UNIVERSITY
OF TURKU

Virtual reality tools in developing industrial training for additive manufacturing

Software Engineering
Master's Degree Programme in Information and Communication Technology
Department of Computing, Faculty of Technology
Master of Science in Technology Thesis

Author:
Jaakko Susi

Supervisors:
D.Sc. (Tech) Teijo Lehtonen (University of Turku)
D.Sc. (Tech) Heidi Piili (University of Turku)

December 2022

Master of Science in Technology Thesis
Department of Computing, Faculty of Technology
University of Turku

Subject: Software Engineering
Programme: Master's Degree Programme in Information and Communication Technology
Author: Jaakko Susi
Title: Virtual reality tools in developing industrial training for additive manufacturing
Number of pages: 49 pages
Date: December 2022

Additive manufacturing (commonly known as 3D-printing) is experiencing increasing global popularity in the manufacturing industry. The technology has been adopted by large companies and additive manufacturing services have been outsourced by smaller ones, but first-party adoption of the technology among small and medium-sized enterprises has been slow. Additive manufacturing provides new opportunities for manufacturing but also requires specialized expertise among users of the technology. Studies indicate that modern digital learning techniques such as micro learning and the use of virtual reality and 360° video can provide effective means of learning industrial skills.

The purpose of this thesis was to examine digital learning techniques, 360° video and virtual reality as well as various additive manufacturing technologies in order to produce a virtual reality -based learning application for industrial training of additive manufacturing. It was also necessary to test and validate the effectiveness of the training application and derive future considerations for more advanced iterations. The value of stereoscopic 360° virtual reality video was also examined.

The first version of the training application was successfully completed, and user tests were conducted. A mix of quantitative feedback in the form of a survey, and qualitative feedback in the form of interviews, was gathered from a number of test users. Feedback was overall positive, but some user interface issues, and technical shortcomings were highlighted. Qualitative feedback regarding stereoscopic 360° video indicated the technique to have additional value for learning purposes in virtual reality. The results of these tests will be taken into consideration in the design of a second version of the training application. Topic for further studies were also proposed.

Keywords: additive manufacturing, industry, learning environment, e-learning, micro learning, virtual reality, 360-degree video, 3D-printing

List of symbols and abbreviations

1080p	Full-HD resolution (1920 × 1080 pixels)
4k	4k-resolution (3840 × 2160 pixels is the most common)
3D	Three dimensional
3DoF	Three degrees of freedom
6DoF	Six degrees of freedom
AM	Additive Manufacturing
BJ	Binder jetting
CAD	Computer-aided design
CNC	Computer-numerical control
CPU	Central processing unit
Cyber sickness	Nausea experienced by some users of virtual reality systems
DfAM	Design for additive manufacturing
DED	Direct energy deposition
EPBF	Electron beam powder bed fusion
ESF	European Social Fund
FOV	Field of view
GPU	Graphical processing unit
LMD	Laser metal deposition
LPBF	Laser powder bed fusion
ML	Micro learning
Monoscopic	Flat image that lacks three-dimensional depth
PBF	Powder bed fusion
SM	Subtractive manufacturing
SME	Small- or medium-sized enterprise
Stereoscopic	Viewable with both eyes, giving the image three-dimensional depth
VR	Virtual reality
WAAM	Wire arc additive manufacturing

Table of contents

1 Introduction

The production of physical goods is evolving at a rapid pace. Technologies that have existed for decades in experimental stages are quickly becoming widely applicable in many fields. One of these technologies is additive manufacturing (AM). Originally the technology used materials that were predominantly only usable for rapid prototyping prior to the manufacturing of the actual product using traditional methods. Contemporary AM can use advanced and complex materials to manufacture parts that are durable enough to be usable. [1] The concept of three-dimensional printing is widely known, but the full potential of turning models made with computer-aided design (CAD) into physical objects in the industrial level is not widely understood. There have been many major advancements in AM technology that allow the production of objects that possess physical properties and shape potential that meet or even exceed their earlier equivalents in more traditional manufacturing. For example, objects consisting of a single mass with no assembly required can have internal cavities and structures that cannot be machined using computer-numerical control (CNC). [1] Parts can be implemented with seamless structures of shape memory alloys that can alter their shape based on thermal or magnetic differences. [1] The rest of Europe has seen wider adoption of the use of AM technologies in the day-to-day operations than Finland has, even though Finland is among some of the pioneers of these technologies. It is speculated that the reason for the relative slowness of Finland in this regard is that the manufacturing industry in Finland focuses on the production of large parts, which is perceived to be incompatible with additive manufacturing. [2] [3] These manufacturers would benefit from knowledge of AM.

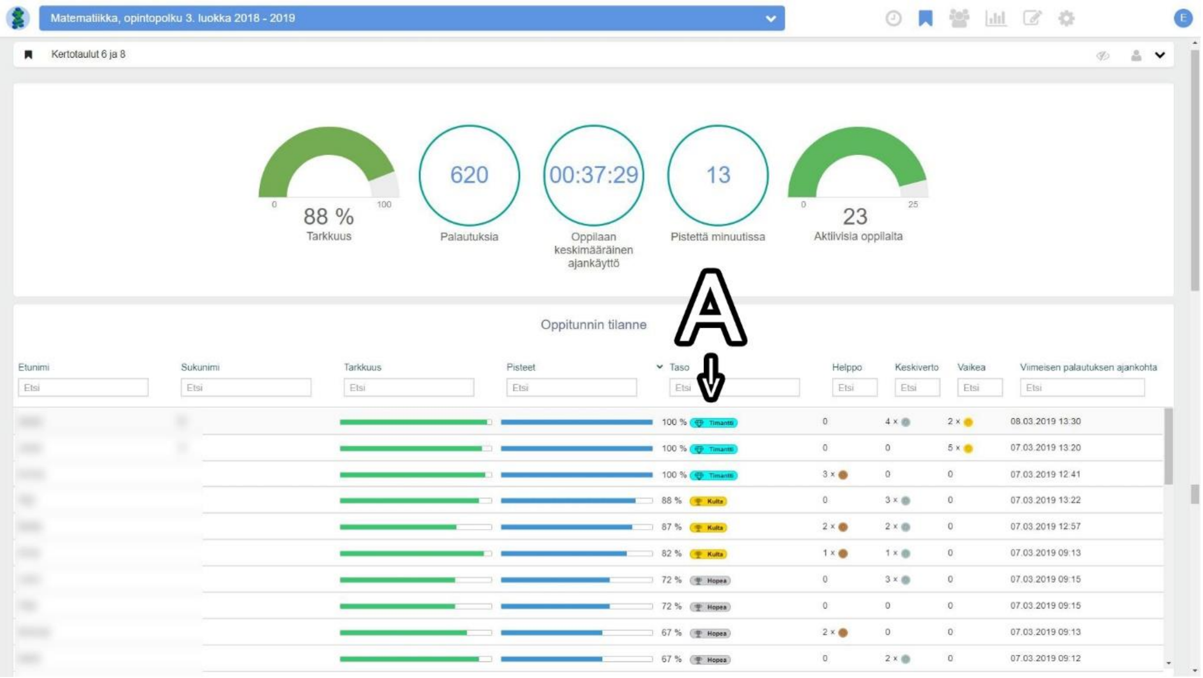
The purpose of this thesis is to determine the viability of virtual reality (VR) -based industrial training of additive manufacturing using 360° video materials based on micro learning (ML) methods. The goal of this thesis is the collection of information about what types of education small and medium-sized enterprises (SMEs) need in the area of additive manufacturing and to examine the benefits of VR training of that knowledge. Consequently, this thesis also aims to focus on how additive manufacturing could be used to enhance the services provided by SMEs. It is also useful to determine what kind of preconceptions and attitudes the representatives of SMEs have regarding AM technologies and virtual reality. The usability aspects of VR-based micro learning are also considered, and feedback about the intuitiveness of the training material is gathered. Additionally, the difference between the value of stereoscopic and monoscopic 360° video in learning materials is evaluated.

2 Micro learning

It is argued that the average attention span has decreased, or at the least, attention is divided due to the increased prevalence of powerful multimedia devices in the possession of each individual in contemporary society, and a ubiquitous access to high-speed wireless internet. When such a large amount of content is available at any given moment to consume, this may create the impression of a lack of time to consume content. It is also discussed that this had led to the common approach to consume and produce content in smaller increments, and services such as Twitter have capitalized on this, by providing an online platform for sharing short pieces of text aka. "microblogs." [4] This change in habits of information consumption provides both a challenge and new opportunities for education. The challenge is that traditional formats of information delivery may not be sufficient for the contemporary audience. An opportunity would be to recognize the new possibilities of an environment saturated with various forms of information delivery, and audiences who wish to receive information in new ways. [4]

Access to high-speed internet has given rise to media sharing services that support more than just text and pictures, and on video sharing services such as YouTube, an extensive culture of video tutorials on many fields has emerged. It is now a common practice among hobbyists, students and even professionals to find solutions to problems they encounter by searching for an answer in the form of a tutorial video online. This is not an instant and miraculous solution to everything. It is still necessary to be able to skim through the contents of the tutorial in order to locate the precise information that is required. This also implies the possession of knowledge about the exact information being sought and the ability to recognize a viable solution to the problem at hand. [4]

The previously mentioned factors have mandated the emergence of a new form of learning, that is meant to take advantage of not only the possibilities provided by modern technology, but also considers the specific properties of the divided attention of a contemporary individual. Micro learning divides the topics that are being taught into short segments that each answer a simple question about a fraction of the entire topic, considering the optimal cognitive load of absorbing new information. [5] Length of segments ranges from 30 seconds to 5 minutes. Each segment employs multiple information delivery channels and minimizes distracting irrelevant information. In other words, each part is by minimum audio-visual and focused on a single aspect without rambling about related subjects. The small segments are categorized for ease of access under well-defined subtopics of the larger main topic. Each small segment may chronologically flow to the next one, but it is not strictly necessary, unless one topic requires the student to be familiar with another. Naturally, this is to be indicated in the preceding content and a disclaimer is to be included in the succeeding one. Narration and demonstration in ML content are preferably to be conducted by an expert of the subject and not merely an actor reading a script provided by an expert. It is helpful for the end of a segment to include the contact details of the expert in case a student requires extra clarification. There may even be an interactive element in more advanced ML setups that supplements the information delivery via sound and sight by having the user actively participate in an example being demonstrated, or having the user answer a simple multiple-choice quiz. Some educational institutions have employed hybrid teaching comprising of the regular student exercises of the class and ML based educational tools. This allows students to focus on the exact topic of the assignment at hand and to simultaneously reinforce their present knowledge and to confirm their understanding via successful completion of related exercises. There may even be a gamification element, such as giving the student an exercise completion rank in the form of a bronze, silver, and gold medal. [6] Figure 1 A displays the ranks achieved by students doing math exercises in the ViLLE online learning environment.



