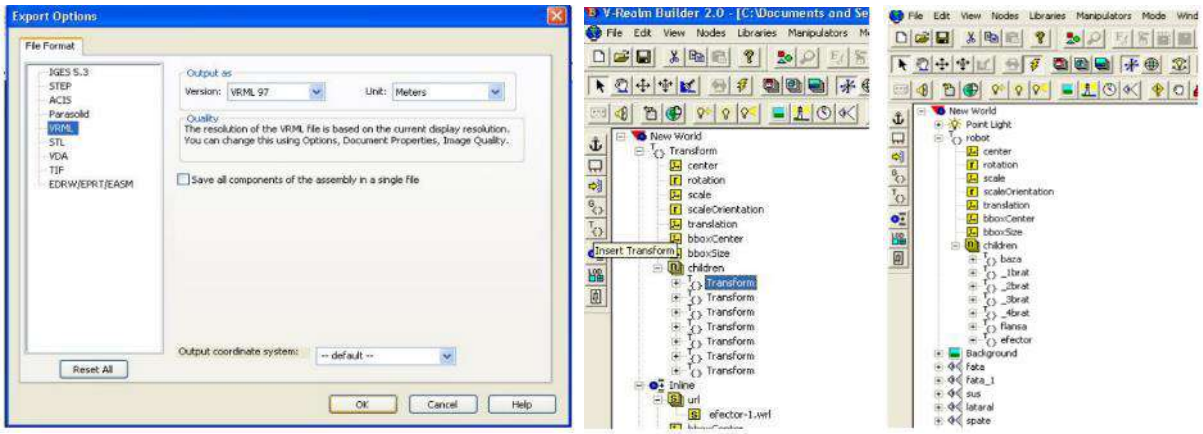


Figure 2.6.31. Exporting of file in „wrl" format and building of VR application using VRealm Builder editor

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The virtual reality aspect is further enhanced by introducing light sources, backgrounds, and viewpoints into the VR module. These features are adjusted to make the model appear as clear and realistic as possible. The light sources, for instance, can be oriented, have their color and intensity adjusted, and be shaped as cones or radials. Fog can also be introduced to fade details with increasing distance. Additionally, the VR environment allows for the selection of custom backgrounds and the placement of observation points based on the model's complexity and size.

In continuing it is possible to further on modify the dynamic model in the Simulink module of Matlab. This involves attaching each robotic element to a coordinate system that aligns with the central coordinate system, ensuring that the movement in the virtual reality matches the simulation's results. Body sensors are needed to be connected to these elements to provide output signals representing their positions and orientations (see Figure 2.6.32). These signals are then sent to the VR module, where a block called "VR Sink" establishes the connection between the VR and the Simulink model.

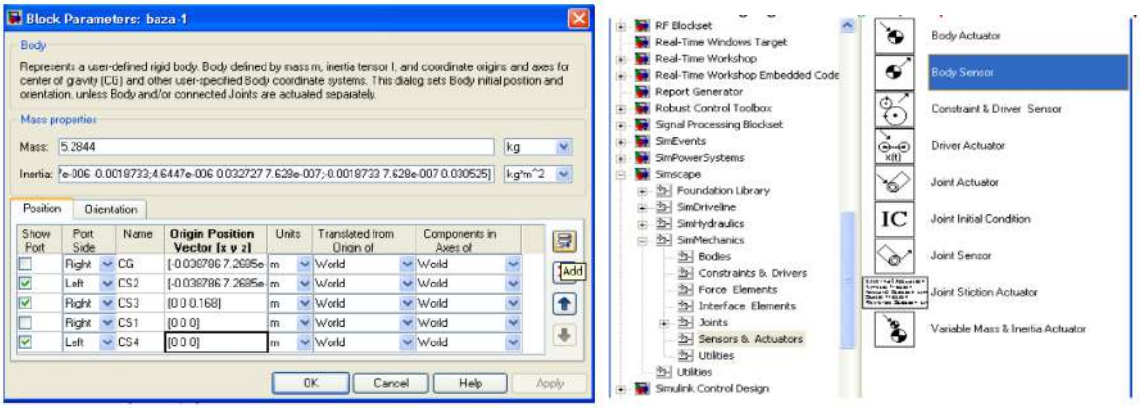


Figure 2.6.32. Inserting coordinate systems and body sensors in Simulink module of Matlab

The virtual reality application culminates in the detailed simulation of the robotic arm's movements and behaviors based on the Matlab simulation. A key component for creating a virtual reality (VR) application in MATLAB iis the "VR Sink" block, found in MATLAB's Simulink under the "Virtual Reality Toolbox." This block plays a crucial role in bridging the Simulink model and the virtual reality environment.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

To establish the connection between the two, the VR Sink block has to be first added to the system. This file contains the components of the virtual reality environment, including the robotic arm elements. The VR Sink block analyzes this file, and the translation and rotation of each robotic element are selected as inputs. These inputs are crucial as they determine how the robot's movements in the simulation are reflected in the virtual reality environment. The speed of visualization in the VR environment is adjusted based on the computer's performance capabilities and the robot's motion speed. The VR Sink block is designed to handle 14 inputs, which correspond to the movements of the robot's various components as shown in the first image of Figure t. In the next step, additional blocks are added to the subsystem that controls virtual reality. These blocks are designed to receive signals regarding the positions and rotations of the robot's components (see second image of Figure 2.6.33). These signals originate from another subsystem containing body sensor blocks. To ensure these rotation signals are understandable by the VR Sink block, they are transformed from rotation matrices into signals that indicate the axis of rotation and the angle of rotation. This transformation is vital for accurately representing the robot's motion in the virtual environment.

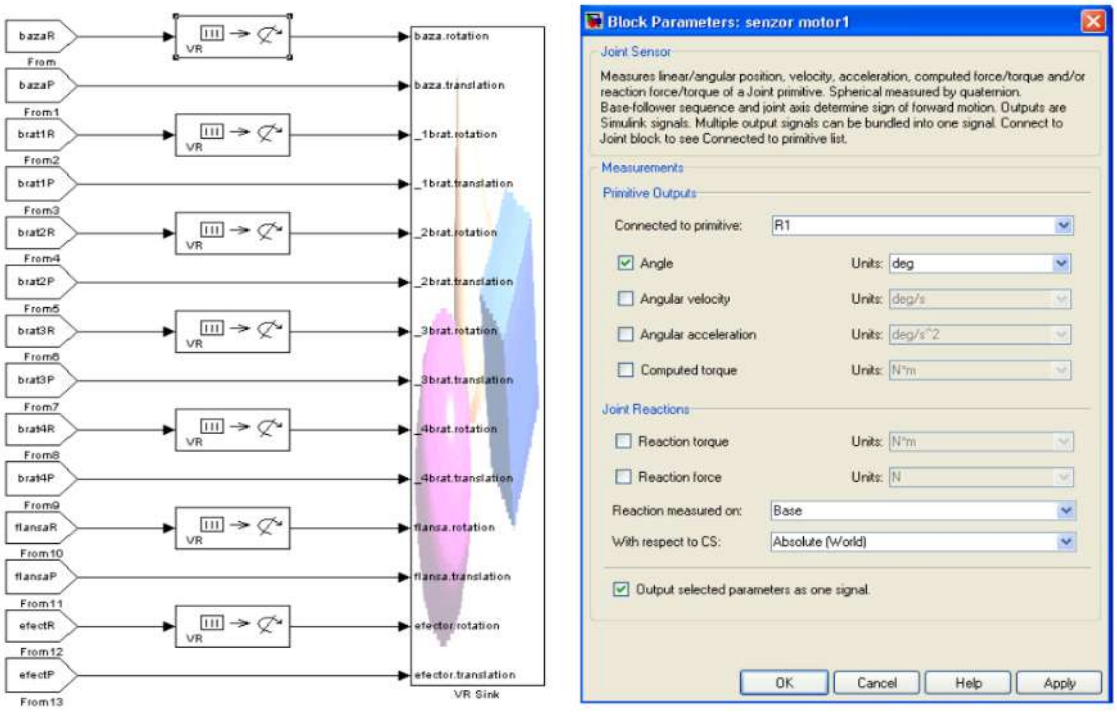


Figure 2.6.33. The VR Sink block designed to handle the movements of the robot's various components and additional blocks added to the subsystem that controls virtual reality

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The VR application also includes a detailed system for controlling the motion of the robot, specifically focusing on the torques in its structure. Actuators are added to each torque, and their parameters are controlled via a block called "Joint Actuator," found in the Simulink library under "Simscape\SimMechanics\Sensors & Actuators." This actuator block allows for the control of the force or torque applied, with options to input the position, velocity, and acceleration in various units of measure. The careful selection and input of these values are essential to ensure the accuracy of the simulation results. Moreover, sensors are added to each torque joint to read data like angular position, velocity, acceleration, and the torque around the rotation axis. These sensors can also measure reactive forces and moments as spatial vectors. The data collected from these sensors are then connected to signal sources and visualization systems for a comprehensive analysis. The entire Simulink model of the robotic arm, after connecting all subsystems, includes the detailed structure of each coupling with motors and sensors attached. This setup provides a thorough representation of the robot's motion control system, laying the groundwork for the virtual reality application that visualizes the robot's movements based on the simulation data (see Figure 2.6.34)

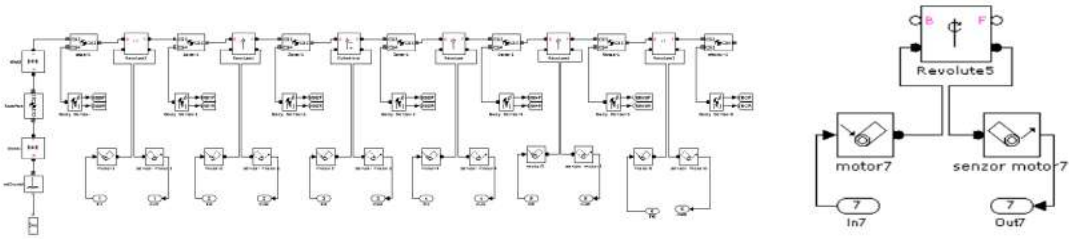
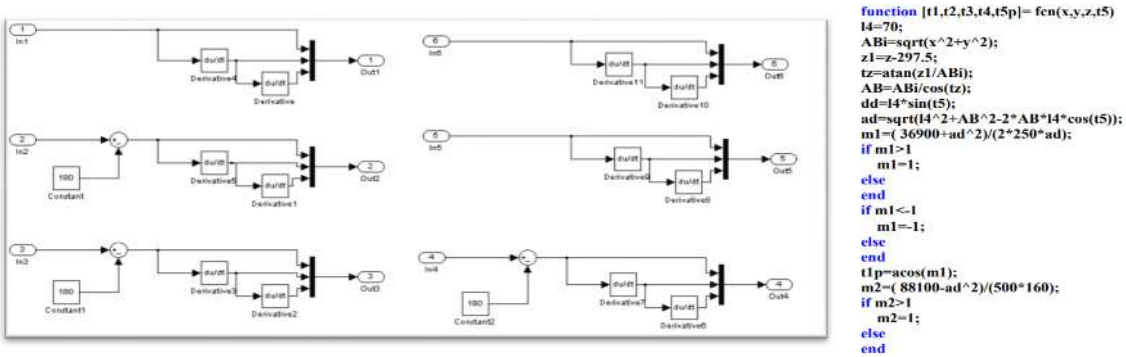


Figure 2.6.34. Structure of the robot with sensors, actuators and motors attached for the simulation

Next step for the Virtual Reality (VR) application consists in a critical step that involves creating a structure within MATLAB to generate control signals for a robotic arm. This process is tailored to the user's desired motion and involves several intricate steps to ensure precise control and simulation. In this context, a subsystem is necessary to be created in MATLAB's Simulink environment. This subsystem's primary function is to transform input signals, given as absolute angular positions, into more comprehensive signals that include three essential components: position, angular velocity, and angular acceleration. These signals are calibrated relative to the robot's initial position, which, in the context of the virtual reality environment provided by MATLAB, serves as a reference point (see Figure 2.6.35). All movements and rotations of the robot's elements and couplings are thus treated as deviations from this initial position.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).



```
function [t1,t2,t3,t4,t5p]= fcn(x,y,z,t5)
l4=70;
ABi=sqrt(x^2+y^2);
z1=z-297.5;
tz=atan(z1/ABi);
AB=ABi/cos(tz);
dd=l4*sin(t5);
ad=sqrt(l4^2+AB^2-2*AB*l4*cos(t5));
m1=( 36900+ad^2)/(2*250*ad);
if m1>1
   m1=1;
else
end
if m1<-1
   m1=-1;
else
end
t1p=acos(m1);
m2=( 88100-ad^2)/(500*160);
if m2>1
   m2=1;
else
end
```

Figure 2.6.35. Subsystems that controls control signals and programming for generating the signals

The transformation process of these signals is detailed and methodical. The position data is first differentiated to derive the angular velocity. Subsequently, this angular velocity is differentiated to obtain the angular acceleration. These steps ensure that the signals are broken down into their fundamental components, providing a more nuanced control over the robotic arm's movements. Once these components are obtained, they are combined into a single signal using a MATLAB function block called "Mux." This unified signal encapsulates all the necessary information about the robot's motion and is then fed directly into the actuator block, which controls the movement of the robotic arm (see Figure 2.6.36).

