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EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC MECHATRONIC SYSTEMS

MODULE 4 - VR/AR

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 4 – Virtual Reality & Augmented Reality**
Date of Delivery	**July 2022**
Authors	**Filip GÓRSKI**
Version	**Final Version**

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1. Introduction

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

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

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

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

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

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

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

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

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2. XR technology – basic concepts

2.1 Basic definitions

2.1.1. Virtual Reality

The classic definitions of VR are given below:

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

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

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

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

– immersion (ang. immersion),

– interaction,

– imagination.

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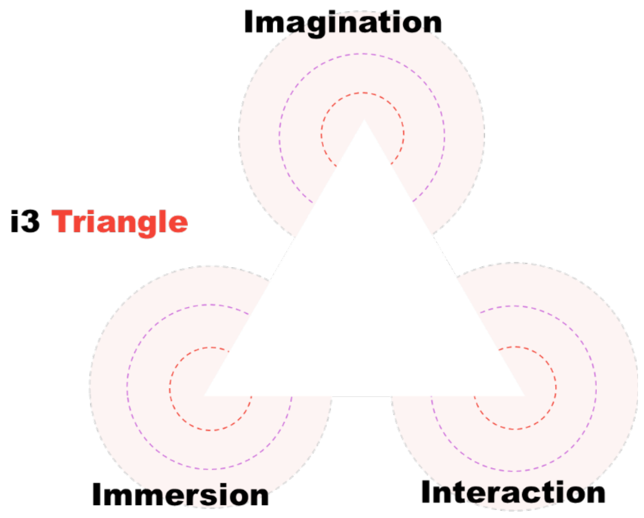

Figure 2.1 I3 Triangle, on the basis of [Burdea & Langrana 1993]

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

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

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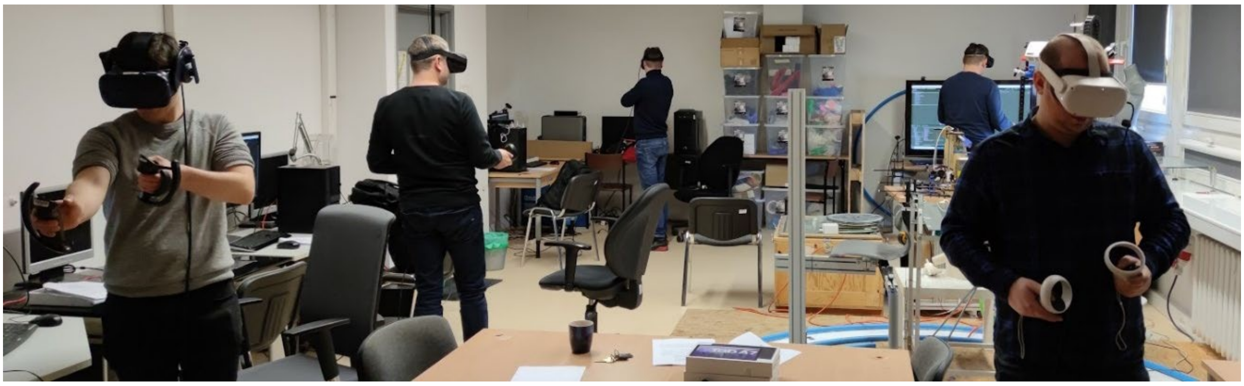