88 % Tarkkuus

620 Palautuksia

00:37:29 Oppilaan keskimääräinen ajankäyttö

13 Pistettä minuutissa

23 Aktiivisia oppilaita

Oppitunnin tilanne

Etunimi	Sukunimi	Tarkkuus	Pisteet	Taso	Helppo	Keskiverto	Vaikea	Viimeisen palautuksen ajankohta
Etsi	Etsi	Etsi	Etsi	Etsi	Etsi	Etsi	Etsi	Etsi
[redacted]	[redacted]			100 % Timantti	0	4 × ●	2 × ●	08.03.2019 13:30
[redacted]	[redacted]			100 % Timantti	0	0	5 × ●	07.03.2019 13:20
[redacted]				100 % Timantti	3 × ●	0	0	07.03.2019 12:41
[redacted]				88 % Kulta	0	3 × ●	0	07.03.2019 13:22
[redacted]				87 % Kulta	2 × ●	2 × ●	0	07.03.2019 12:57
[redacted]				82 % Kulta	1 × ●	1 × ●	0	07.03.2019 09:13
[redacted]				72 % Hopea	0	3 × ●	0	07.03.2019 09:15
[redacted]				72 % Hopea	0	0	0	07.03.2019 09:15
[redacted]				67 % Hopea	2 × ●	0	0	07.03.2019 09:13
[redacted]				67 % Hopea	0	2 × ●	0	07.03.2019 09:12

Figure 1: ViLLE learning environment – University of Turku: Centre for Learning Analytics

Bottom line is that active problem solving is valued, and information is absorbed more efficiently when the student gets to immediately apply the knowledge and can receive feedback on their success at once. [7]

It has been determined that ML is best utilized in cases where the individual already possessed basic knowledge of the wider subject but needs additional instruction in intermediate level studies and higher. ML may not be suitable for teaching every type of skill. For example, mastering spoken languages is better accomplished with traditional teaching methods where students can engage each other and communicate with their teacher, in order to properly hone their ability to communicate using their newly learned language. [4] Studies that benefit from that physical presence are less suited for ML, however students of other subjects have indicated that ML allows them to manage their study time better by freely choosing when and where to study, due to the shortness of the content pieces and the ability to access it anywhere. [8] Some disadvantages of ML have been recognized. Depending on the device there may be problems of information overexposure, distraction by other functions, poor internet connection and hardware affordability. Remote use also precludes immediate access to advice by a teacher. [7]

2.1 Case studies

Several case studies have indicated that ML can bolster learning results of trainees. Studies have been conducted where a control group was to employ traditional learning methods and the observation group was to employ a micro learning method. Results of these studies have shown better test scores for those engaging in ML. [8] [9] Self-reporting of the competence and learning satisfaction of trainees has been higher among those engaging in ML. [9] Some studies have also included a retention assessment, which tests the ability of trainees to recall their learnings over a longer period of time, and observation groups using ML have been shown to perform better than control groups using more traditional methods. [10]

3 Virtual reality

Virtual reality is a visual- or audio-visual interactive interface, which immerses a user in a digital three-dimensional (3D) environment with the use of a stereoscopic high-resolution display headset that spans the entire field of view of the user. The headset has motion sensors that allow users to look around in a virtual environment by turning their heads. The interaction within the environment is usually controlled with the use of one or two motion-sensitive handheld controllers. A selection cursor is projected into the virtual environment, and many VR systems also project a virtual 3D representation of the controller to make the interaction more intuitive. The controller is used to select interactions within the virtual environment, and sometimes it is also used for moving within said environment. VR videogames use these controllers for various actions in combination and often employ the full functionality of a controller in both hands. VR implementations are often divided into two categories. VR with six degrees of freedom (6DoF), also known as room-scale VR implement tracking beacons that are installed in the room around the user, and these beacons allow the body movements of the user to transfer into the VR environment, so the user has a larger range of movement and interaction options within the virtual environment. [11] Some 6DoF VR systems also allow the user to define the "playing area" of the room inside which the system can track the movements of the user. VR with three degrees of freedom (3DoF) includes tracking of the orientation of the head of the user and the ability to select things using the controller, but the movement of the user in the room is not used as an input method, as illustrated in Figure 2 A. The full range of spatial interactions including rotation and translation is illustrated in Figure 2 B.

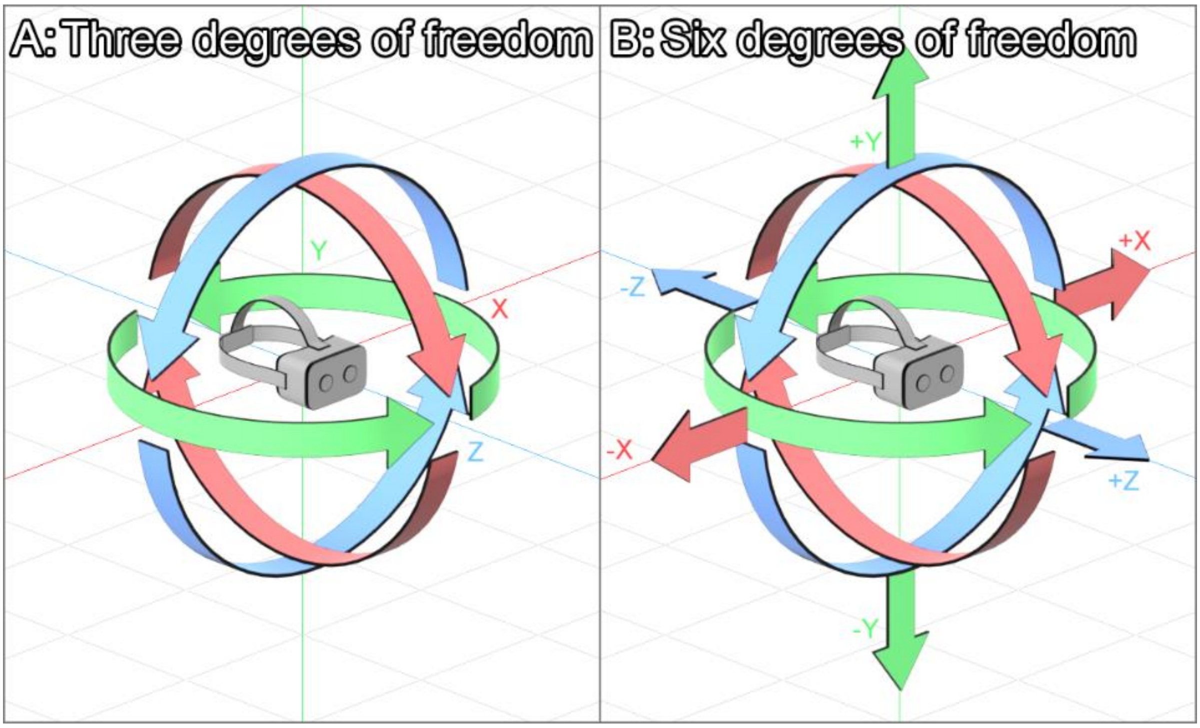


Figure 2: Degrees of freedom

The controller in a 3DoF setup essentially acts like a traditional PC selection cursor, giving 2-dimensional control over the interface, as the position of the controller cannot be translated to additional axes of input. 3DoF VR systems often employ a 3D representation of the controller within the virtual space, but it has a default position approximating where the controller could be in relation to the eyes of the user, instead of a true relative position reflecting the actual real-world position of the controller. The 3D representation of the controller can still receive rotational data and can accurately reflect its orientation.

Virtual reality as a tool for training has been explored by various institutions and companies. VR introduces the possibility of a student being able to view the subject of the training up close and in detail. In certain implementations, direct interaction can train them in the use of a skill. For example, a virtual simulation of a basketball court can allow users to train the motor skills of successfully throwing a ball into a basketball hoop. Improvement in proficiency based on VR training has been recognized. [12] In medicine, surgeons can prepare for an operation using virtual interaction with a 3D model of a patient that was generated out of data collected using computer tomographic scans and magnetic resonance imaging. The use of simulation has shown to increase the proficiency of surgeons as well as to decrease surgery complications. [13] The operation and maintenance of large and complex machinery can be trained using interactive virtual reality. Users can virtually move around the machine, interact with various parts in ways that exactly replicate the real-world function of the device, and receive detailed instructions. [14] These are examples of VR being useful in educational settings where direct interactivity with the subject matter is the most useful form of training. However, there are other related technologies that can be used for education in less intensive ways.