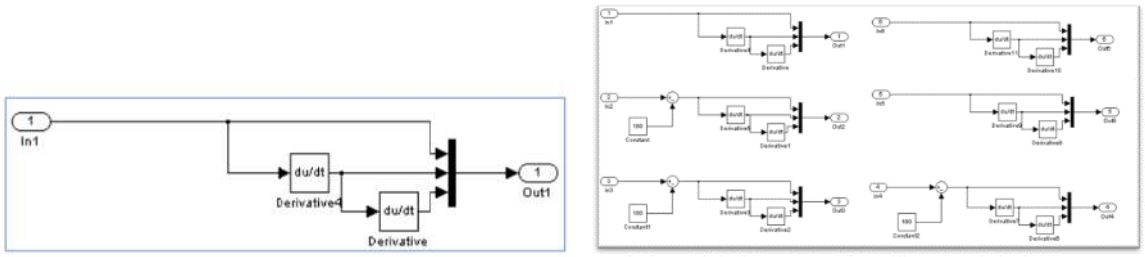


Figure 2.6.36. Signal Processing of a unit and creating of the whole subsystem that processes the control signals in MATLAB

Lastly, the position of the end-effector element is obtained and visualized. This is done by opening the block representing the end effector, making its center of gravity's access port visible, and then connecting a body sensor to this port. The body sensor is then connected to a Demux block, which is used in MATLAB to separate multiple signals transmitted on a single data. The signals, representing the X, Y, and Z coordinates of the end effector's center of gravity, are then sent through output ports for retrieval and visualization of the whole sub-system as shown in Figure 2.6.37.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

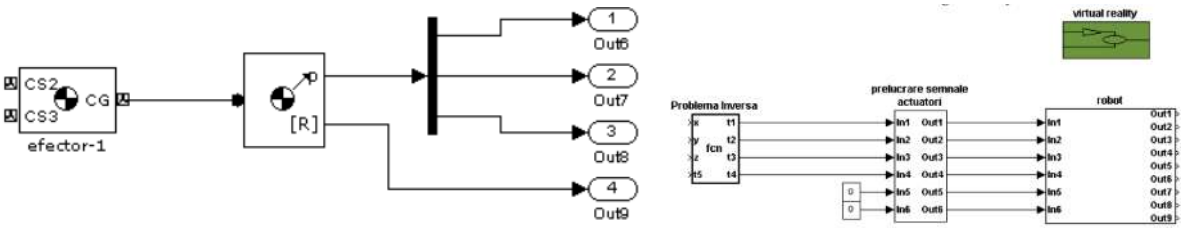


Figure 2.6.37. The effector with attached position, orientation sensor and connection module of the subsystem

In the virtual reality application described, a joystick was ingeniously used for position control of a robotic arm. The process of inserting the joystick begins with establishing of a connection between the joystick and MATLAB's Simulink environment using a "Joystick Input" block. This block reads the tilts and button states of the joystick, with the number of output signals varying based on the joystick type, including its tilt values and button states (see first image of Figure 2.6.37). Subsequent steps involve several blocks for processing these joystick signals. A "Selector" block is employed to choose specific values for processing, while a "Dead Zone" block eliminates minor tilt values, addressing issues like minor joystick calibration errors or the impact of gravity. Following this, a "Gain" block amplifies and adjusts the joystick signals, effectively converting the joystick's tilts into rate-of-change signals for the X, Y, and Z coordinates (see second image of Figure 2.6.38).

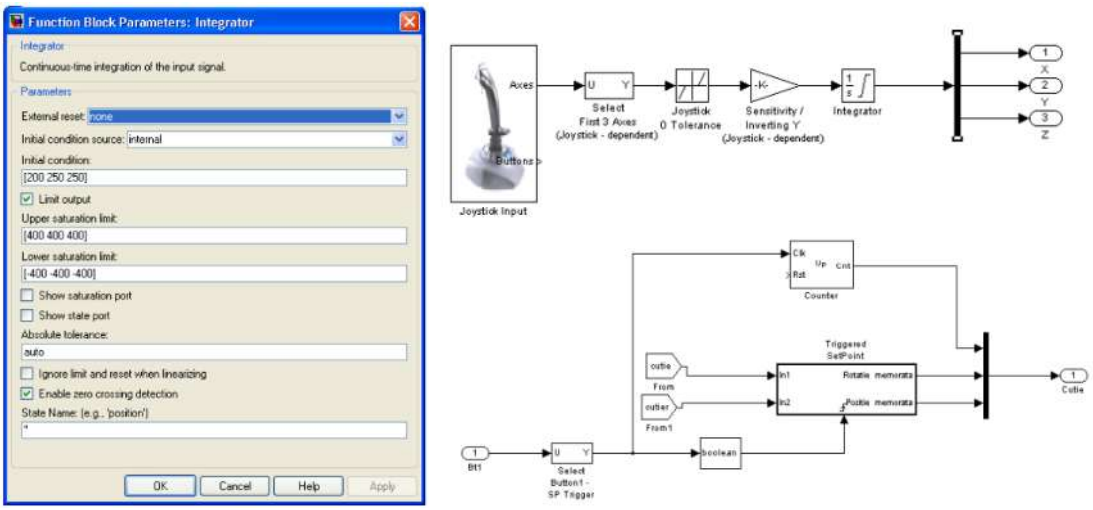


Figure 2.6.38. Functioning block of the joystick, joystick signal and converting of tilts into signals

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

For position control using predefined curves, subsystems are created for each curve type, like circles, ellipses, or squares (see Figure 2.6.39). These curves are generated using trigonometric functions, linear functions, and the "Signal Builder" block, with their coordinates varying over time. To add realism to the model, motor models have been introduced, replacing the ideizeald actuators. These models include elements like a "Controlled Voltage Source" block and a "DC Voltage Source" for power. The introduction of these motor models necessitates the use of a PID (Proportional-Integral-Derivative) control algorithm to correct errors between the input control signals and the motor's actual velocity (see Figure 2.6.40).

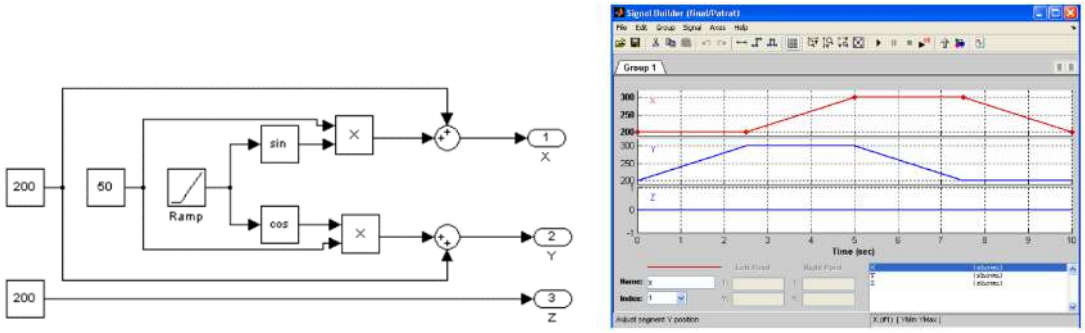


Figure 2.6.39. Subsystem for generating one circle or one square

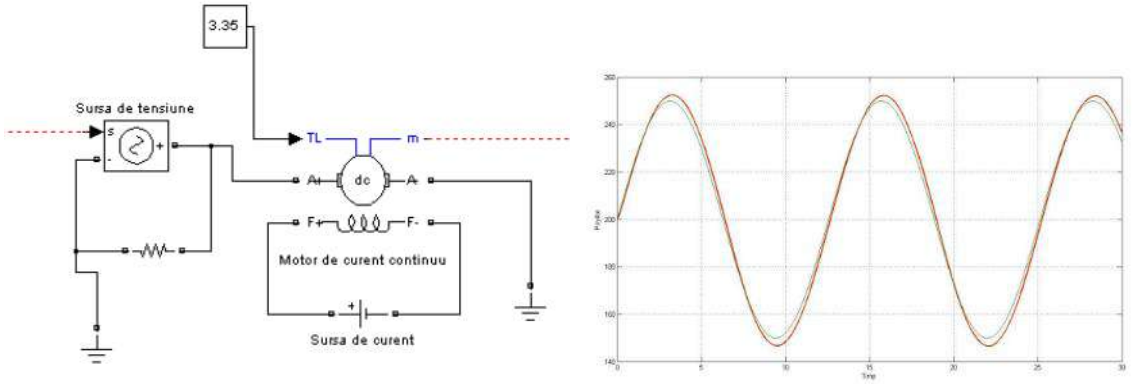


Figure 2.6.40. Motor connected to the power sources and errors between the input control signals and the motor's actual velocity

Finally, in the virtual reality application, a PID (Proportional-Integral-Derivative) controller was implemented to enhance the precision and effectiveness of motor control (see figure 2.6.41).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

This advanced control algorithm is crucial for correcting discrepancies between the desired and actual velocities of the robotic arm's actuators. The PID controller operates by calculating the difference between reference values (desired outcomes) and actual velocities. This difference, or error signal, is then fed into the PID block, which uses three key coefficients: Kp (proportional), Ki (integral), and Kd (derivative), to adjust the motor's response. These coefficients play distinct roles: Kp influences the system's reaction to the current error, Ki deals with past errors, and Kd predicts future errors. Adjusting these parameters shapes how the motor responds to discrepancies in velocity, allowing for smoother and more accurate control.

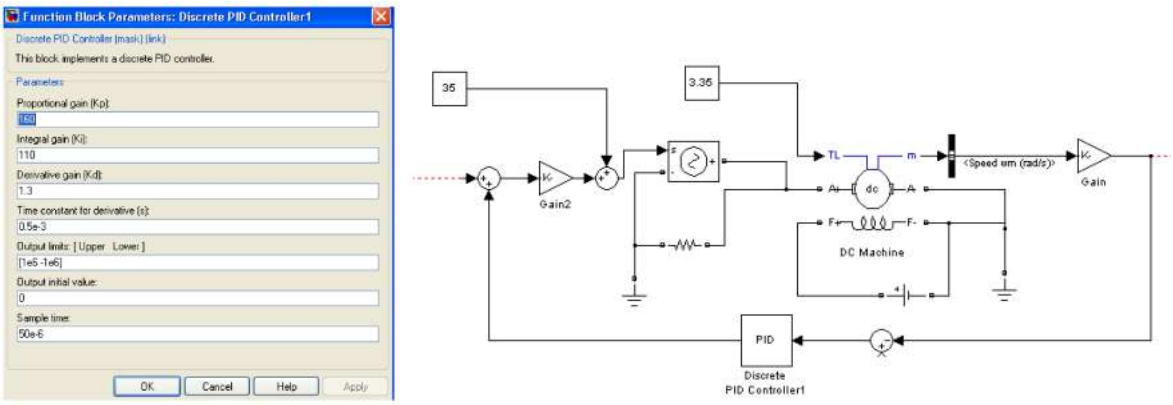


Figure 2.6.41. PID control block and diagram of a motor controlled by PID

Once the PID controller is configured and connected to the voltage source controlling the motor, it significantly reduces the error between the input points and the end effector's position. This reduction is noticed in the minimized distance error, which is crucial for precise robotic movements. In addition to motion control, the application also uses a joystick for interactive force feedback (see Figure 2.6.42). This joystick can exert force along one or both the X and Y axes, enhancing the user's sensory experience. The system can modulate the force exerted by the joystick, offering a range of force values and allowing for realistic simulation and control of the robotic arm.