Figure 2.2 Immersive interactive VR system users

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

2.1.2. Augmented and Mixed Reality

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

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

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

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

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

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

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

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

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

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

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

2.1.3. XR technologies – similarities and differences

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

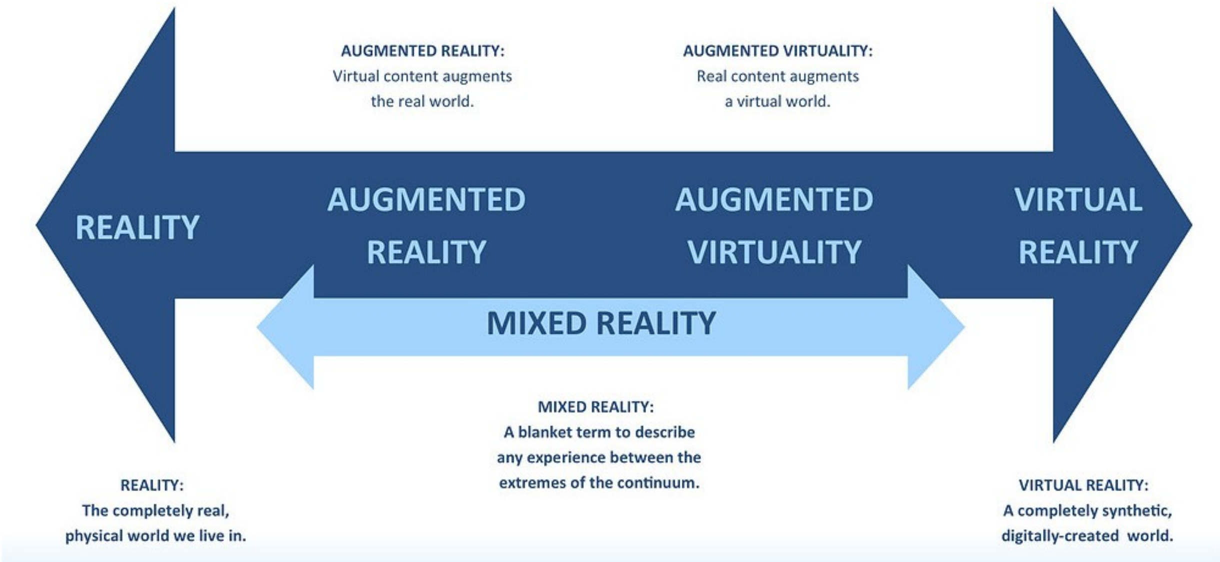

Figure 2.4 Milgram's XR continuum [Milgram et al. 1994]

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

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

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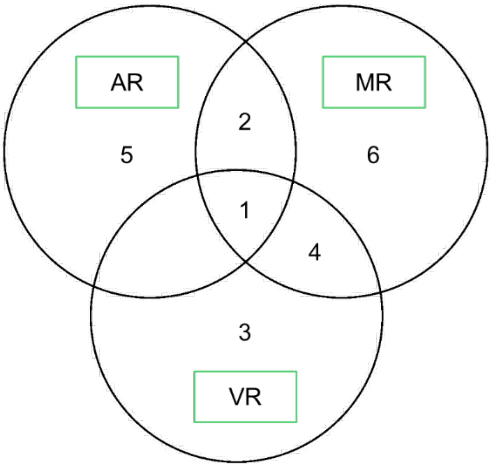
The diagram in Figure 2.5 shows the common and distinctive features of all main XR spectrum technologies.



1 – digital images
2 – real world visible
3 – immersion
4 – user tracking
5 – marker recognition
6 – spatial mapping

Figure 2.5 Common and distinctive features of main XR technologies

2.2 XR systems

2.2.1. Definition, structure, classification

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

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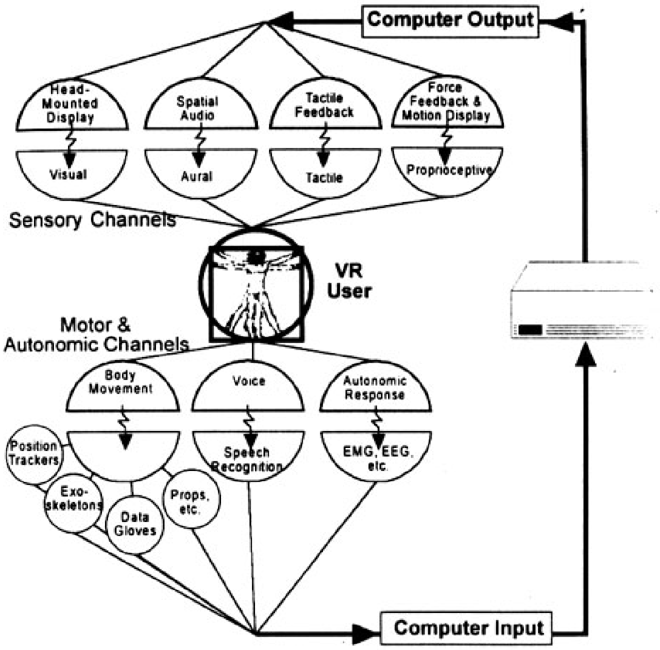