3.1 360° video

Increase in data storage capacity and data transfer bandwidth has introduced the possibility of using 360° video, which can be viewed through a VR headset. Playback and interaction with 360° video are done within a 3DoF implementation of VR, as only the head orientation of the user can be used to orient the viewing angle of the video. Movement within the space in a 6DoF VR setup cannot translate to altering the perspective of the camera within a pre-recorded video. 360° video is spherical, omni-directional video captured using multi-lens cameras that can simultaneously record their entire surroundings as multiple pieces of footage. These pieces are then algorithmically stitched together to form a seamless, spherical image that displays the full scene as a single video, as illustrated in Figure 3 B. In contrast, Figure 3 A illustrates a real-time 3D-rendered space, where the objects consist of 3D-models and the VR user is capable of moving around and potentially interacting with the environment dynamically.

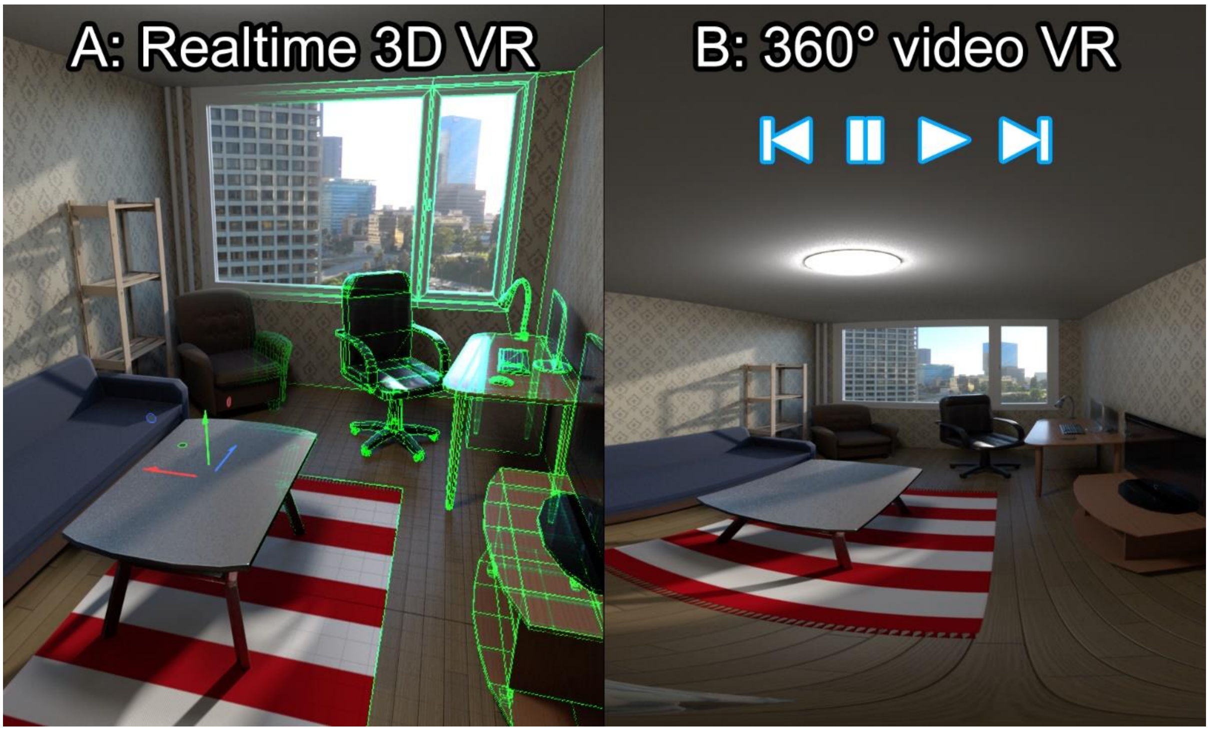


Figure 3: Real time 3D VR and 360° video VR

Until relatively recently, 360° cameras only had the capability of recording a monocular view of their surroundings using two or more camera elements. One element captures a wide-angle view from the front, and another element does the same from the back. Modern 360° cameras have a spherical array of camera elements arranged in a way that allows depth information to be recorded, as two adjacent camera lenses essentially act as two human eyes, producing spherical footage that is also stereoscopic. Simply having two cameras is not enough, because the user can look around in the 360° video, so looking sideways would entirely remove the stereoscopic disparity and the perception of depth. Therefore, omnidirectional stereo approximation is used. This is a set of algorithms that stitch together footage from a spherical array of cameras in a way that ends up with one video for the left eye and another for the right eye, and at each point of the image, the perspective is calculated so that a user looking into that direction experiences the stereoscopic disparity that creates the impression of three-dimensional depth. [15]

There has been some experimentation on the field of 360° videos in education. According to those studies, 360° video is an affordable alternative to true VR solutions. [16] As opposed to the use of 360° video, proper VR solutions require high-fidelity 3D modelling and software development expertise. Also, due to the use of true 3-dimensional depth via 3D-models, they benefit most from the use of a dedicated VR setup that implements six degrees of freedom, as depth perception is amplified with the addition of motion parallax. The use of 360° video only requires the subject matter to be filmed and a playback system can be very simple. Proprietary 360° video solutions often have their own playback systems that do not require extensive customization, although they usually facilitate the easy addition of interactive elements. For example, the user can see an icon displayed on a specific part of the video and clicking on the icon can start the playback of another video on the relevant sub-topic. This property can be combined with the principles of micro learning that are discussed in Chapter 2. The use of a proper VR headset is not strictly required and only three degrees of freedom are required. 360° video content can be consumed on a device with a traditional 2D display, such as a desktop PC, smart phone, or a tablet device. Naturally, if the 360° video in question is stereoscopic, a standard 2D display cannot convey the 3-dimensional depth of the footage without additional equipment. Affordable hardware designed to allow a smart phone to be used as a VR display with three degrees of freedom is available. This hardware consists of a headset with a phone attachment slot and can potentially also support stereoscopic 360° video.

3.1.1 360° video limitations

When producing 360° videos to be viewed through VR goggles, it is a good practice to have a clearance of space around the camera. Users have been known to feel uncomfortable when something can be perceived to be too close by and the effect is further amplified if it is another person. Elevation factors can also introduce discomfort. Raising the camera up high may give a better view of something, but in certain situations it may have undesired psychological effects. [17] [18] Moving a 360° camera while recording needs to be handled very carefully, preferably with a proper gimbal stabilization system that maintains a smooth transition from point A to point B within the space. Movement needs to be performed without altering the angle of view, as changing the angle is supposed to be under the control of the user via the three degrees of freedom. Motion sickness is a very common occurrence when the view of a camera has sudden changes, even when viewing something on a desktop display. In stereoscopic footage, due to the array of camera lenses being horizontal, depth perception does not exist for areas directly above and directly below the camera. Also, during video processing of stereoscopic footage, because the stitching algorithm does not know exactly what it is looking at, it can misinterpret parts of the footage and produce distortions. Straight lines may appear bent, or parts of details may get lost in the stitching process as the algorithm prioritizes a different segment of the image to create a more consistent whole. The severity of these distortions increases the closer those details are to the camera. Below minimum distance, the cameras are physically incapable of capturing a single part of the image with multiple lenses and thus the correlation between the left and right eye cannot be calculated by the stitching algorithm. Therefore, it is good practice to keep at least one meter of distance to any objects around the stereoscopic camera.

3.2 Educational applications

Pedagogical experts have recognized the compatibility of 360° video and existing pedagogical concepts such as blended learning, flipped classroom approaches and constructivist ideals. The sense of physical presence enhances the engagement of students with the subject matter, as well as motivation. Interactive elements facilitate the active participation of students in the learning experience. These are recognized as key contributors in positive learning outcomes and academic success. Some studies have indicated that the use of 360° video in education may have a slight distraction effect on the viewer due to the novelty of the technology. [16] [19] However, it is also proposed that the immersion of the viewer and their sense of presence helps in conveying the learning subjects in a less abstract manner than listening or reading, and thus the benefits outweigh the downsides. [16] When considering the perception of the public of 360° video in education, data analysis of social media trends has indicated that the majority of people have either a positive or neutral impression of the technology as a useful tool. [19] The visual element of this technology may also work to make the learning subjects appear more interesting right from the start. For example, a selection of 360° video thumbnails specifically tailored to represent the subject matter in a way that draws the attention of the user can make the prospect of consuming the educational material more appealing. This is where micro-learning can take advantage of the subtleties of visual marketing. The creation of working online video thumbnails is a highly valued skill as it is art with a function, and it is difficult to assess its effectiveness. Proper application of this skill can enhance the engagement with video-based learning materials.

4 Industrial additive manufacturing

4.1 Metal additive manufacturing technologies

The cutting edge of additive manufacturing involves the production of metal objects. The training of the use of these technologies is of high importance, and a large portion of the knowledge is also applicable to other forms of AM.

4.1.1 Powder bed fusion

In powder bed fusion, a thin layer of metal powder is distributed onto the build plate of the build chamber, and an energy source selectively melts the powder into solid shapes. After each melt, the build plate is lowered, a new layer of powder is distributed and thus the object is produced layer by layer. This setup is illustrated in Figure 4.