Figure 2.6.42. Force feedback generation diagram and generating position signals by the Joystick

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.6.9. Step 7 - Application realized for visualizing models in VR using GLTF mode

In addition to the provided lecture, one presentation concerning a particular application of VR has been prepared by TUCN in the frame of O3,with the main aim of showing how GLTF mode can be used for realizing such applications, this presentation being integrated in the VR /AR laboratory of the e-learning platform (figure 2.6.43), being also possible to be accessed and downloaded on the following link: https://drive.google.com/file/d/1kQ0Hhtpw0sm5bs31wxAF_9ayIGZxfwzJ/view

Figure 2.6.43. Presentation on how to create application for visualizing models in VR using GLTF mode

The realized presentation focuses on the process and technologies involved in creating 3D assets and their applications in virtual reality (VR). Sketchfab is mentioned as a source for 3D assets and references VR Home on Oculus, indicating the presentation's relevance to VR environments (see Figure 2.6.44).

Figure 2.6.44. Sketchfab source for creating 3D assets to create applications to be visualized in VR

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

In order to be able to realize applications in VR based on 3D modeling one important aspect is related to the file formats that are suitable for this type of applications (see Figure 2.6.45). One of the most recommended files are GLB type (a binary file format representing 3D models) which can be optimally used for the creating process of VR applications through the glTF (GL Transmission Format) and STL (Stereolithography) formats.

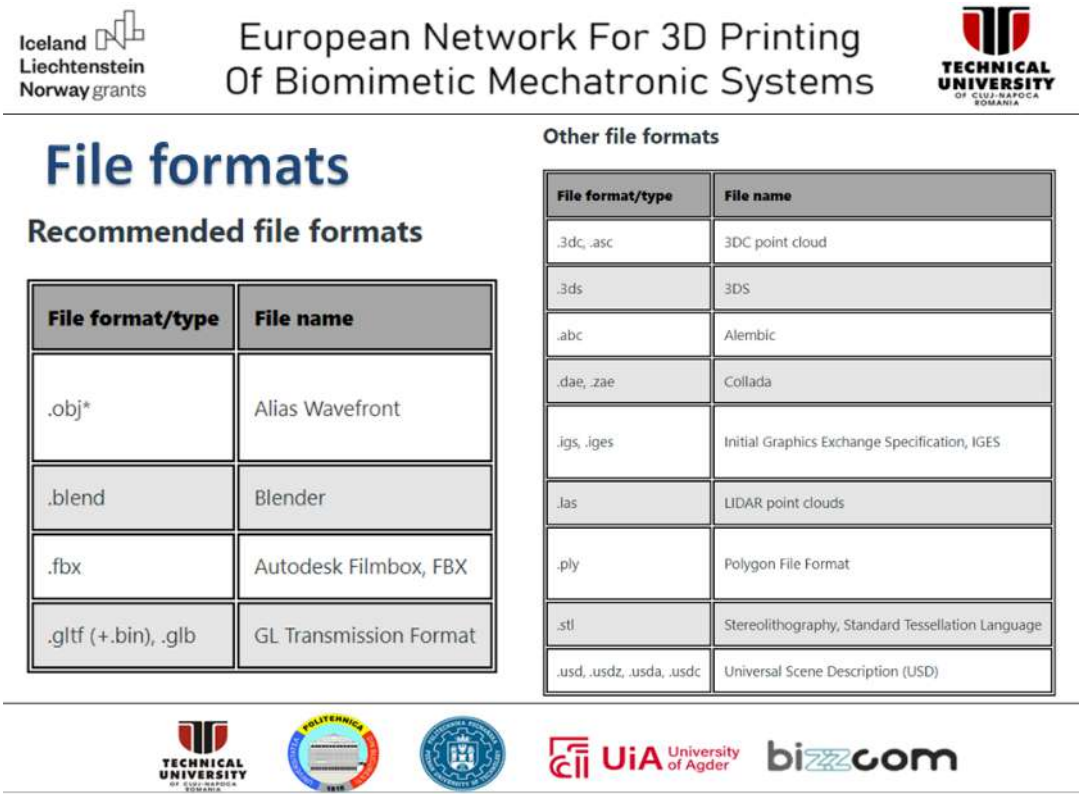


Figure 2.6.45. Recommended file formats for creating applications in VR

"glTF" format is highlighted as a royalty-free specification for efficiently transmitting and loading 3D scenes and models, designed to minimize the size of 3D assets and the processing required to unpack and use them in "GLB" format. (see Figure 2.6.46). This type of format is also well known for its role in streamlining authoring workflows and enabling interoperable use of 3D content across the industry. In this content the use of software tools like Paint 3D and SOLIDWORKS for exporting or importing STL files are also a reliable option in the process of creating GLB files from STL files for generating easily different types of models that can be visualized easily in VR.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.46. GLB packer and facilities of SolidWorks and Paint 3D software for creating applications in VR

Few examples of VR applications realized in this mode as it has been described above can be visualized as they have been created by TUCN in Figure 2.6.47. Full library of models created in VR can be visualized, accessed and downloaded from the VR /AR laboratory of the e-learning platform as shown on Figure 2.6.47 or by accessing the following link: https://sketchfab.com/Alin.PLESA

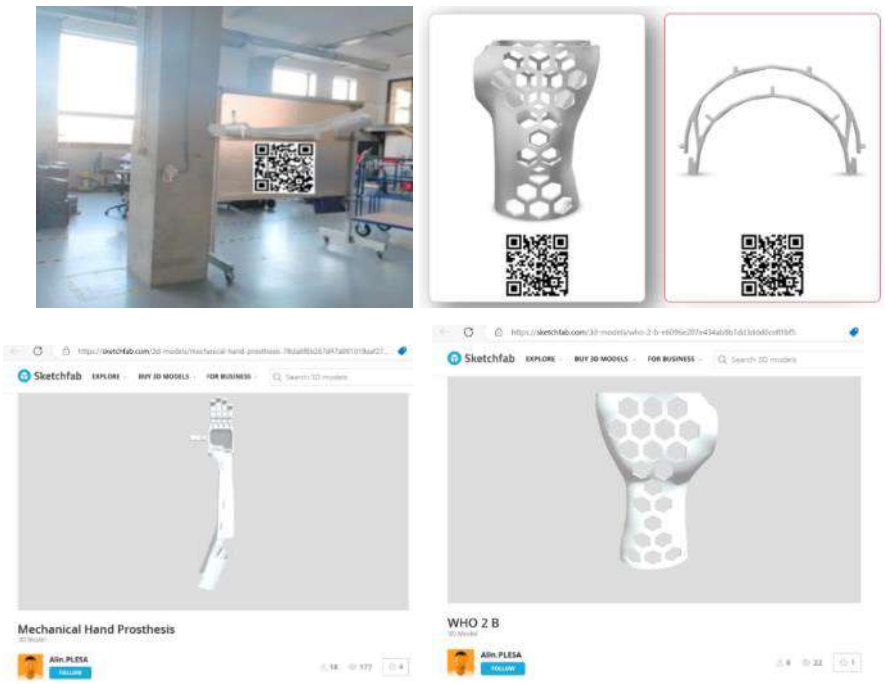


Figure 2.6.47. VR library integrated in VR / AR laboratory of e-learning platform

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

2.6.10. Step 8 – Tutorial and application realized for virtual reality realized using Godot

In addition to realized applications one comprehensive tutorial for creating a virtual reality (VR) application using the Godot game engine has been also realized by TUCN, as one may notice in Figure 2.6.48. Tutorial can be accessed directly through the e-learning platform or by accessing the following link: https://drive.google.com/file/d/1s5TkwImTqFEllJrbBY_07x4NayjgdnIc/view

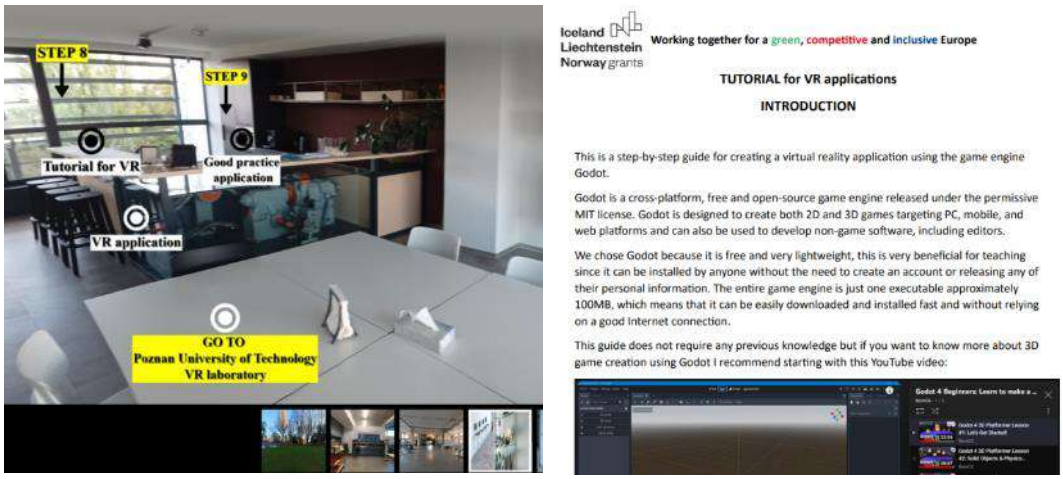


Figure 2.6.48. Tutorial and application for virtual reality realized using Godot

Godot application shown in Figure 2.6.49 is highlighted for its accessibility, being free, lightweight, and not requiring personal information for use. The tutorial targets beginners, suggesting a starting point with a YouTube video for those interested in 3D game creation using Godot.

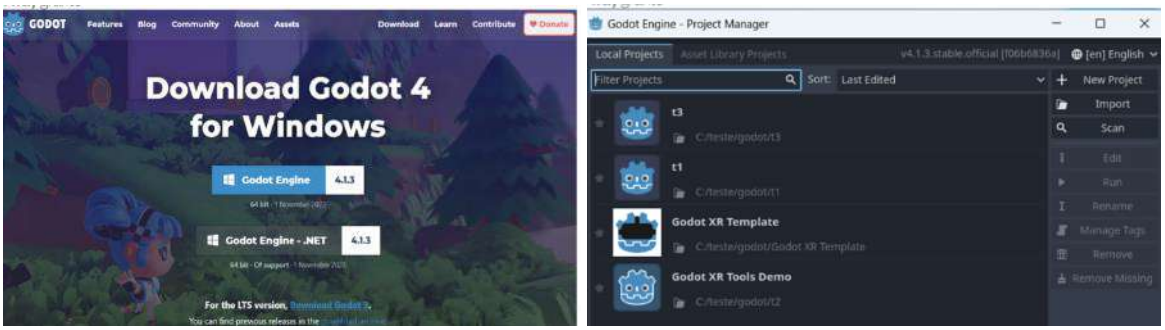


Figure 2.6.49. Creating a VR application using Godot

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The project's aim is to create a VR environment for viewing PowerPoint presentations. It begins with guiding the reader through installing Godot, detailing the steps to download and start the game engine. The tutorial then walks through the process of setting up a new VR project in Godot, including creating a new project, adjusting project settings, and enabling certain features like OpenXR and shaders. Following the setup, the guide dives into the creation of the 3D VR environment, explaining how to add essential assets like 'XROrigin3D' for the VR system origin point, 'XRCamera3D' for 3D view perspective linked to head tracking, and 'XRController3D' for hand tracking. It also covers scripting in Godot, with instructions on replacing the script with the provided code or from a specified address (see Figure 2.6.50).