Figure 2.6 Basic input/output channels of VR system [Biocca & Delaney 1995]

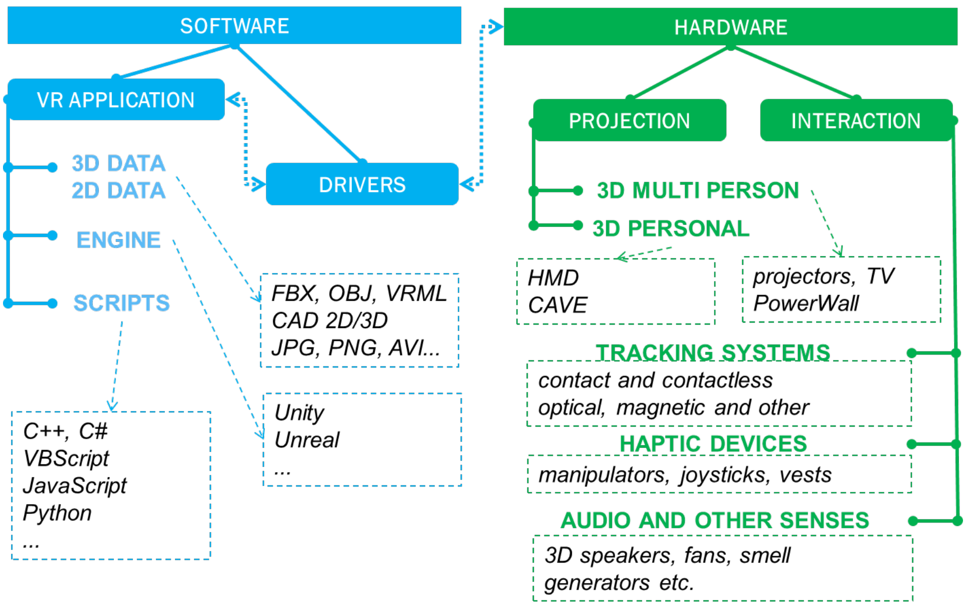

Figure 2.7 Basic hardware/software components of VR system [Górski et al. 2017]

Virtual reality systems can be divided into the following classes:

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

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

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

2.2.2. Hardware

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.2.3. Software

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

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

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

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

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

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

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

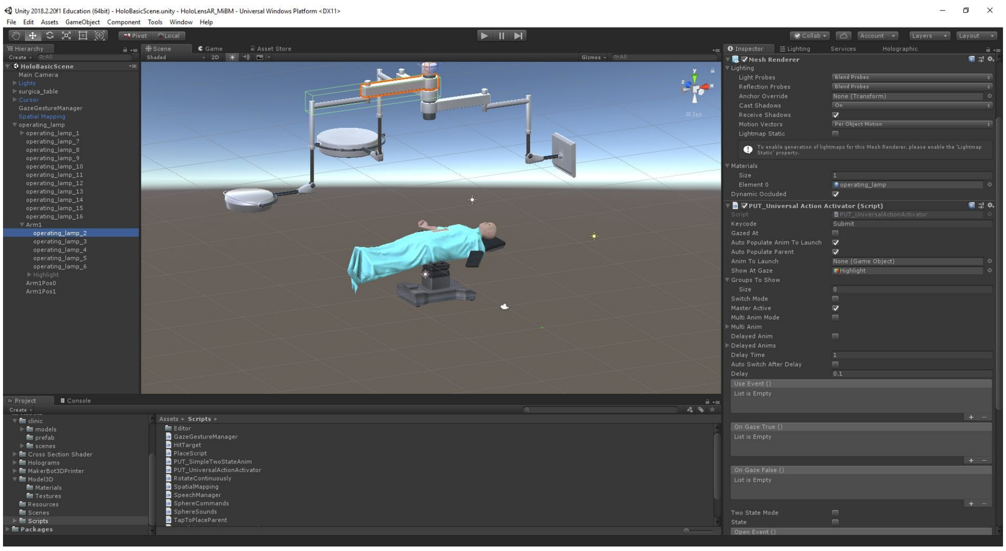

Figure 2.11 Unity game engine

2.3 Applications of XR technologies

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

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

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

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

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

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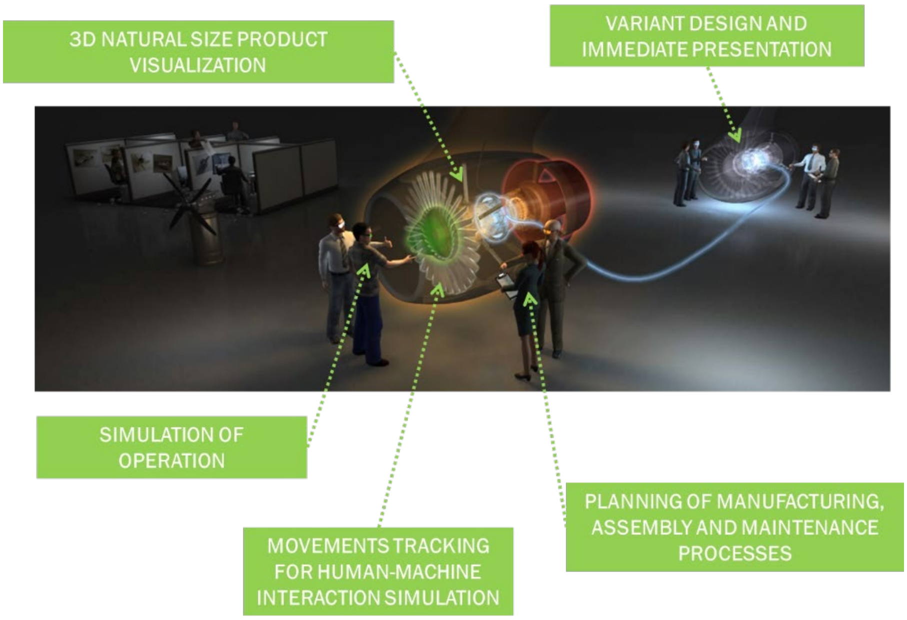

Figure 2.12 Applications of VR in engineering, based on [Górski 2019]

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

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

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

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

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

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

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

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

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3. XR technologies in biomedical applications

3.1 XR simulation and application - definitions

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

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

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

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

– immersion and realism,

– three-dimensional, dynamic 3D graphics,

– free navigation and interaction.

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

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

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

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

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

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3.2 Designing VR/AR applications for medicine and biomedical engineering

3.2.1. Requirements and types of applications

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

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

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

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

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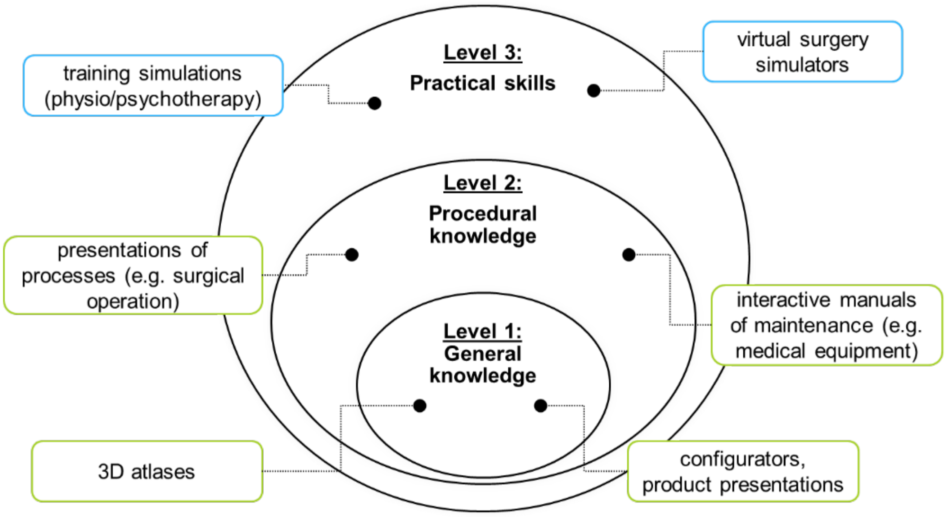