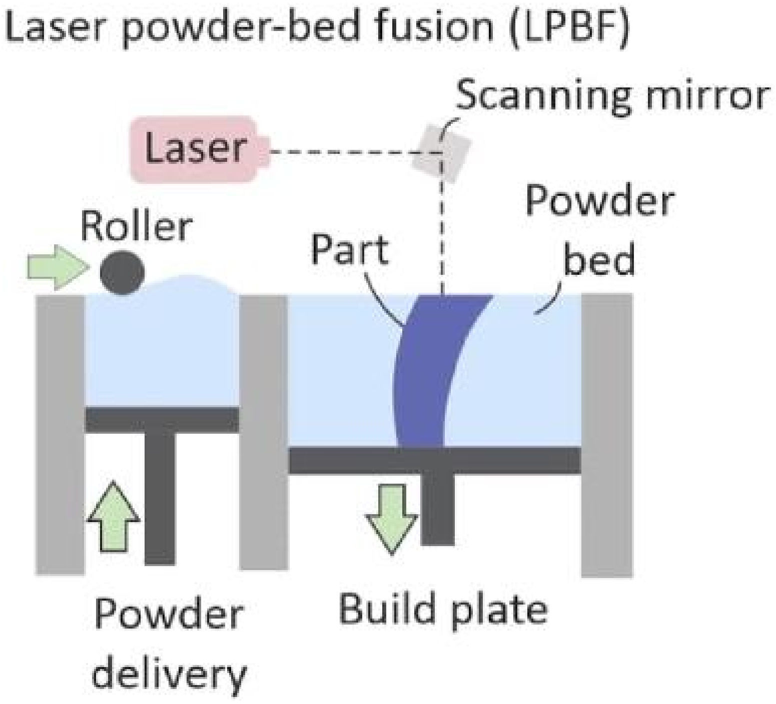


Figure 4: Laser powder-bed fusion

After the AM process is finished, the remaining powder can be recycled. In laser powder bed fusion (LPBF), lasers are used as the energy source for the melting of powder. The process is conducted in an atmosphere of inert gas to remove condensate, prevent oxidation and to prevent explosion of powders due to high temperatures. [20]

In electron beam powder bed fusion (EPBF), high-energy electron beams are used to melt metal powder instead of lasers. This process is conducted in a high vacuum and with pre-heated powder to prevent oxidation, contamination, and the so-called smoking phenomenon, which is the scattering of powder particles due to accumulation of repellent negative charge. [20] EPBF is illustrated in Figure 5.

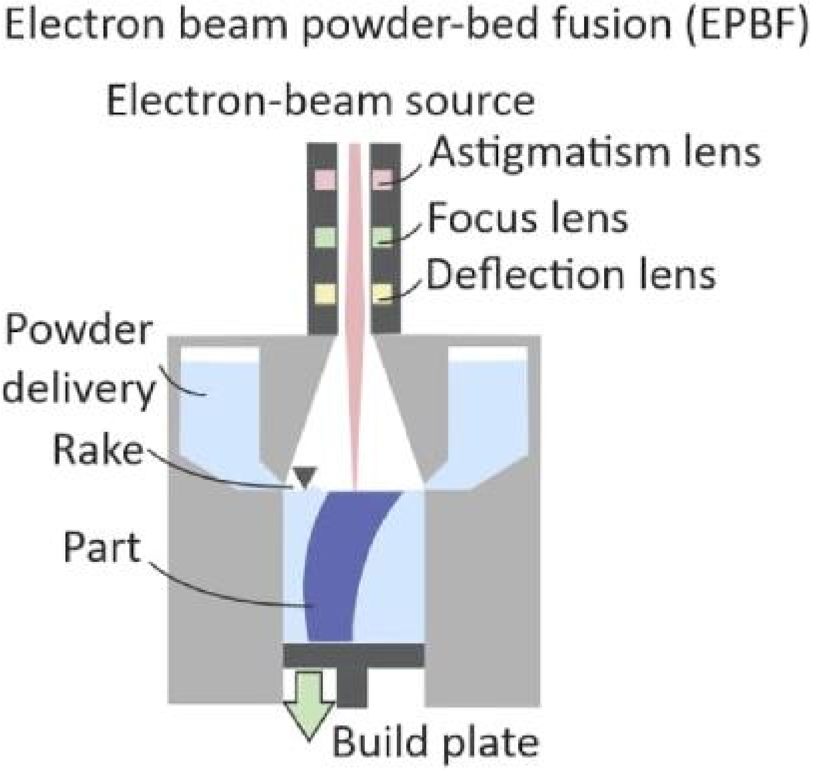


Figure 5: Electron beam powder-bed fusion

4.1.2 Directed energy deposition

In directed energy deposition (DED), an energy source is used in combination with a material feeder to place and melt material in specific positions simultaneously. This is illustrated in Figure 6.

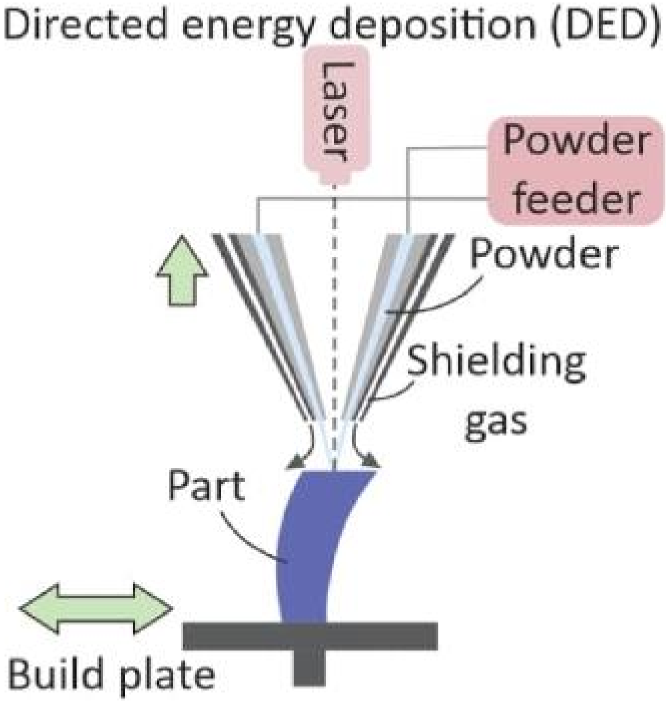


Figure 6: Directed energy deposition

With lasers this is called laser metal deposition (LMD). The metal material in different LMD systems comes either in powder or wire form and is introduced into the melting area via a nozzle. Some LMD systems move the nozzle upwards after each layer of the object has been manufactured, and other systems move the build plate downwards instead. The advantage of LMD is the lower amount of waste material left over to be recycled, since material is only deposited directly into positions in which it is needed. [20] Wire arc additive manufacturing (WAAM) uses a metal inert gas arc welder to deposit welding wire as the build material. WAAM is used as the subject of a stereoscopic 360° video experiment in Chapter 6.2.5.

4.1.3 Binder jetting

Binder jetting (BJ) has a build plate on top of which a layer of powder is introduced in the same manner as in powder bed fusion, but instead of an energy source melting the powder, a liquid binding agent is deposited onto it via a printhead, and the binding agent then hardens and binds the metal particles together. The build plate is lowered after a layer is finished and another layer of powder is introduced. This is illustrated in

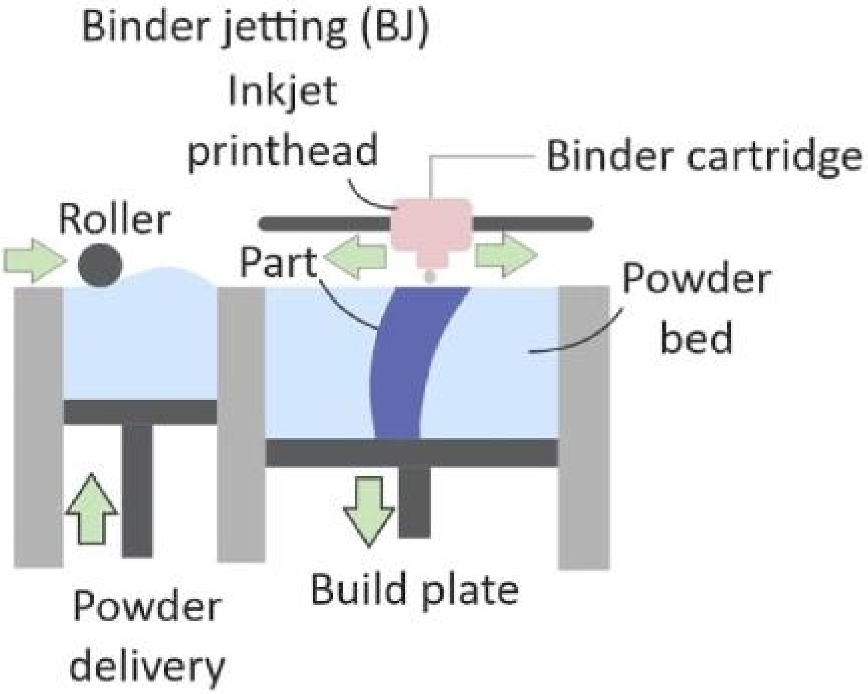


Figure 7: Binder jetting

After all of the layers have been produced with the binding agent, the part is removed from the powder. A furnace is then used to burn out the binding agent, leaving a porous and fragile part. In the next step, a powder of low melting temperature is infiltrated into the porous structure in order to strengthen it. A final sintering process in a high-temperature furnace partially melts the metal powder, filling leftover voids and increasing density. These post-processing steps make manufacturing time-consuming and costly, and the increase in density also causes some shrinkage in the final object. [20] In a way, this AM method is reminiscent of metal injection moulding, it is simply performed without a mould and thus does not suffer from the limitations of that technology.

4.2 Misconceptions about AM

A common misconception regarding additive manufacturing is that it is a new technology that can help a manufacturer create the same things they've already been making using more traditional methods, but in a new way. Firstly, AM is not a new technology at all, having started with, among other technologies, stereolithography in the 1980's. [21] Secondly, using AM just to accomplish the same things using a different process is a waste of potential. In other words, an object designed for traditional manufacturing is best manufactured traditionally. Adopting AM as a practice requires the adoption of completely different ways of thinking about design, and manufacturing processes need to be considered from completely different angles. For those who have been aware of AM these few decades, there may still be misunderstanding regarding how far the technology has progressed. The ability to quickly produce mock-up products that can be iterated with consequent AM phases, also known as rapid prototyping, may have been cutting edge at some point. The people who have engaged in that practice may not have realized that with modern advancements, AM does not need to be limited to mock-ups, but instead can be used to create fully functioning end products out of the proper materials. [22] AM opens new possibilities of design that are not possible to utilize in other manufacturing methods. It also comes with its own challenges that need to be considered for successful adoption of the technology. When considering the use of additive manufacturing, the manner by which the product can be designed differently in a way that takes advantage of the properties of AM must be considered.