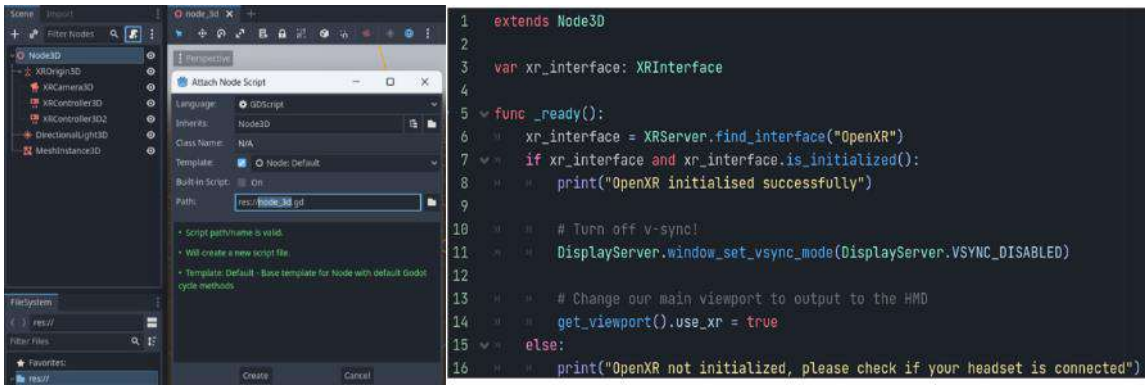


Figure 2.6.50. Steps of creating VR application using Godot (including for editing scripts)

Adding lighting, a floor, and the PowerPoint presentation itself is covered next. The tutorial explains how to use 'DirectionalLight3D' for lighting, 'MeshInstance3D' for the floor, and 'Sprite3D' for displaying PowerPoint slides as textures. It also guides on animating the presentation slides using 'AnimationPlayer', including scripting to simulate a PowerPoint presentation's behavior (see Figure 2.6.51).

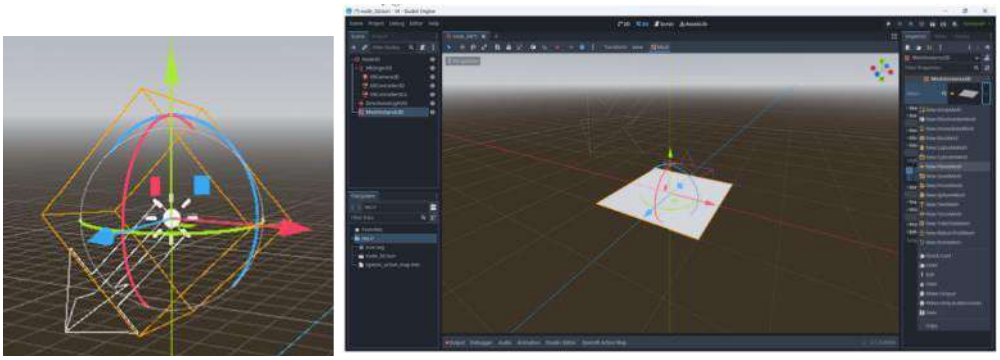


Figure 2.6.51. Additional steps in Godot as 'DirectionalLight3D' for lighting

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Finally, the tutorial outlines the process of exporting the application as an executable, ensuring the export template is correct, and using the Export option in Godot (see Figure 2.6.52).

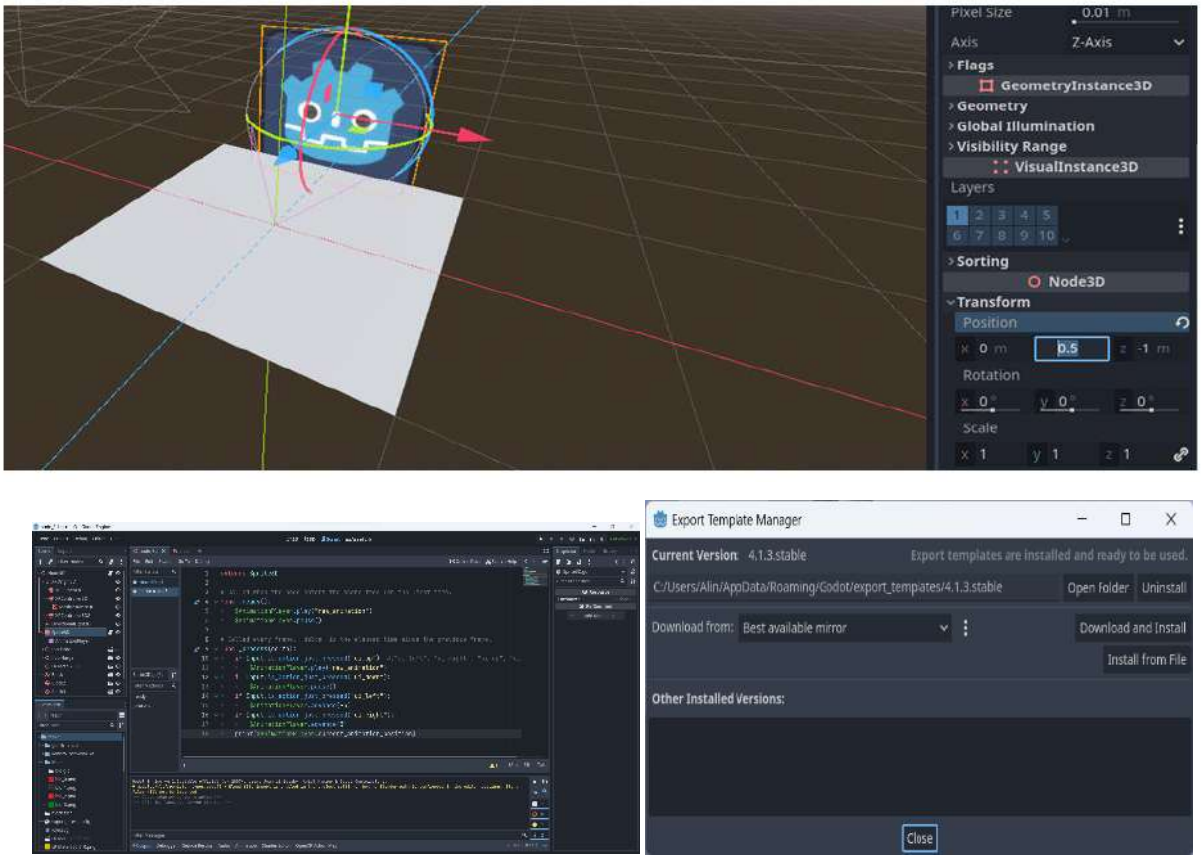


Figure 2.6.52. Exporting the VR application and script

Final application generated using this tutorial has been included in the e-learning VR / AR platform, being possible to be accessed on the next following link: https://drive.google.com/drive/folders/1LT-ix9_5_i6bVpRYGVS41RP-8Lq8_3Rs

2.6.11. Step 9 – Good practice examples done by students in VR

Good practice examples of applications realized by the students (applications on which BIZZCOM company brought contribution in providing feedbacks and assistance to them) have been integrated in the VR /AR laboratory room of the e-learning platform as one may notice in Figure 2.6.53. Library of models and presentations realized by the students can be accessed also on the next following link: https://drive.google.com/drive/folders/1s_qE85H6cpy3jZXwGlYABtg_wEbCf6ov

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

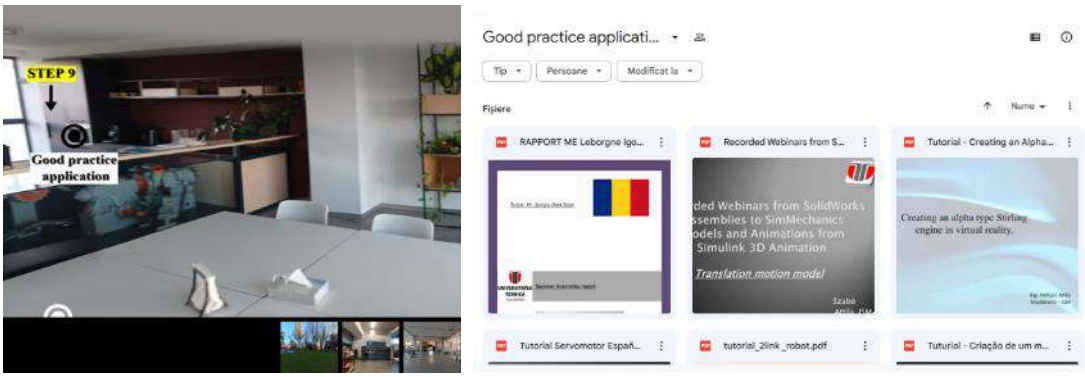


Figure 2.6.53. Good practice application realized by the TUCN / ERASMUS students

In Figure 2.6.54 are exemplified a selection of representative images few of the most relevant applications done by the students using Matlab Simulink, confirming in this way the usefulness of information provided for building VR applications by the students using the educational resources integrated into the e-learning platform.

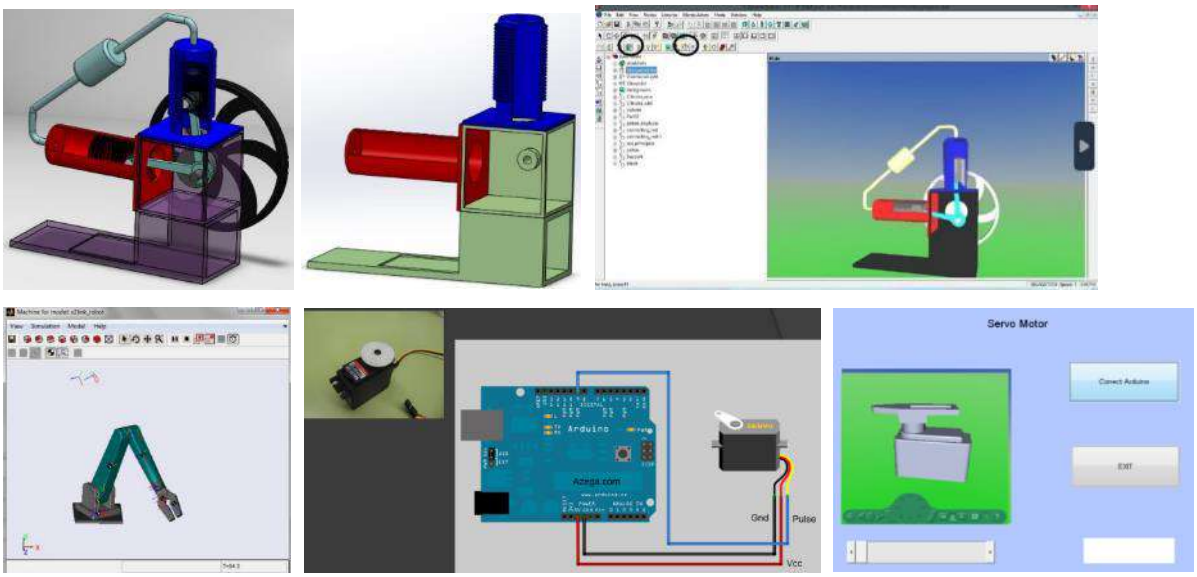


Figure 2.6.54. Examples of VR applications realized by students in MATLAB Simulink

2.6.12. Step 10 – Teleporting to PUT VR laboratory room

In order to explore more about VR resources and applications, the users are in the final step of visiting laboratory at BIZZCOM to teleport themselves to the VR laboratory room of Bizzcom as one may notice in Figure 2.6.55.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