Figure 3.1 Levels of XR applications by knowledge [Górski et al. 2017]

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

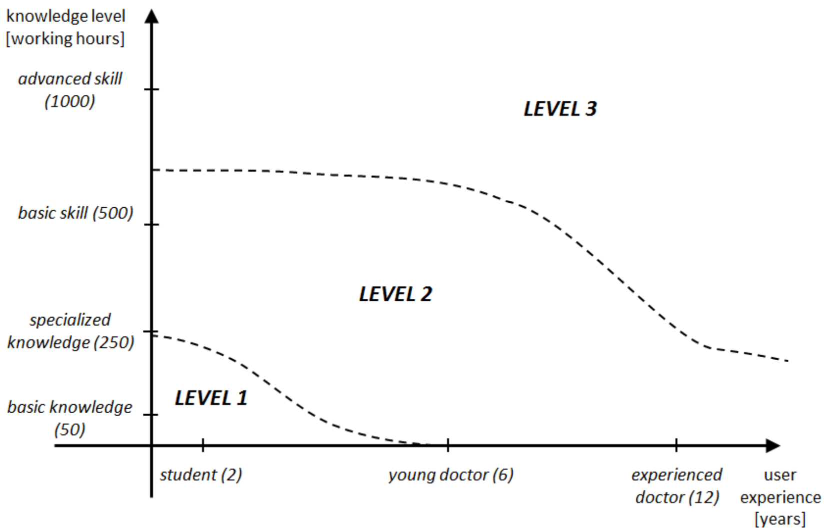

Figure 3.2 Levels of XR applications and mapping to specific user classes [Górski et al. 2017]

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

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

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

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3.2.2. Process of VR/AR/MR application design

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

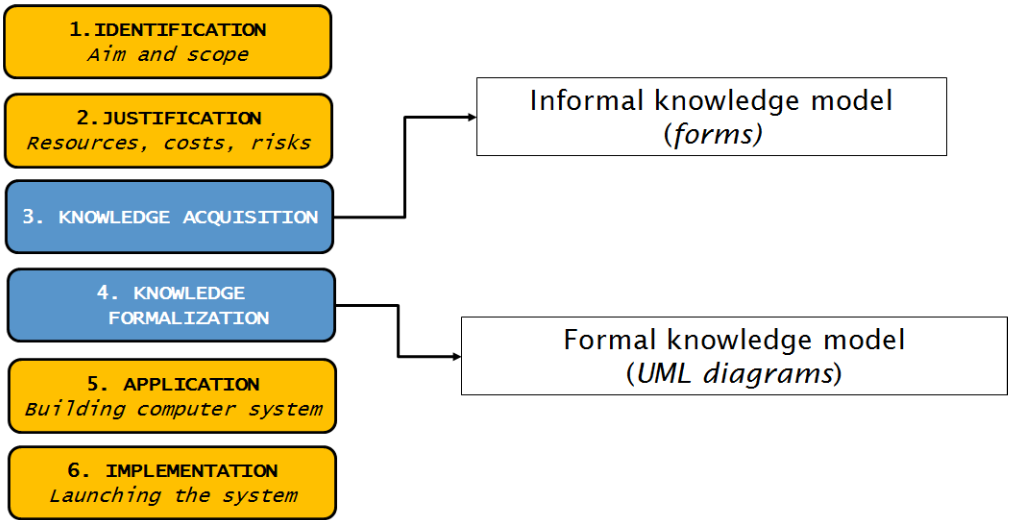

Figure 3.3 Stages of XR application design and preparation process [Górski 2019]

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

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

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

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

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

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

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

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

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

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

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

3.3 Building medical VR/AR applications

3.3.1. XR application development process

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

1. Visualization.

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

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2. Behavior programming.