4.3 Traditional manufacturing vs additive manufacturing

Traditionally manufactured parts need to be designed according to the limitations of their respective manufacturing methods. An example of a widely used traditional manufacturing method is metal casting, which refers to the melting of metal into a mould, in which the material hardens, after which the mould can be removed. Casting into a mould first and foremost requires a mould. It is also required for the object to be of a shape that can by physically extracted from the mould, unless the mould is disposable and can be destroyed, or the mould consists of multiple interlocking parts. In any case, the object needs to be able to detach from the mould when the casting is complete. Casting usually also leaves visible seams between mould sections. In metal injection moulding, metal powder and a binding agent is mixed into a feedstock, which is then injected into a mould. A post-process is then applied in order to remove the binding agent and to densify the metal, reducing the volume of the object by 15-20%. Injection artefacts in the sections where material is being injected into the mould often remain. These may require further post-processing to remove if necessary. Also, it is often not feasible to produce customized moulds for singular custom objects because producing the moulds can be a complicated and time-consuming process. [23] Binder jetting is an AM technology that similarly uses a binding agent and requires post-processing, but it requires no moulds and leaves no injection artifacts. [20]

In contrast with casting into moulds, additively manufactured objects can take shapes that would not be easily removable from a mould. They can have complex internal structures that would normally prevent them from being detached from moulds. An object additively manufactured using powder bed fusion or binder jetting can simply be removed from the powder bed and any excess powder is left behind. An object manufactured using directed energy deposition is built layer by layer from the bottom up. [1] No seams or injection artefacts are left after production. Also, before an object can be cast into a mould, the mould must first be produced in the first place, which is not necessary in AM. Additive manufacturing can also remove some of the limitations of producing moulds for casting, by applying AM to the creation of the mould itself. [24] [25] This, in turn, can help casting produce customized objects.

Machining is another example of traditional manufacturing. It refers to the use of various mills, lathes and cutting devices to remove material from an object in order to arrive at the desired final shape. These methods fall under the definition of subtractive manufacturing (SM). Historically, machining was performed by human operators manually, but after the industrial adoption of microprocessors, machining in the manufacturing industry has widely utilized computer numerical control (CNC). CNC allows automated subtractive manufacturing systems to precisely remove material using mathematical parameters specified by a computer aided design (CAD) blueprint file. Because the SM technologies are computer-controlled, limited amount of individual object customization in small batches is possible. [26]

The fact that CNC machining requires the application of tools that remove material from an object, those tools introduce limitations due to the necessity of them reaching the requisite areas. Cavities cannot be designed too deep and having to reorientate the object to allow tools to access areas increases the risk of positional errors. Also, the smaller a detail is, the smaller the tool needs to be, and that adversely affects manufacturing time. These limitations often lead to compromises in design that result the end products having higher mass, higher material cost and more requirement for assembly from multiple parts. [27] With additive manufacturing, material is added where it is needed instead of removed from where it is not needed. The design does not need to consider tools being able to reach sections of the object and the object does not need to be reoriented during manufacturing. The shape can also be optimized to have minimal mass and to use minimal manufacturing material.

4.4 Design for additive manufacturing

Design for additive manufacturing (DfAM) means the fundamentally different approach to designing products to be manufactured with AM as opposed to traditional manufacturing methods. Objects do not need to be designed to be parts to be cast, assembled, or carved out of blocks using a CNC device. In fact, structures that are interlocked from the start with no need for assembly can be manufactured using AM. For example, a hinge can be additively manufactured so that its axle is already inserted into its counterpart, with an interior block that prevents the removal of the axle. Such a structure cannot be manufactured traditionally because an axle like that could not be inserted without disassembling the structure. Another thing that is often said about AM is that complexity is free. Regardless of whether a piece of an object consists of a solid wall or a complex grid, the object must still be manufactured layer by layer. Therefore, choosing the grid structure over a solid one can reduce mass and material usage without adverse effects on anything else, including production time. Another important thing to note about 3D-modelling for AM is that the objects need to be solid structures where the entire shape is defined, with no missing geometry. When all of the geometry is defined, the model can be sliced to layers. These layers represent the layers that are to be laid on top of one another to produce the final object. The number of layers is determined by layer thickness, with lower thickness resulting in more layers, longer manufacturing times, and generally, results that have higher precision.

4.4.1 Optimization

In computer-aided design, various properties of objects can be simulated, and those simulations can be used to inform further refinement of the structure of the object. For example, by simulating the mass of the material, the effects of gravity can be anticipated and accounted for, as demonstrated in Figure 8.

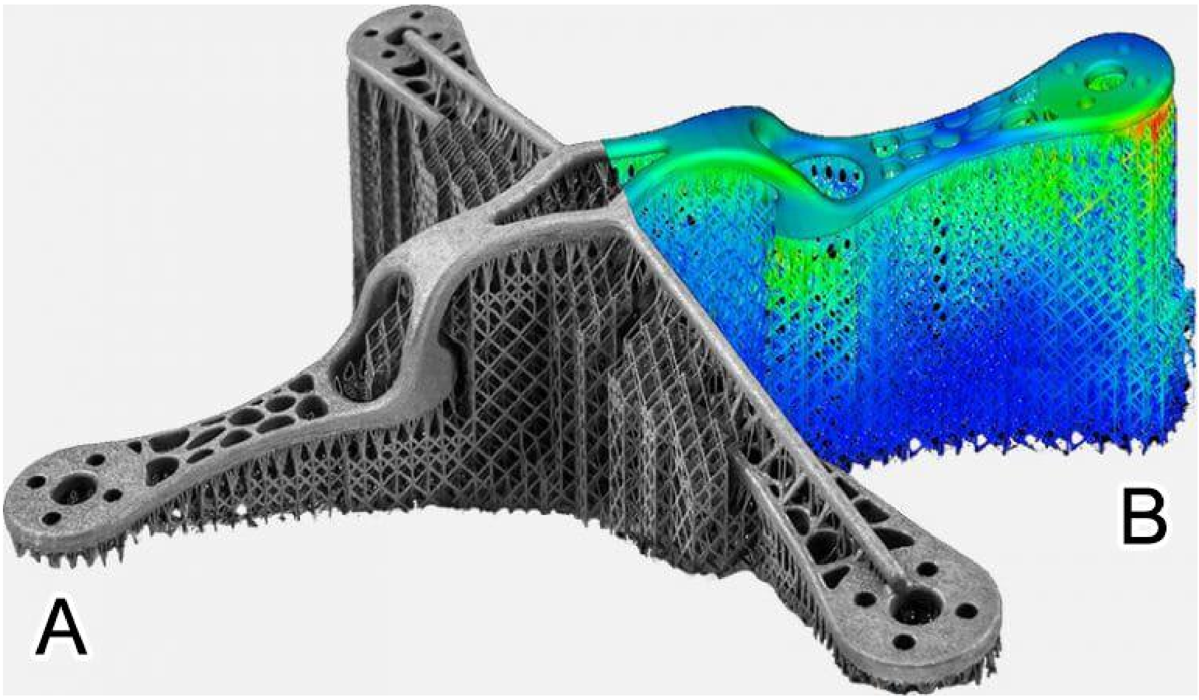


Figure 8: Finite Element Analysis

The segment visible on side A is a photo of the additively manufactured object. The coarse grid structures visible on top of the object are a result of topology optimization, which decreases mass while maintaining structural integrity. This is made possible by the simulation of various stresses on the material. On side B of Figure 8, a digital image of the finite element analysis of the object, the gravitational stresses are shown in a spectrum of colours, with red having high stress and blue having low stress, and the rest being in between. This is the result of simulating gravitational effects, and it has informed the generation of the complex grid of support structures below the object. After the support structures have been generated onto the 3D-model, the simulation can be run again in order to determine if the newly added supports are adequate. [28] After the object is additively manufactured, the support structures below it are removed in the post-processing phase.

In traditional manufacturing, parts of a structure may need support struts that bear the load and stress of the structures around them. Large sections that are welded onto others may require the drilling of holes in order to decrease mass or improve air flow. In additive manufacturing, the simulation of the various stresses and simulation of air flow and heat distribution can be used to determine the type of structure that is required so that the object fulfils its intended purpose without any aspect of those considerations being compromised by things mandated by traditional manufacturing methods. Many solid segments of objects can be altered to comprise of different grid structures instead, to reduce mass and the use of manufacturing materials without changing the function of the object.

Figure 9 demonstrates the optimization potential between traditionally manufactured and additively manufactured mechanisms. [29] The mechanism illustrated in Figure 9 A is traditionally manufactured, with little consideration for mass optimization or material savings. The mechanism illustrated in Figure 9 C was machined using CNC and has smaller mass but identical function. The mechanism illustrated in Figure 9 B used computer simulation to determine the strength requirements of all segments of the mechanism and was additively manufactured, leading to the smallest possible mass and manufacturing material usage, still retaining identical function. Also, the mechanism was capable of having segments that would not be possible to produce using traditional manufacturing methods. Those segments can further optimize the strength of the mechanism with no impact on its mass, and it can sometimes even reduce the mass.