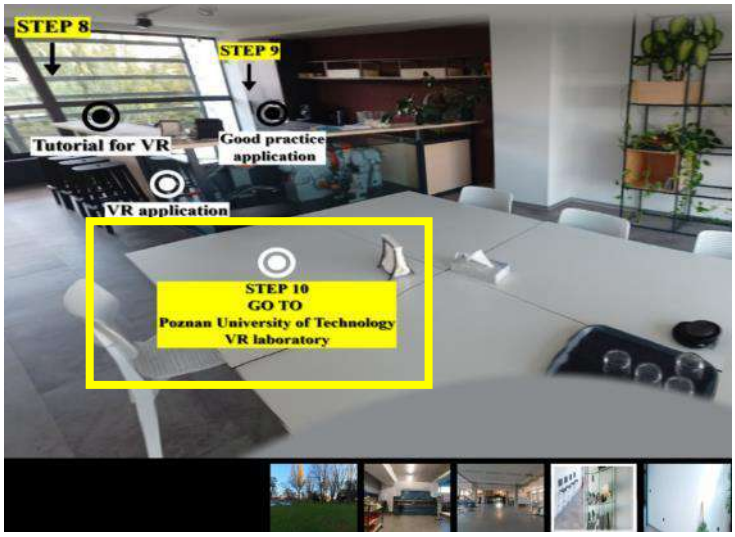


Figure 2.6.55. Teleporting to PUT 3D scanning laboratory

2.6.13. Accessing of XR virtual laboratory room *and e-learning resources at PUT*

XR virtual laboratory room is the same room as 3D scanning virtual laboratory, so it can be accessed using EMERALD project website (refer to Figure 2.6.56), or directly by a following link:

https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-2.95,.1&ss=37

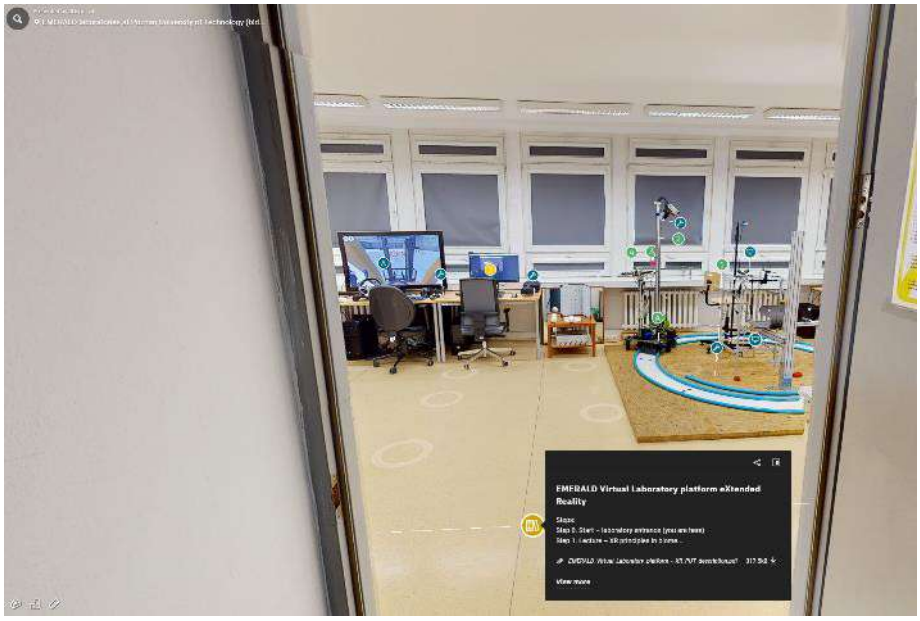


Figure 2.6.56. Main entrance of the XR laboratory of PUT

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The 3D scanning virtual laboratory room at PUT that can be seen in Figure 2.6.51, has been realized using Matterport Pro camera, the captured images undergoing in further processing using Matterport software, allowing the integration of educational materials related to Virtual, Augmented and Mixed Reality that have been developed within the EMERALD project related to this topic in particular. The VR/AR/MR applications and tutorials available here are different than the ones available at Bizzcom – they are directly related to EMERALD case studies. The course is also shorter, but more practical.

2.6.14. XR at PUT VL - teaching resources overview

In this Virtual Laboratory, it is possible to explore possibilities of building XR applications for development and use of customized biomechatronic devices (case studies of the EMERALD project). The users can get familiarized with XR techniques – virtual, augmented and mixed reality, as well as various equipment available in the laboratory. Then, for each of 3 XR techniques, a separate instruction tutorial with materials to create applications in Unity engine is made available.

The course of XR available in the laboratory has been divided into 4 main steps (Figure 2.6.57), with some additional information available besides these steps.

Steps are the following Step 0. Start – laboratory entrance, Step 1. Lecture – XR principles in biomechatronic devices, Step 2. Augmented Reality application tutorial, Step 3. Mixed Reality application tutorial, Step 4. Virtual Reality application tutorial

Figure 2.6.57. XR at PUT – steps of the course

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Step 0, accessible right after entering the laboratory (yellow marker), contains overview of all the other steps and a short document with information for the Virtual Laboratory user. Direct link to this starting point is here:

https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-2.47%2C-.07&ss=37&tag=AQ4CglfwQTE&pin-pos=-20.49%2C.96%2C2.25

2.6.15. Step 1 - PUT – XR principles in biomechatronic devices

The course module that provide the describing of main methods of XR in development of biomechatronic devices is provided and can be accessed like shown in Figure 2.6.57 being possible to be accessed directly on the VL of the e-learning platform, using the green marker no. 1 (refer to Fig. 2.6.58 and link below) and the first link contained there.

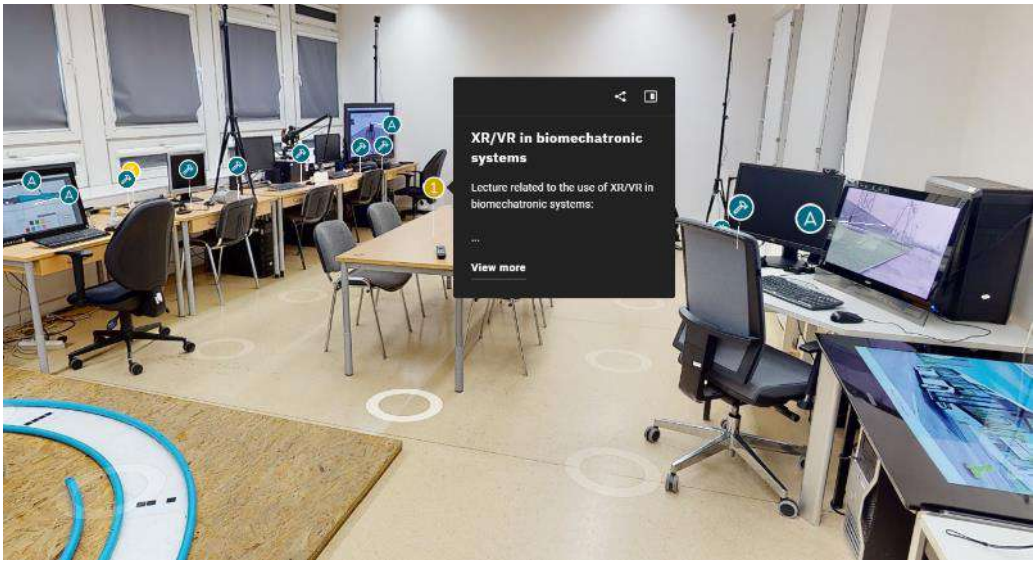


Figure 2.6.58. XR in biomechatronic systems lecture - access

The presentation contains teaching materials prepared by Filip Górski, Professor at PUT Faculty of Mechanical Engineering. It provides a comprehensive overview of Extended Reality (XR) technologies and their applications in biomechatronics. XR encompasses a group of interactive 3D technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These technologies can be used separately or integrated for modern applications (See Figure 2.6.59).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

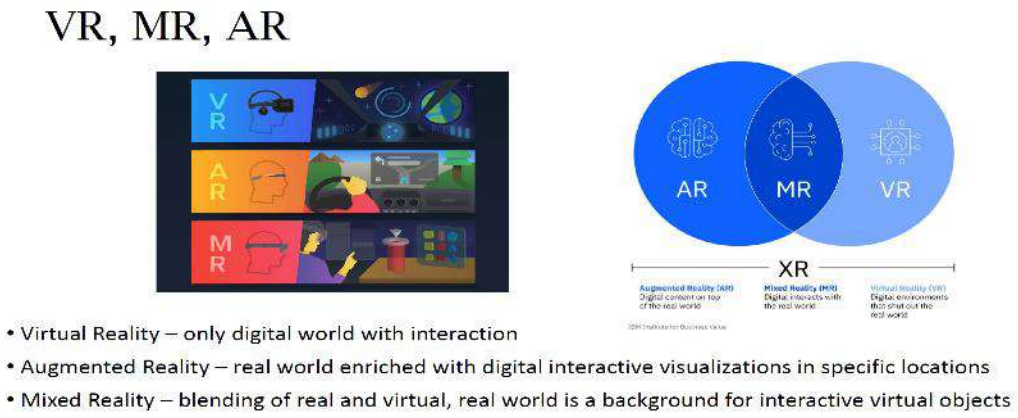


Figure 2.6.59. XR technologies, as presented in the lecture

Virtual Reality creates an entirely digital world with interactive elements. It's a computer-generated three-dimensional responsive environment where the user becomes a part of the simulation and influences its behavior, thus engaging the human senses. The concept of VR, known since the early 60s, was first labeled "Virtual Reality" in 1989 by Jaron Lanier. A key aspect of VR is its "responsive" virtual world, which reacts to user behavior (see Figure 2.6.60).

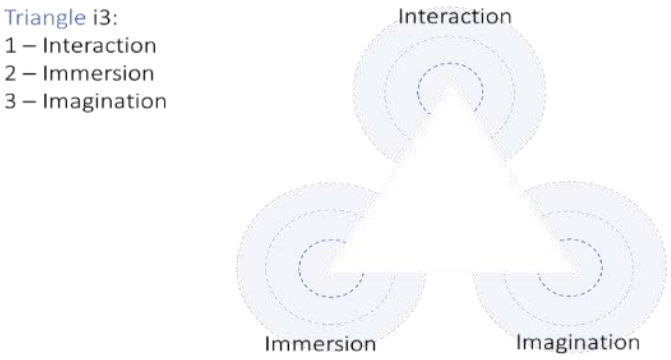


Figure 2.6.60. VR main features, based on Burdea and Coiffet triangle (2003)

Augmented Reality, first defined by Ronald Azuma in 1997, blends the real world with digital interactive visualizations. Unlike VR, AR does not immerse the user in a virtual environment; instead, it augments the real world with virtual elements that have fixed spatial contexts. Mixed Reality (MR) combines elements of both VR and AR, allowing for the free placement of virtual objects (holograms) in the real environment. MR is characterized by real-time terrain mapping and user position tracking, demanding high hardware capabilities (see Figure 2.6.61).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

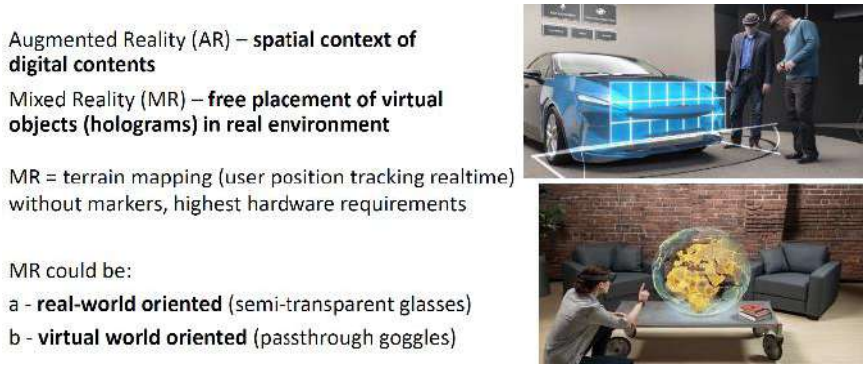


Figure 2.6.61. AR/MR technologies and their differences, as presented in the lecture

The document also covers common terms related to XR technologies, such as digital 3D images, real-world visibility, immersion, user location tracking, markers, and environment mapping. It references Milgram's 1994 continuum of XR technologies, illustrating the spectrum these technologies cover (see Figure 2.6.62).

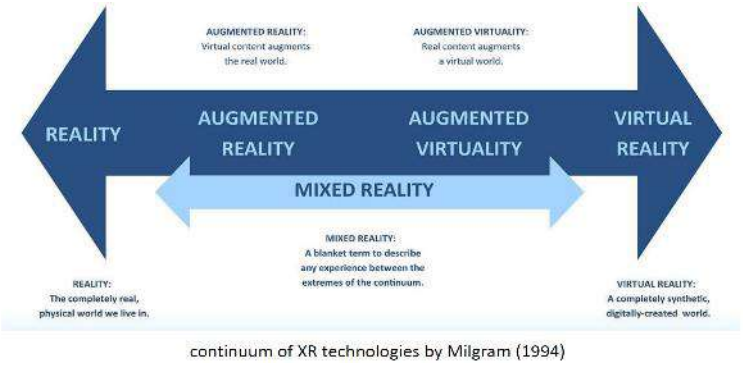


Figure 2.6.62. XR technologies – Milgram continuum

Different hardware systems are outlined for VR, AR, and MR. VR systems range from desktop setups with 3D monitors or goggles to immersive environments like large-surface projections and CAVE systems. AR/MR hardware includes handheld devices like tablets and smartphones, as well as immersive smart glasses and headsets with various interaction capabilities.