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

3. Interface programming.

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

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

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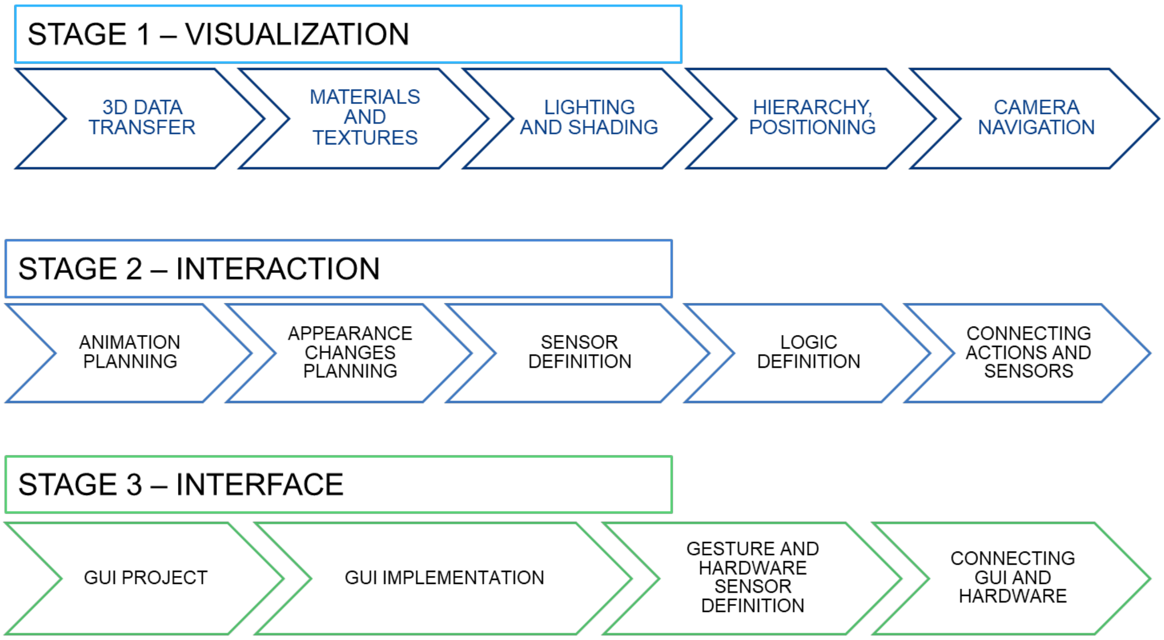

Figure 3.4 Phases of XR application development process

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

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

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

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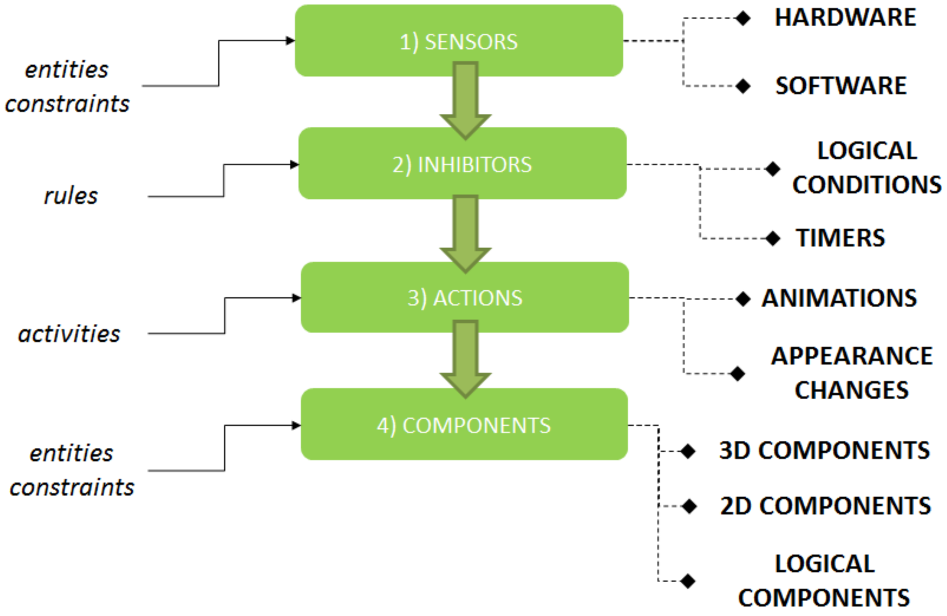