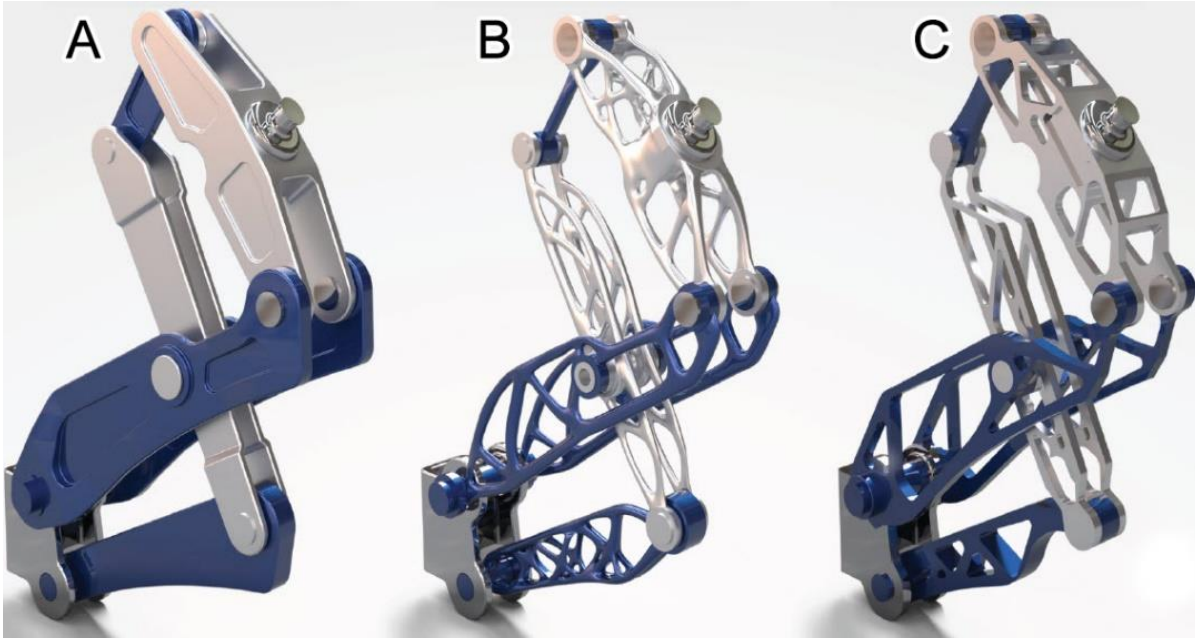


Figure 9: Optimized geometry

When it comes to simulation in the designing of additively manufactured objects, the effects of gravity, torque, tensile strength, and other properties of solid objects are not the only thing that a computer can anticipate. Simulation also makes it possible to optimize the aerodynamics and hydrodynamics of structures that involve the flow of substances like air or water. Traditionally manufactured channels and conduits can be optimized to an extent, but the limitations of the physical manufacturing processes preclude some of the possibilities of optimization. Hewlett-Packard applied fluid dynamic simulation to a piece of their own Multi Jet Fusion polymer 3D printer, a cooling air duct for its printhead. The original part of the device is displayed in Figure 10 A.

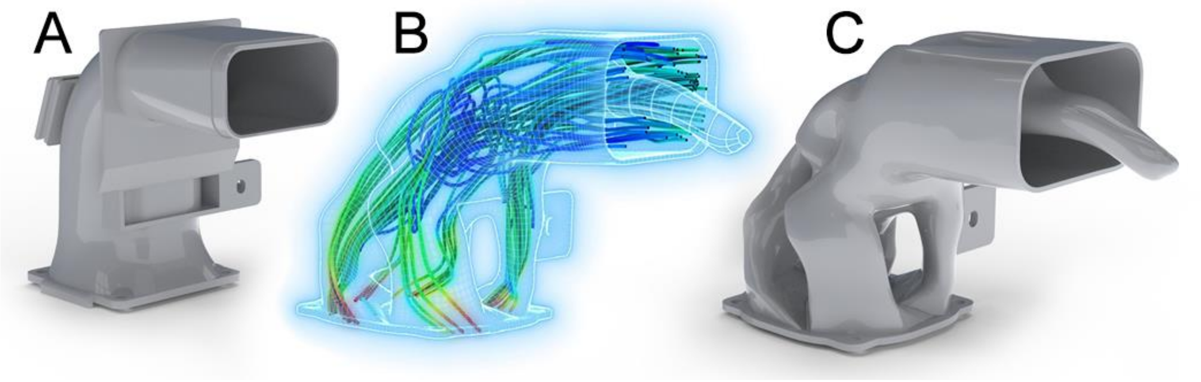


Figure 10: New air duct of the HP Multi Jet Fusion 3D printer

This part was designed for a traditional manufacturing process and performed adequately but not optimally. Simulation of air flow through the duct allowed the designing of a variant where the flow is optimized by channelling it through a more complex and more organic-looking network of ducts. This simulation is illustrated in Figure 10 B. Iterating designs through the simulation resulted in a new additively manufactured design for the part with a more optimal air flow, as seen in Figure 10 C. [30]

One of the most important aspects of DfAM is to consider what kind of new things could be manufactured using these methods, not simply converting existing products to be additively manufactured. Existing products can be upgraded to take advantage of this technology, but if a product was originally designed to be manufactured traditionally, the question whether it was already compromised in some way by that traditional design thinking must be asked. AM makes it possible to design products with functionality that would not be possible to achieve using traditional methods. For example, a rocket engine can simultaneously incorporate flow-optimized conduits, interlocking nozzle designs and complex internal lattice structures in a single piece that requires no assembly, as shown in the cross-section of a rocket engine in

Figure 11 A. Power plant heat exchangers can incorporate an interweaved network of flow channels inspired by the biological structures in a human lung, to optimize the heat transference from a hot substance flowing through one channel to the coolant flowing through the other, as shown in the cross-section of a GE Research heat exchanger in Figure 11 B. [31]

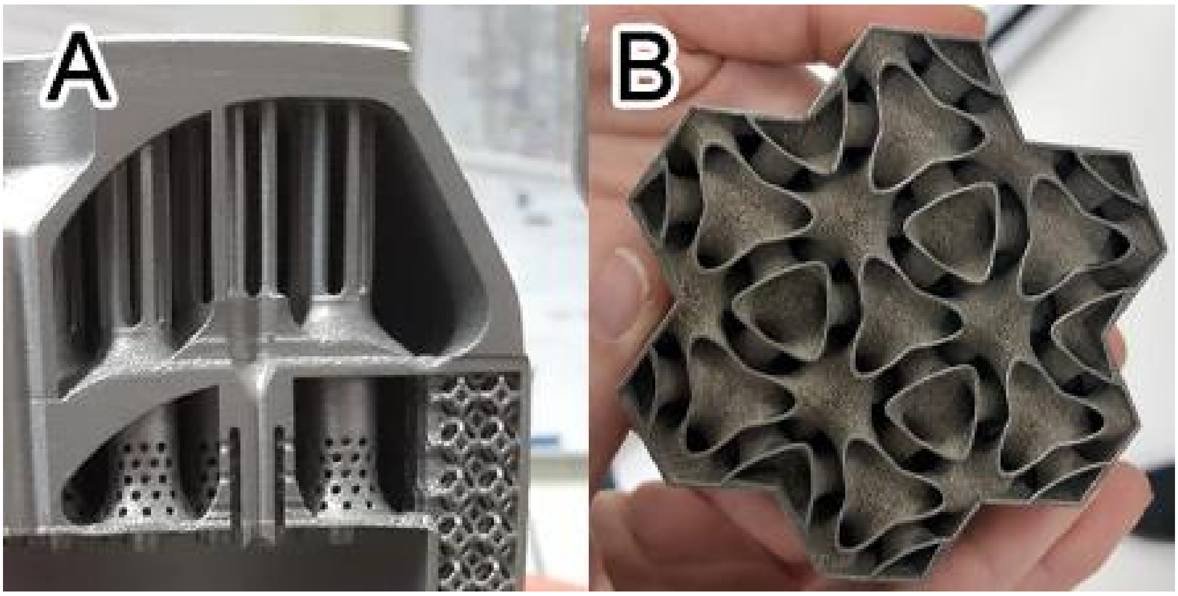


Figure 11: A: Rocket engine cross-section, B: GE Research heat-exchanger cross-section

Figure 12 illustrates a cross-section of an additively manufactured rocket engine, with internal structures in its design optimized by artificial intelligence.

Figure 12: A cross-section of a rocket engine optimized by artificial intelligence. Picture: Patricia Nyamekye. The object was designed using algorithms by Hyperganic and manufactured by EOS.

4.5 Challenges of DFAM

4.5.1 Heat accumulation and thermal deformation

Some AM methods, e.g., laser powder bed fusion (LPBF), electron beam powder bed fusion (EPBF) and directed energy deposition (DED) use a source of energy to melt materials with heat. When dealing with this type of AM, the effects of heat need to be considered. When producing an object layer by layer, heat accumulates unevenly depending on the structure of the object. The heat from the manufacturing process can keep structures malleable, and subject them to the effects of gravity, allowing spontaneous deformation of shapes. By simulating the thermal properties of the AM process, the designers of objects can determine whether or not to adjust the shape in order to prevent deformations. Figure 13 illustrates the difference between the heat distribution of two different designs.