Applications of XR in engineering include design varianting, assembly, and manufacturing process improvements, as well as work simulations and training (see Figure 2.6.63). Real-world examples from companies like Volkswagen, Ford, and Boeing demonstrate the practical utility of XR technologies in reducing training time and work injuries.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.63. Engineering applications of XR

In the medical field, XR applications extend to therapy, rehabilitation, phobia treatment, immersive patient data visualization, and simulated surgery training (see Figure 2.6.64). Virtual Prototyping (VP) is another key application, using VR to create and test digital prototypes for design optimization, training, marketing, and sales process planning.

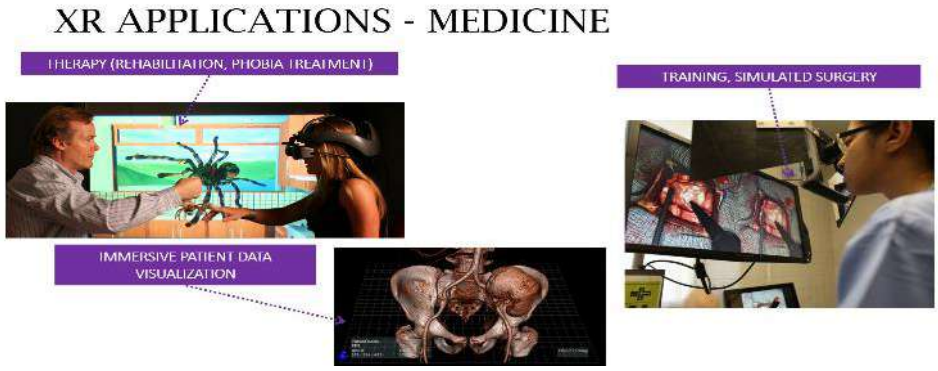


Figure 2.6.64. Medical applications of XR, as presented in the lecture

The creation of virtual products involves simulation of work and interaction, assembly, disassembly, and maintenance instructions, among other aspects. VR applications are defined as programmatic entities, focusing on 3D graphics, free movement, interaction, and striving for immersion and realism. Different types of XR applications include simulators, configurators, and virtual instructions, each serving a distinct purpose in knowledge transmission and client engagement . These applications are classified based on the level of knowledge they present, ranging from general to procedural and practical skills.The lifecycle of professional XR applications is discussed, from initial excitement and idea formation to project realization, implementation, and eventual obsolescence. This process involves identification, justification, knowledge gathering and application, and implementation stages (see Figure 2.6.65).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

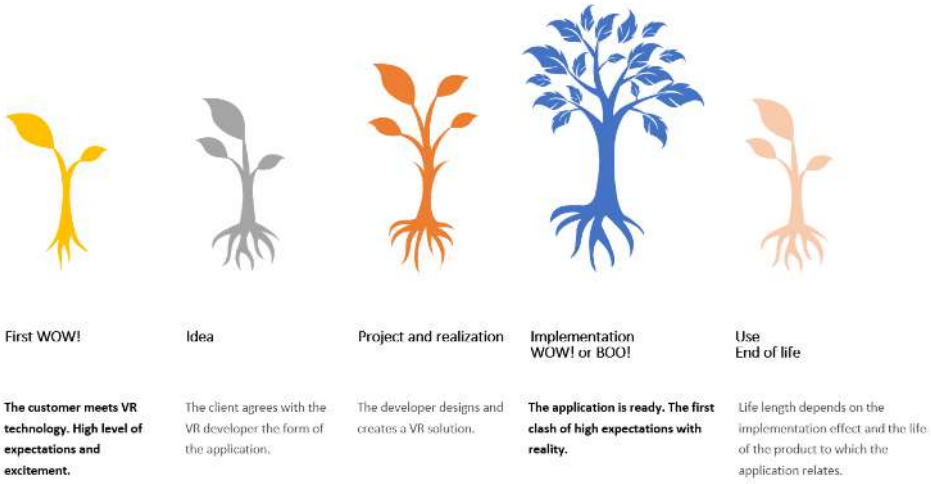


Figure 2.6.65. Lifecycle of XR applications

Key steps in building XR applications include planning, visualization, interaction programming, user interface creation, and verification. These steps involve operations on objects, scenes, and visualization techniques (see Figure 2.6.66).

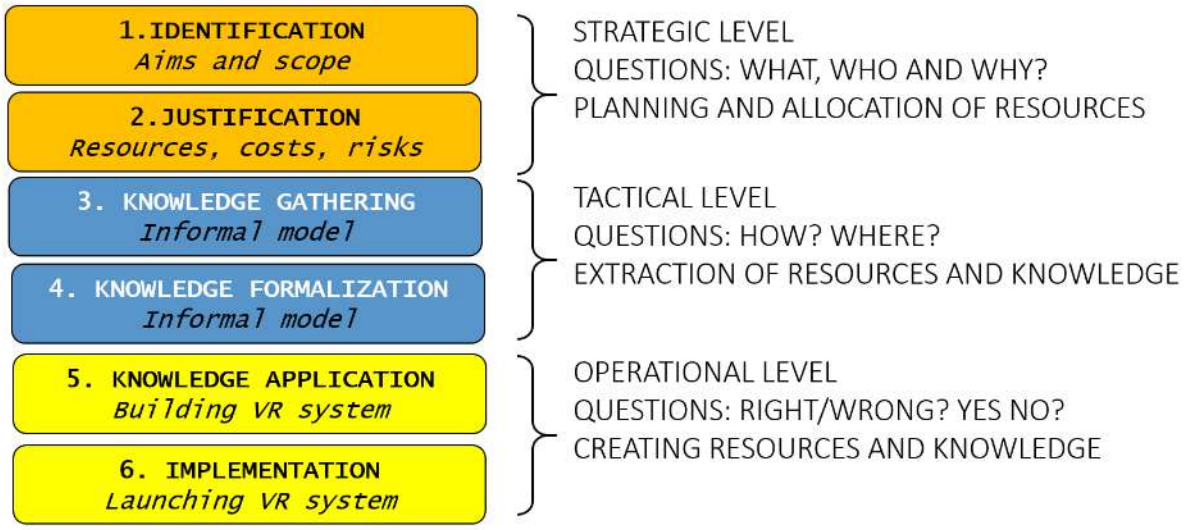


Figure 2.6.66. Building stages of XR applications, as proposed by Gorski in 2016

Case studies provided include the digital twin of the AutoMedPrint system, prosthesis design and fit, and VR-aided rehabilitation using biomechatronic orthosis. These examples showcase the real-world impact and potential of XR technologies in various fields (see Figures 2.6.67 and 2.6.68).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

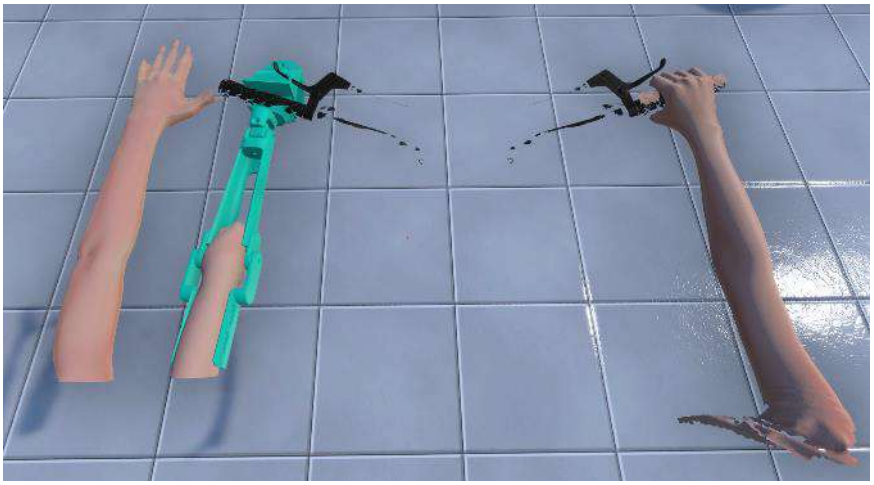


Figure 2.6.67. VR use case related to EMERALD case study #1 – virtual fit of a bicycle prosthesis

Figure 2.6.68. VR therapy game with use of biomechatronic orthosis (EMERALD case #3)

The presentation highlights the breadth and depth of XR technologies and their multifaceted applications in engineering, medicine, and beyond.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Additionally, the step 1 of the XR course available in the virtual laboratory contains link of the published open access common paper on XR use in development of mechatronic bicycle prosthesis – direct link to PDF file (see Figure 2.6.69).

applied sciences

MDPI

Article

Experimental Evaluation of Extended Reality Technologies in the Development of Individualized Three-Dimensionally Printed Upper Limb Prostheses

Filip Górski [1,*], Remigiusz Łabudzki [1], Magdalena Żukowska [1], Filippo Sanfilippo [2], Morten Ottestad [2], Martin Zelenay [3], Diana-Irinel Băilă [4] and Razvan Pacurar [5]

1 Faculty of Mechanical Engineering, Poznan University of Technology, 60-965 Poznan, Poland; remigiusz.labudzki@put.poznan.pl (R.Ł.); magdalena.zukowska@put.poznan.pl (M.Ż.)
2 Department of Engineering Sciences, Faculty of Engineering and Science, University of Agder (UiA), Jon Lilletuns vei 9, NO-4879 Grimstad, Norway; filippo.sanfilippo@uia.no (F.S.); morten.ottestad@uia.no (M.O.)
3 Bizzcom s.r.o., Šľachtiteľská ulica 591/2, 919 28 Bučany, Slovakia; martin_zelenay@bizzcom.sk
4 Department of Manufacturing Engineering, Faculty of Industrial Engineering and Robotics, University Politehnica of Bucharest, Blv. Splaiul Independenței, No. 313, Sector 6, 060042 Bucharest, Romania; diana.baila@upb.ro
5 Department of Manufacturing Engineering, Faculty of Industrial Engineering, Robotics and Production Management, Technical University of Cluj-Napoca, Blv. Muncii, No. 103-105, 400641 Cluj-Napoca, Romania; razvan.pacurar@tcm.utcluj.ro
* Correspondence: filip.gorski@put.poznan.pl; Tel.: +48-61-665-2756

Featured Application: The work presented in this paper will be applied in the process of design and the production of customized, low-cost upper limb prostheses, using the AutoMedPrint technology. The developed extended reality (XR) applications will be used for training and facilitating communication with customers.

check for updates

Citation: Górski, F.; Łabudzki, R.; Zukowska, M.; Sanfilippo, F.; Ottestad, M.; Zelenay, M.; Băilă, D.-I.; Pacurar, R. Experimental Evaluation of Extended Reality Technologies in the Development of Individualized Three-Dimensionally Printed Upper Limb Prostheses. *Appl. Sci.* **2023**, *13*, 8035. https://doi.org/10.3390/

Abstract: This paper presents results from experimental studies that assess the utilization of virtual, augmented, and mixed reality (VR, AR, MR) at different stages of developing personalized 3D printed upper limb prostheses for adult patients. The prostheses are designed automatically using the AutoMedPrint system, leveraging 3D scans as described in various prior publications. Various stages of development of the prosthesis are made as applications of different extended reality technologies. An assembly instruction is implemented as an immersive VR application, a configurator is designed as AR application and a configurator and try-on application is prepared and deployed in MR. The applications are tested by an international group of experts during a scheduled experiment.

Figure 2.6.69. The common scientific paper on development of prosthesis using XR – document available in Virtual Platform, step 1

This paper presents results from experimental studies that assess the utilization of virtual, augmented, and mixed reality (VR, AR, MR) at different stages of developing personalized 3D printed upper limb prostheses for adult patients. The prostheses are designed automatically using the AutoMedPrint system, leveraging 3D scans as described in various prior publications. Various stages of development of the prosthesis are made as applications of different extended reality technologies. An assembly instruction is implemented as an immersive VR application, a configurator is designed as AR application and a configurator and try-on application is prepared and deployed in MR. The applications are tested by an international group of experts during a scheduled experiment.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The experts then participate to surveys and comparatively evaluate the potential of all the XR technologies. The paper presents the development of these applications, provides a detailed account of the experimental process, including the rankings of XR technologies for different applications throughout the lifecycle of a prosthetic device. The main experiment described in this paper was realized during the Short Term Staff Training Event, in the course of the EMERALD project.