Figure 3.5 Main concepts in creating interactions in XR applications

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

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

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

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

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

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

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

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

3.3.2. Implementing and maintaining professional XR applications

The implementation stage of the VR application consists mainly of two types of activities – related to the construction of the hardware layer and integration with the software layer, and related to iterative testing and improvement of the application until a fully functioning solution is obtained. The moment of completion of the tests and obtaining confirmed full operational efficiency is the beginning of the VR system operation phase in a given place (institution, company etc.). At this stage, it is also necessary to allocate appropriate material and human resources within the entity to maintain the solution.

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

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

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

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

3.4.1. Wheelchair designer

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

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

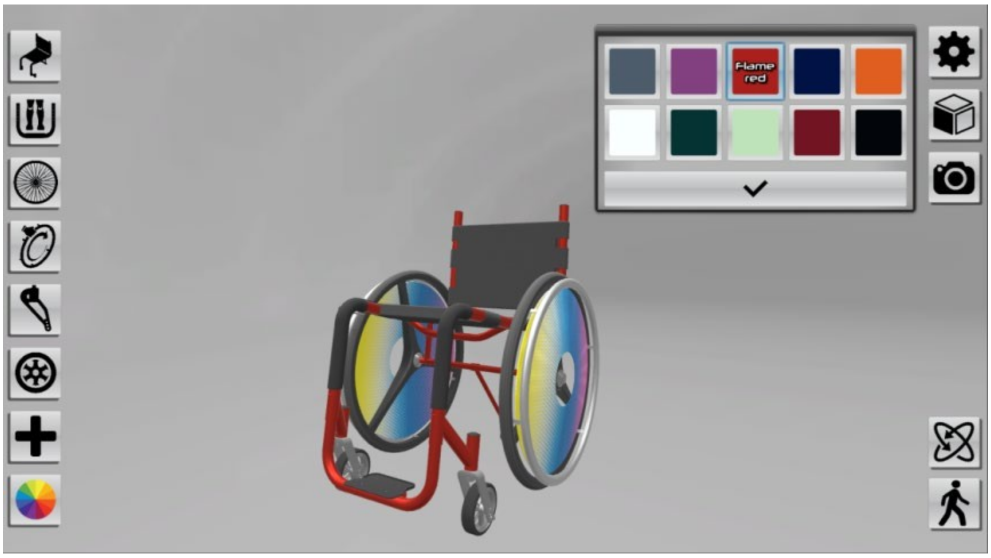

Figure 3.6 Application - wheelchair configurator [Myślewska 2017]

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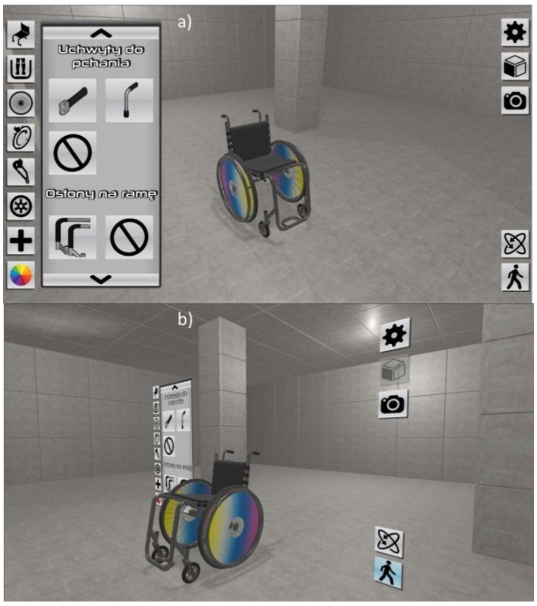

Figure 3.7 Wheelchair configurator – standard and immersive mode

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

3.4.2. Fear of heights therapy

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

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

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

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

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

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

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

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

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

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

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

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

4. Summary

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

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

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