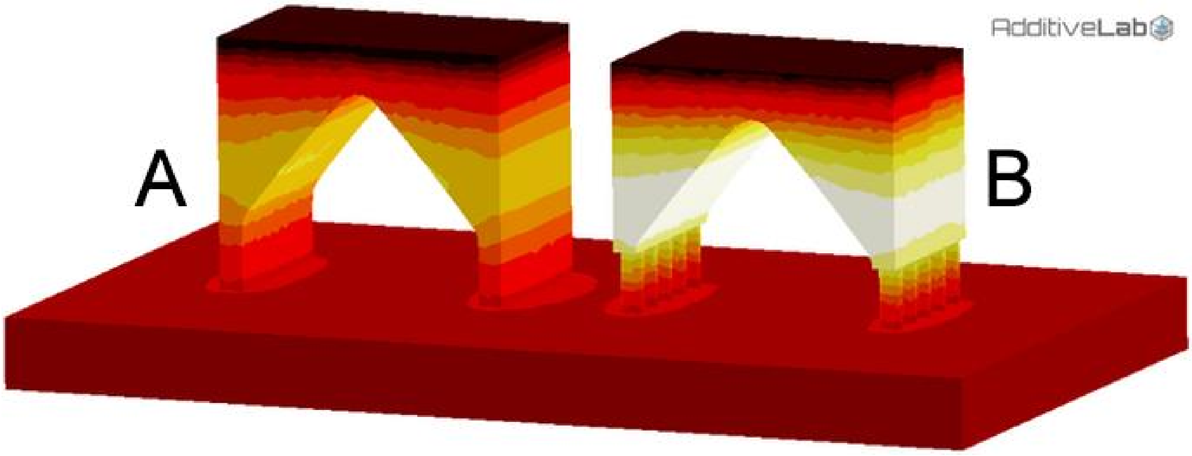


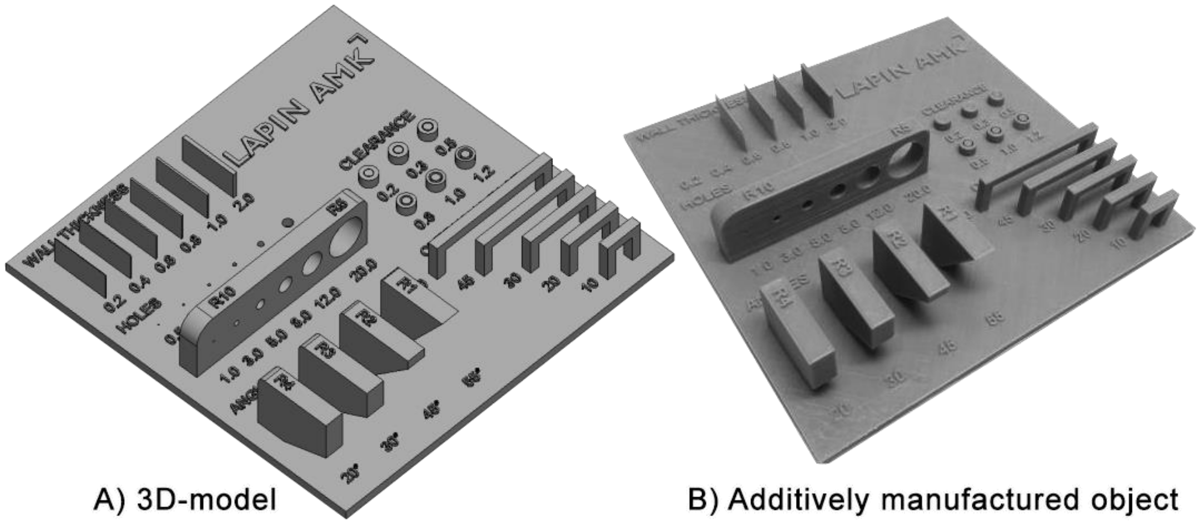
Figure 13: Heat simulation.

In Figure 13 A, the object includes thicker supports underneath that attach it to the build plate of the AM device. This initially causes heat to accumulate in the base of the manufactured object, but the heat is distributed more evenly, and it conducts better into the build plate as more material is added onto the object. The thick supports require some extra work when removing the object from the build plate after the manufacturing process is finished. In Figure 13 B, multiple thin support structures are used instead. Thinner supports allow easier removal of the object from the build plate. Initially, heat is able to escape more efficiently because it is radiating and being conducted away from a larger number of shapes of lower volume. However, as more material is added onto the object, the thin supports end up acting as an insulator. The thick sections of the main shape above retain more heat and as the mass of the object increases, the risk of thermal deformation increases as well. [32]

4.5.2 Dimensional accuracy

Another important thing to consider is the accuracy of the manufacturing capability of the AM device. Depending on the technology that is used, minimum wall thickness and minimum gap clearance varies, and values provided by the manufacturer may not always be accurate. It is best practice to evaluate these capabilities by having the device manufacture a test piece with geometries of various properties, then compare the produced object with the 3D-model on which it was based.

Figure 14 by Ari Pikkarainen shows the discrepancies between the 3D-model and the additively manufactured object.



A) 3D-model

B) Additively manufactured object

Figure 14: Additively manufactured test object showing discrepancies

Figure 14 A is a render of a 3D-model designed with various properties meant to evaluate the limitations of an AM device. These properties include wall thickness, gap clearance, hole diameter, angle of overhang and length of unsupported overhang. Figure 14 B demonstrates the results of a test product based on the 3D-model. The AM device was incapable of properly producing the narrowest walls and smallest gaps. Some failures were contradicting the specifications provided by the manufacturer of the device. [33]

4.5.3 Staircasing

All AM technologies must deal with the factor of layer thickness, which introduces an issue commonly known as the “staircasing” phenomenon, as illustrated in Figure 15.

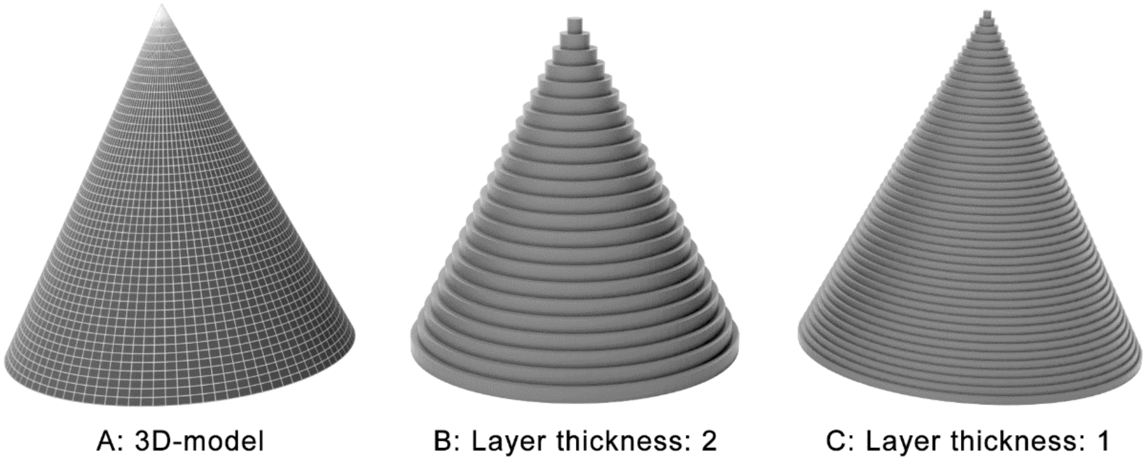


Figure 15: Staircasing phenomenon

When a 3D-model has angles that are not horizontal or vertical, those angles end up consisting of staircase-like geometry on the manufactured object, as illustrated in Figure 15. Figure 15 A shows the geometry of the digital 3D-model. Figure 15 B illustrates how that model would exhibit staircasing after being additively manufactured. Figure 15 C illustrates how that effect is mitigated with half the layer thickness of the previous iteration. Decreasing layer thickness increases the time it takes to additively manufacture an object.

Instead of trying to avoid all of it during the initial production, post-processing of additively manufactured objects can help mitigate the staircasing phenomenon, along with other surface imperfections. Treatments using various abrasive mechanisms and chemicals that can reduce the surface imperfections caused by staircasing. [34]

4.5.4 Occupational safety aspects of AM

Metal additive manufacturing in most cases utilizes powder comprised of very small metal particles. These particles are harmful to breathe and can cause skin irritation and damage to mucous membranes. Therefore, powder and powder containers must only be handled when wearing protective gloves, protective clothing, and a filtered breathing mask with eye protection. The same is true for the process of extracting manufactured objects from the build chamber, and for the object post-processing. Many AM devices include a closed-loop handling system which gives the user access to the build chamber without having to open it. [35] [36] With binder jetting technologies, the chemicals used for the process pose their own safety hazards that can be mitigated with the use of protective clothing. [36]

The particles also have a high surface area to volume ratio, which makes them potentially highly reactive when aerosolized. This causes a fire- or explosion hazard. It is recommended that powders are stored in designated powder handling areas with additional fire safety measures. Electrostatic discharges can ignite aerosolized powder, so electrostatic dissipative flooring and other grounding measures help to mitigate fire hazards. [36]

Metal AM also often uses inert gas in its operation. It is important for AM facilities to include oxygen sensors to monitor the contents of the air. An inert gas leak in a confined space can displace enough oxygen to induce asphyxiation. [36]

In direct energy deposition AM, ionizing radiation is a hazard to be considered due to the higher accessibility to the source compared to powder bed fusion. Safety screens to prevent user exposure and radiation monitoring can be used to mitigate this hazard. [37]

4.6 Costs of AM

Research indicates that additive manufacturing is cost effective in the manufacturing of small batches and centralized manufacturing that brings the creation of all parts of a larger whole to a single location. Many studies agree that AM is not cost effective in large scale mass production compared to traditional manufacturing methods. [38] [39] [40] However, efficient utilization of the build plate allows the manufacturing of many objects at once and some studies have indicated large volume manufacturing to also be cost-effective. [41] Measuring the costs of AM are difficult due to the multitude of ways it can impact different aspects of production. For example, a supply chain in traditional manufacturing has many links, but with AM the length of the chain can be reduced, as transportation of parts from multiple production facilities, need for storage inventory and even assembly itself can be reduced. Reducing the length of the supply chain also mitigates risk of links of the chain experiencing failure and disrupting the entire system of production. Being able to manufacture on demand also means that large numbers of parts will not end up sitting in a warehouse, becoming obsolete, but updated and specialized custom variants can be designed and additively manufactured. The need for forecasting part demand is also reduced. [39] [42]