2.6.16. Step 2 – PUT - Augmented Reality application tutorial

The next step is Augmented Reality tutorial. It has been selected as the first laboratory work for students, due to its simplicity – it can be done by persons that have never previously used Unity engine. The tutorial and all necessary materials can be accessed like shown in Figure 2.6.57 being possible to be accessed directly on the XR virtual laboratory of the e-learning platform, using the yellow marker no. 2 (refer to Fig. 2.6.70) or direct link below:

https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-2.69%2C-.33&ss=65&tag=vqr0zpattZo&pin-pos=-19.71%2C1.09%2C6.55

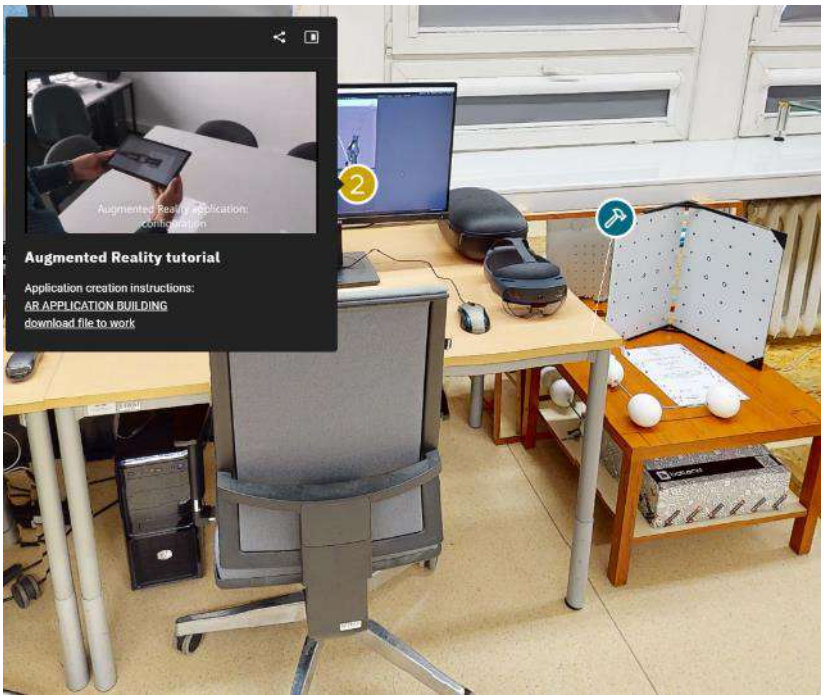


Figure 2.6.70. Augmented Reality tutorial materials, Virtual Platform, step 2

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The tutorial document provides a comprehensive guide for creating an Augmented Reality (AR) configurator for a prosthesis using the Unity 3D engine and Vuforia Engine. The project aims to build an AR application for a 3D printable modular upper limb prosthesis, for a device with Android system (a tablet, or a cellphone, or - potentially - smart glasses) (see Figure 2.6.71).

Figure 2.6.71. Augmented Reality tutorial – concept image

Introduction to Unity and Vuforia Engine The document begins by introducing Unity and the Vuforia Engine, focusing on building an AR application for Android systems. It details the steps to create a new Unity project named ARExercise, emphasizing the importance of using ASCII characters in the project folder path for proper Android app generation.

Task 1: Preparing Unity Project for AR The first task involves setting up the Unity project for AR work. This step includes creating the project in Unity, specifying the path, and ensuring the correct folder naming conventions.

Task 2: Importing 3D Model and Applying Material The second task deals with importing the 3D model of the prosthesis into Unity and applying materials. This includes creating folders for materials and textures, importing texture files, and creating a material named 3DPrintedMaterial. The material is applied to all elements of the prosthesis to imitate a surface resembling a 3D print. The prosthesis model with different versions of sockets and end effectors is added to the scene, and the Image Target is set up to display the 3D objects when a webcam points at a printed marker (Figure 2.6.72).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.72. Augmented Reality tutorial – prosthesis visible over a marker image

Task 3: Adding Color Change and Animation In this task, a color change feature and a simple animation are added to the prosthesis model. Scripts for color switching are imported, and a new canvas is created in the Unity scene for the color change interface. The interface includes buttons for different color options, which are set up to change the color of the prosthesis model upon interaction

Task 4: Configuring Modular Elements with 3D AR Interface (see Figure 2.6.73) Task four focuses on choosing different prosthesis components using a 3D AR interface. It involves duplicating and adjusting elements of the prosthesis model, setting up an Event System for mouse or touch interactions, and adding an interactive script for component selection. This setup allows users to select different prosthesis configurations by clicking on the respective 3D models displayed after pointing the camera at an AR marker.

Figure 2.6.73. Augmented Reality tutorial – modular elements configuration

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Task 5: Compiling and Testing the Application on a Tablet The final task covers compiling the AR application and testing it on a tablet. The document guides through setting up the PlayerSettings in Unity, connecting the mobile device to the computer, selecting build settings, and compiling the application. The operation of the application is then tested by directing the tablet to the AR markers and checking the interaction with the 3D objects and the 2D interface.

The document thoroughly explains each step of creating the AR configurator for the prosthesis, ensuring a comprehensive understanding and successful implementation of the AR project. Additionally, YouTube video is provided with presentation how the application should work when deployed on the tablet (see Figure 2.6.74).

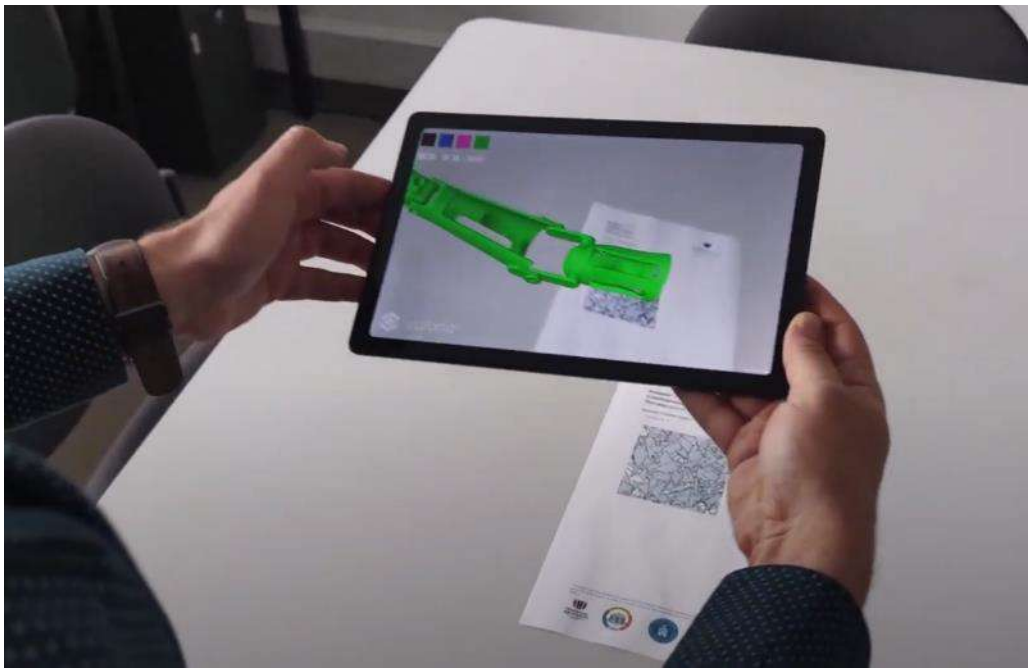


Figure 2.6.74. Augmented Reality application video

2.6.17. Step 3 – PUT - Mixed Reality application tutorial

The next step is Mixed Reality tutorial. It has been selected as the second laboratory work for students, it can be done by persons with basic experience in Unity engine. The tutorial and all necessary materials, including basic project with MRTK and Oculus toolkits can be accessed like shown in Figure 2.6.57 being possible to be accessed directly on the XR virtual laboratory of the e-learning platform, using the yellow marker no. 3 (refer to Fig. 2.6.75) or direct link below:

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-2.5%2C-.25&ss=51&tag=zWH1m3ogPfy&pin-pos=-25.28%2C1.08%2C6.69

Figure 2.6.75. Mixed Reality tutorial materials, Virtual Platform, step 3

The tutorial document provides a detailed guide for creating a Mixed Reality (MR) try-on of a biomechatronic device using Unity 3D engine and Mixed Reality Toolkit by Microsoft. The project focuses on the digital try-on of a mechatronic device, either a prosthesis or orthosis, previously designed, and its implementation on Meta Quest VR goggles with passthrough view capability (Figure 2.6.76) .

Figure 2.6.76. Mixed Reality tutorial – concept image

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Task 1: Preparing Unity Project for MR The first task involves setting up the Unity project for MR. This includes unpacking a provided ZIP file, renaming the main folder, and opening the project in Unity. The basic scene, named OculusSampleInteractionScene, is located and saved under a new name, OculusProsthesisMR. The saved scene contains test interaction objects, and users are guided to test interactions in the Unity Editor using mouse and keyboard, simulating user movement and hand interaction.

Task 2: Importing 3D Models and Scene Layout The second task deals with importing 3D models and setting up the basic scene layout. A Model3D folder is created in the project's Assets folder, along with Materials and Textures subfolders. Textures are imported into the Textures folder, and the FBX model of the prosthesis or orthosis is imported into the project. The object is then inserted into the scene and placed horizontally in front of the initial camera location. Additionally, a 3D printed material is created using supported textures.

Task 3: Adding Configuration Options In this task, configuration options are added to the project. The PressableRoundButton prefab from the Mixed Reality Toolkit Examples is dragged to the Variant1 object in the scene structure. The button is positioned and rotated, and label text is edited to reflect the name of the variant. A PUT_PowerSwitch script is added to the Variant1 object, and objects representing two variants are linked to the script for functionality (see Figure 2.6.77).

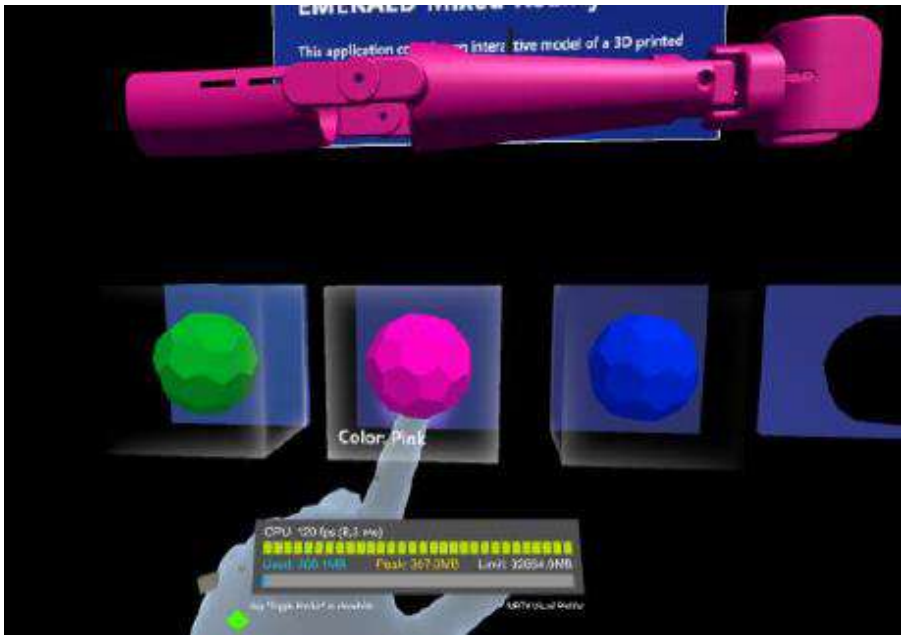


Figure 2.6.77. Mixed Reality tutorial – adding color change

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Task 4: Manipulation and Animations of the Prosthesis This task involves introducing manipulation and animations to the prosthesis. Standard manipulation type is copied from one of the original MRTK objects and applied to the main object (prosthesis/orthosis). The Box Collider is adjusted to cover the whole object, and manipulation is tested in Game mode. Users are encouraged to create additional interactions, such as animations or exploding views, if time permits (see Figure 2.6.78).

Figure 2.6.78. Mixed Reality tutorial – prosthesis manipulation

Task 5: Compiling and Testing the Application The final task covers compiling the application and testing it on the goggles. This involves setting company and product names in the PlayerSettings, connecting the device to the computer, selecting build settings in the Unity editor, and compiling the application. The application is then tested on the goggles, with users manipulating objects using their hands and controllers.

These tasks collectively guide users through the process of creating an MR application for a biomechatronic device. The document meticulously details each step, ensuring a comprehensive understanding and successful implementation of the MR try-on project. Additionally, YouTube video is presented, demonstrating how the application should work while deployed on a Meta Quest device. (see Figure 2.6.79).

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.79. Mixed Reality application video

2.6.18. Step 4 – PUT - Virtual Reality application tutorial

The final step is Virtual Reality tutorial. It is the most complex application to build of the presented three tutorials in PUT VR lab, however the instructions are detailed, so it can be done by persons with just basic experience in Unity engine. The tutorial and all necessary materials, including basic project with MRTK and Oculus toolkits can be accessed like shown in Figure 2.6.57 being possible to be accessed directly on the XR virtual laboratory of the e-learning platform, using the yellow marker no. 4 (refer to Fig. 2.6.80) or direct link below:

https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-1.68%2C-1.09&ss=65&tag=r0nQA6uecmA&pin-pos=-17.61%2C.98%2C5.18

Figure 2.6.80. Virtual Reality tutorial materials, Virtual Platform, step 4

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

The tutorial document is a comprehensive guide for creating a Virtual Reality (VR) application focused on the assembly of a biomechatronic device. This project employs Unity 2019.4 and the SteamVR package for its development. The document guides users through the entire process, from setting up the Unity project to compiling the final application (see Figure 2.6.81).

Figure 2.6.81. Virtual Reality tutorial – concept image

The exercise's goal is to create an immersive VR application for assembling either a bicycle prosthesis with sensors or a therapeutic hand orthosis, both simplified EMERALD case studies. Essential prerequisites include the Unity engine (version 2019.4.24 or higher), VR goggles in PC mode, SteamVR installation, and converted STP models in FBX format. The project employs scripts and 3D models from the Virtual Design Laboratory of Poznań University of Technology, which are the intellectual property of the university and can be used solely for educational purposes within the scope of the EMERALD project.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Task 1: Preparing Unity Project for SteamVR

A new Unity project is created, named "EMERALD_VRExercise," using a 3D template. Standard Unity packages required for VR applications with the SteamVR plugin are installed. The SteamVR package and additional scripts from the PUT VR laboratory are imported to convert the project for VR programming.

Task 2: Importing 3D Models and Setting Up the Scene

The environment is set up with 3D models, including the prosthesis or orthosis model and a doctor's office environment. The prosthesis model is prepared with a 3D printed material texture to enhance realism. The structure of imported objects is adjusted to ensure they are hierarchically related and visually accurate.

Task 3: Creating the Assembly Procedure

An interactive assembly procedure is developed, where duplicate parts of the prosthesis or orthosis are converted into throwable objects. Put down zones are created for these parts so that they lock in place when assembled correctly. This process is meticulously detailed for both the prosthesis and orthosis models (see Figure 2.6.82).

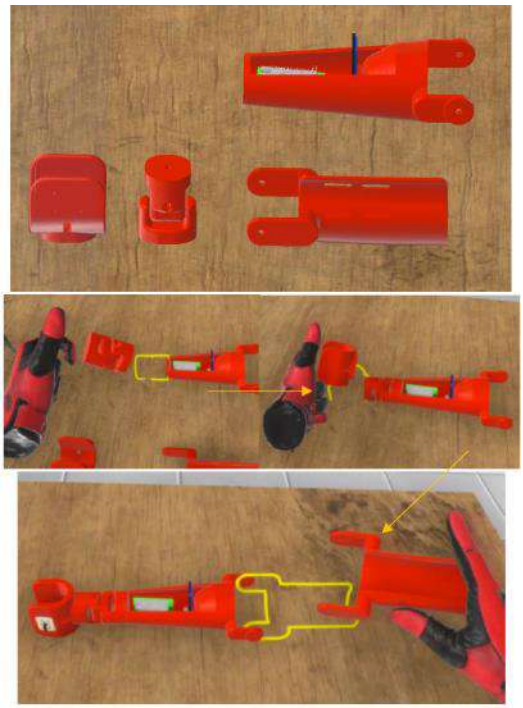


Figure 2.6.82. Virtual Reality tutorial – programming assembly sequence

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Task 4: Adding Help and Annotations

Text hints displaying the names of prosthesis parts are created and programmed to constantly face the camera for readability. An interactive 3D help button is also added to toggle these hints on and off during the application play. This helps guide the user through the assembly process (see Figure 2.6.83).

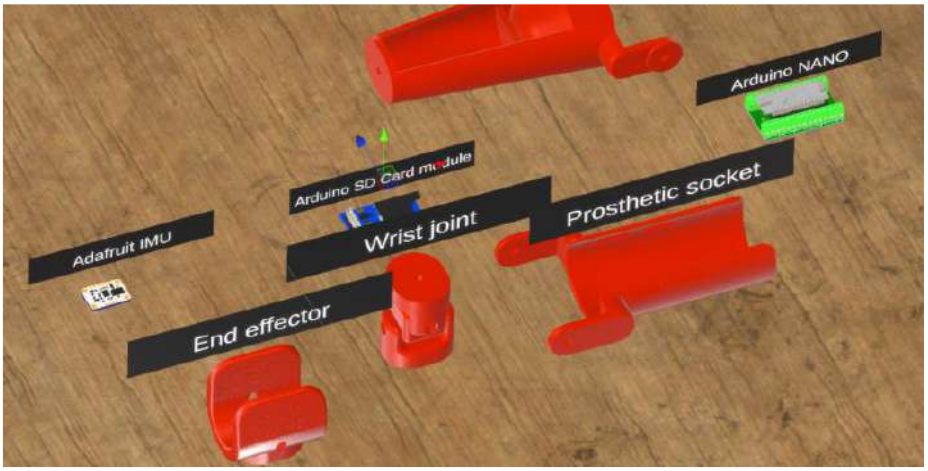


Figure 2.6.83. Virtual Reality tutorial – adding help to the virtual instruction

Task 5: Compiling the Application and Testing It

The final application is compiled into an executable format, with the company and product name set as EMERALD. The functionality of the application is tested using VR goggles to ensure that all interactions and assembly procedures work correctly.

The document is a thorough instructional guide, ensuring a detailed understanding of creating a VR application for biomechatronic device assembly. It serves as an educational tool, merging technical VR development skills with practical applications in biomechatronics.

Additionally, a YouTube video is provided, showing the use of the application. The application in an executable form is also available for downloading, so that it can be tested without necessity to go through the tutorial (see Figure 2.6.84)

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.84. Virtual Reality application video

2.6.19. Additional VR materials related to EMERALD project

The Virtual Reality laboratory at Poznan University of Technology also contains additional materials for the students. These include the following:

- Virtual Reality executable application – interactive tutorial on how to realize work with AutoMedPrint system in the aspect of 3D scanning, design and 3D printing – the students may learn the whole scanning procedure on their own from the video (see Figure 2.6.85)

Figure 2.6.85. Interactive Virtual Reality tutorial application – to be downloaded from the platform

- best practices presentation example – made by a student at PUT, VR application for therapy, in form of YouTube video (direct link to spot in the lab (see Figure 2.6.86 and the next following link: https://my.matterport.com/show/?m=NXHcatKcdW7&sr=-1.1%2C1.1&ss=55&tag=R62qACStQ7M&pin-pos=-26.15%2C.77%2C2.89)

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

Figure 2.6.86.Virtual Reality in therapy – EMERALD case #3 – student work

- description of work and operation of Mixed Reality goggles – Oculus Meta Quest 2, Meta Quest 1, Microsoft HoloLens 1, Microsoft HoloLens 2, HTC Vive Pro and others, in various places of the laboratory (students are encouraged to find them on their own) (see Figure 2.6.87)

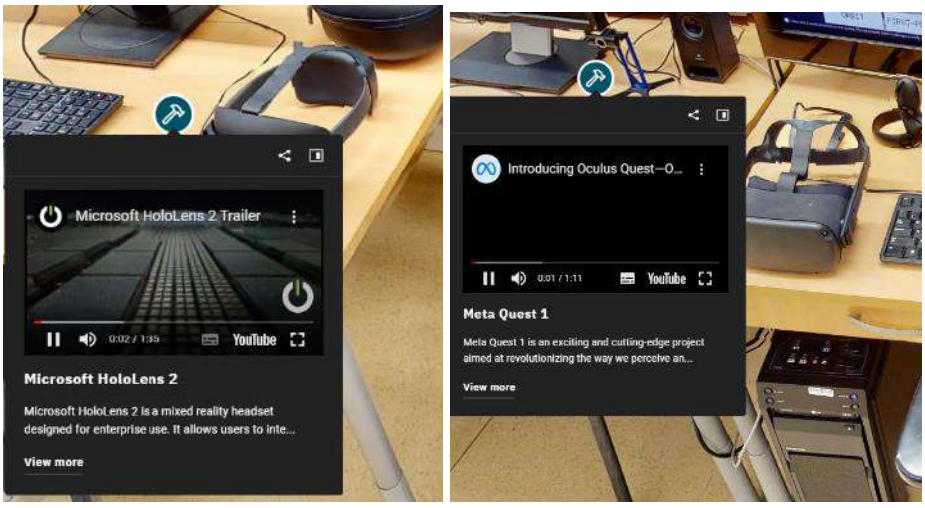


Figure 2.6.87. Virtual Reality laboratory – XR hardware descriptions

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

These materials are complementary towards the main path of the course, however they provide interesting insights on how to work with the VR for the development and use of innovative biomechatronic devices for people with special needs.

2.6.20. Conclusions about VR / AR teaching resources of the e-learning platform

The materials contained in the Virtual Platform regarding XR present a unique opportunity for any student to get familiarized with the newest possibilities in building Virtual, Mixed and Augmented Reality applications concerning development of customized biomechatronic orthopedic and prosthetic devices. The comprehensive, detailed instruction tutorials presented allow the students to get a grip on the programming methods and possible use Great expertise of authors of the materials (coming from Poznan University of Technology) brings possibilities to learn a great deal about the VR mostly by practicing building software in well-known, industry standard Unity Engine. Such a course is unprecedented and unavailable at any other e-learning platform. It is also well complemented with the basic VR/AR course contained in the Bizzcom Virtual Laboratory, altogether presenting a wide spectrum of possibilities of building applications and using these cutting-edge technologies.

3. Final conclusions

The e-learning virtual laboratory platform developed in the frame of O3 by the EMERALD consortium presents a significant advancement in the field of bio-mechatronics, specifically catering to the needs of individuals with amputated arms. This online platform stands out for its ease of access and use, offering a comprehensive educational experience that goes beyond expectations. The e-learning virtual laboratory platform provides a realistic laboratory experience, making users feel as though they are physically present in the labs. The virtual laboratory platform is not just a virtual space; it's a full-fledged learning environment. Each digital room, accessible in VR mode, focuses on different stages of developing bio-mechatronic systems, offering a variety of learning materials.

These include VR/AR applications designed to help users understand the construction elements of bio-mechatronic systems, practical tools for VR/AR programming, and detailed explanations and annotations about the equipment used. The platform also provides links to instructional videos,

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).

course modules, toolkits, and free software for CAD, CAE, and 3D printing, enhancing the learning experience. A crucial component of the EMERALD platform is its e-library resources. These include CAD/CAE models and VR/AR applications that users can download and interact with. These resources have been employed in producing the e-toolkit and can be replicated using 3D printing technologies, with instructions provided on the platform. Many of these VR/AR applications were created by professors and students during various learning and teaching activities, like the staff for training events organized in Bucany and the Norway summer school in 2023. The impact of the EMERALD platform was significant and has been noticed especially during these organized events. Students have been used, experience, and test the e-learning platform, providing valuable feedback. This feedback led to significant updates in the platform's scientific and educational content, with additional presentations, courses, and applications added based on user needs. The e-learning platform, with its comprehensive and freely accessible resources aims to serve as a starting point for new projects involving innovative 3D printing solutions for developing and customizing bio-mechatronic systems on a larger scale in the end.

Disclaimer: This results was realised with the EEA Financial Mechanism 2014-2021 financial support. Its content (text, photos, videos) does not reflect the official opinion of the Programme Operator, the National Contact Point and the Financial Mechanism Office. Responsibility for the information and views expressed therein lies entirely with the author(s).