The majority of the costs of AM come from investment into the equipment itself and the manufacturing material. The material can in some cases be ten times the cost of a traditional manufacturing equivalent. Therefore, it is a significant investment with indirect savings that can come from many different directions. However, AM machine prices and efficiency have decreased significantly in the last few decades, by about half between 2001 and 2011, and further adoption of additive manufacturing can decrease prices of both equipment and materials. [40] Recycling of manufacturing material and optimization of object shapes in ways that are not possible in traditional manufacturing also contribute to savings. When compared to traditional methods that utilize moulds, AM also has the advantage of requiring no moulds to be produced. Other factors also impact the costs in various ways, including the orientation of objects in the build chamber and the build time depending on layer thickness. The value of new capabilities of objects that can only be additively manufactured is difficult to estimate. They may be able to perform new functions, be longer-lasting in use, or reduce the material or human resources required for their use. [39] There have also been relatively few studies regarding the effect of energy consumption and the need for post processing in the costs additive manufacturing. [38]

5 Industrial training of additive manufacturing

Adopting additive manufacturing as a common practice in businesses is not a straightforward thing. In many fields of industry, the potential of 3D printing is being discussed, but actual expertise in the field of AM is concentrated in those who actually specialize in AM. The technology is being hyped up with little substance to back it up. This practice also paradoxically simultaneously exhibits overblown impressions of the technology as a miracle cure that can effortlessly revolutionize everything, and underestimations about its actual potential stemming from ignorance of its actual applicability and properties. This is why industrial training is needed in the field of additive manufacturing. [43] [44] There already exists some training material as well as certification in the field of AM. Some universities have introduced AM training, but it has been mainly aimed at students and scientists rather than companies that need to gain the necessary expertise in order to decide whether or not to adopt the technology. [45] Industry standards are also important, and some have already been developed, to set requirements for recognized expertise in the field, and to inform those engaging in AM about the best practices regarding the technology. [45]

The Knowledge Transfer on Rapid Manufacturing project conducted a survey on industrial additive manufacturing training needs. Approximately 150 survey responses were gathered, from 15 countries, mostly from Europe. The responses indicate that expertise in metal AM is significantly lower than non-metal AM, and the outsourcing of AM is significantly more popular than companies investing in the technologies themselves. Overall, the results indicated relatively low AM knowledge among companies, and large companies had lower levels of knowledge than small or medium-sized enterprises. The survey also evaluated the popularity of E-learning, the method of receiving training online with little disruption to the daily activities of the company. The results indicated that this approach to the training of AM was received positively. [45]

5.1 Training resources

Some training resources are available for free online. For example, the European Powder Metallurgy Association offers an introductory guide to the fundamentals of AM. Their aim is to increase awareness of AM technologies, to improve the understanding of the benefits of metal AM, and to assist in the development of standards in AM. The material introduces the vocabulary and basic concepts, the benefits and limits of AM, the different metal AM technologies, and metal powder properties. It also includes familiarization to design guidelines. Finally, case studies help to solidify the knowledge using real world examples. This training material is suitable for beginners and intermediate level trainees. The material does not include knowledge assessment, so trainees must determine how well they have absorbed the information themselves. Also, due to being an online reading resource without external links, it does not take advantage of videos or interactivity, and cannot properly demonstrate any of the technologies in any hands-on manner. [46]

5.2 Certification

SME, formerly known as the Society of Manufacturing Engineers, is a non-profit association of students and professionals dedicated to supporting the manufacturing industry in North America. They offer certification exams in the field of additive manufacturing on a fundamental and technician level. The fundamentals level certification CAM-F includes a comprehensive overview of AM, the seven AM technologies and basic safety guidelines. The technician level certification CAM-T focuses on the methodology of AM, including the seven AM technologies, processes, material selection, post-processing, and basic safety guidelines. Certification is accomplished via online- or paper exams. Applicants must score 70% on an exam in order to pass. The certification exam is available for a lower price to SME members and at a further discount for college students. [47]

6 Experimental part

6.1 Aim and purpose of the experimental part

Osuu ja Uppoaa, also known as O&U, is a research project attempting to identify the additive manufacturing training needs of small and medium-sized enterprises (SME) and to produce a micro learning -based virtual reality application to facilitate this training. The principles of micro learning are specified in Chapter 2. The O&U project takes place over a period of two years and is carried out in cooperation with the Turku School of Economics and the Faculty of Technology of the University of Turku. The main funder of the project is the European Social Fund (ESF), and the representative of the sponsor is the Central Finland Centre for Business, Transport, and Environment. The content in the training application is produced in Finnish. [48]

Small and medium-sized enterprises of various fields in Southwest Finland that could benefit from additive manufacturing were contacted at the beginning of the project in order to gather information about their previous knowledge and experience regarding AM and their need for training in the use of the technology. The companies that participated in the project were Brinter Oy, Afore Oy, Ajatec Prototyping Oy, Elomatic Oy, Drop Design Pool Oy, Koneteknologiakeskus Turku Oy, Suomen Hitsausteknillinen Yhdistys, VAK Oy and VS Automaatio Oy. After the development of the first version of the application was completed, an evaluation was conducted on its usefulness in industrial training of additive manufacturing, as well as generally relevant usability aspects and matters relating specifically to VR. A secondary experiment was conducted to evaluate and the significance of stereoscopic depth perception in VR video. Representatives of the involved companies participated in the testing of the application. Feedback gathered on the application can be used for verifying the viability of this format of industrial training and for refining the design of the application in the second iteration.

6.2 Experimental setup

6.2.1 The design of the application

The design process of the logical structure of the application and training content was conducted by the Osuu & Uppoaa project team. The author of this thesis was an integral part of the design process of the structure of the application and usability and also took part in testing during the evaluation phase. Initial design was formulated through brainstorming sessions and via the creation of mind maps and flowcharts to sketch out the structure of the application. The design session participants had expertise in the fields of education, additive manufacturing, and virtual reality, so that the correct breadth of information about the topic could be conveyed, in a manner that adheres to the principles of micro learning. The author of this thesis was tasked to ensure that the design results in a format suitable for virtual reality, with aspects of usability taken into consideration. The design was also informed by feedback provided by the participating companies that were mentioned previously. When a rough concept of the application had been created, the sub-contractor Elomatic Oy who would be responsible for the actual production was consulted regarding the design and how it would be realized within the parameters specified. The role of Elomatic was to conduct the filming of the 360° video content under the direction of the Osuu & Uppoaa project team, post-processing of audio, and the creation of the VR application based on designs specified by the project team. The 3dVista virtual tour platform [49] was chosen due to recommendation by the sub-contractor team at Elomatic Oy, who had prior experience with it. [50] The platform uses 360° images and 360° videos with three degrees of freedom in its interaction in virtual reality. VR-interface with three degrees of freedom was chosen as a target platform because when using 360° videos, the additional spatial interactivity of 6DOF is not required, and the application was also to be made available on PC and mobile platforms. Also, monoscopic 360° content was chosen because no additional value from stereoscopic depth was recognized during the design phase. This decision was later evaluated by the author of this thesis in a separate experiment conducted using stereoscopic videos. As the project progressed, new iterations of the application were produced by Elomatic, which was in turn evaluated by the project team, and the design was refined. Various volunteer test persons were also given the opportunity to test work-in-progress versions of the application and their feedback informed further refinement of the design. Version 1.0 that included all the planned content finished production on June 3rd, 2022.

The 3dVista application is capable of presenting virtual rooms with interactable elements placed within the view of the user and on surfaces so they appear to be part of the environment. The user can select those elements using the VR controller cursor, PC mouse cursor or tapping the screen on mobile. Each virtual room has a low number of interactable elements for the sake of clarity, placed close to the centre of the view of the user in the starting orientation of each room, to accommodate the presumed field of view (FOV). Having many elements would necessitate placing them at angles facing away from the default starting orientation, which could make it difficult for some users to notice them. The presumed horizontal FOV is lower than the 110° that the average virtual reality headset uses. This was partially informed by the fact that the project team uses Pico G2 4k standalone VR headsets for testing during development, which has a FOV of 101°.

The application is structured as a collection of nested menus projected into the virtual environment of the 360° video content. Various interactive elements such as text buttons appear on the surfaces seen in the 360° content at appropriate times, allowing users to engage with the content. The individuals involved in the content are also introduced with elements that list their names and titles. A return button is always present, allowing users to return to the previous menu. Sometimes, follow-up buttons appear that allow users to proceed to the next phase of the current topic. Additional content consists of standard videos, pictures and text screens, and the VR user contextually exits these elements by clicking outside the element in their field of view. On PC, the user can exit the content by clicking the X in the upper right-hand corner.

The application uses monoaural sound played through stereo speakers or headphones, and audio recorded in industrial environments with background noise has been processed to improve the understandability of speech. Monoaural sound was the result of the necessity to use clip-on microphones. These microphones were able to record speech in better clarity in industrial environments that have a large amount of background noise.

Video cuts utilize a subtle fade-in to minimize jarring transitions between edits. Demonstrated procedures with long stretches of tedious manual labour utilize automated fast-forwarding, as the steps of those procedures have already been or will be explained by the experts performing them. Learning content length is always to be minimized in micro learning.

The nested menu structure is illustrated in Figure 16. The application launches into an introduction speech (Figure 16 A), which is conducted in two parts. After the introduction, the main menu opens. The main menu allows the user to select any of the sub-topics, which are laid out in an order that reflects the intended order of how a user is meant to consume the contents, from top to bottom, left to right.

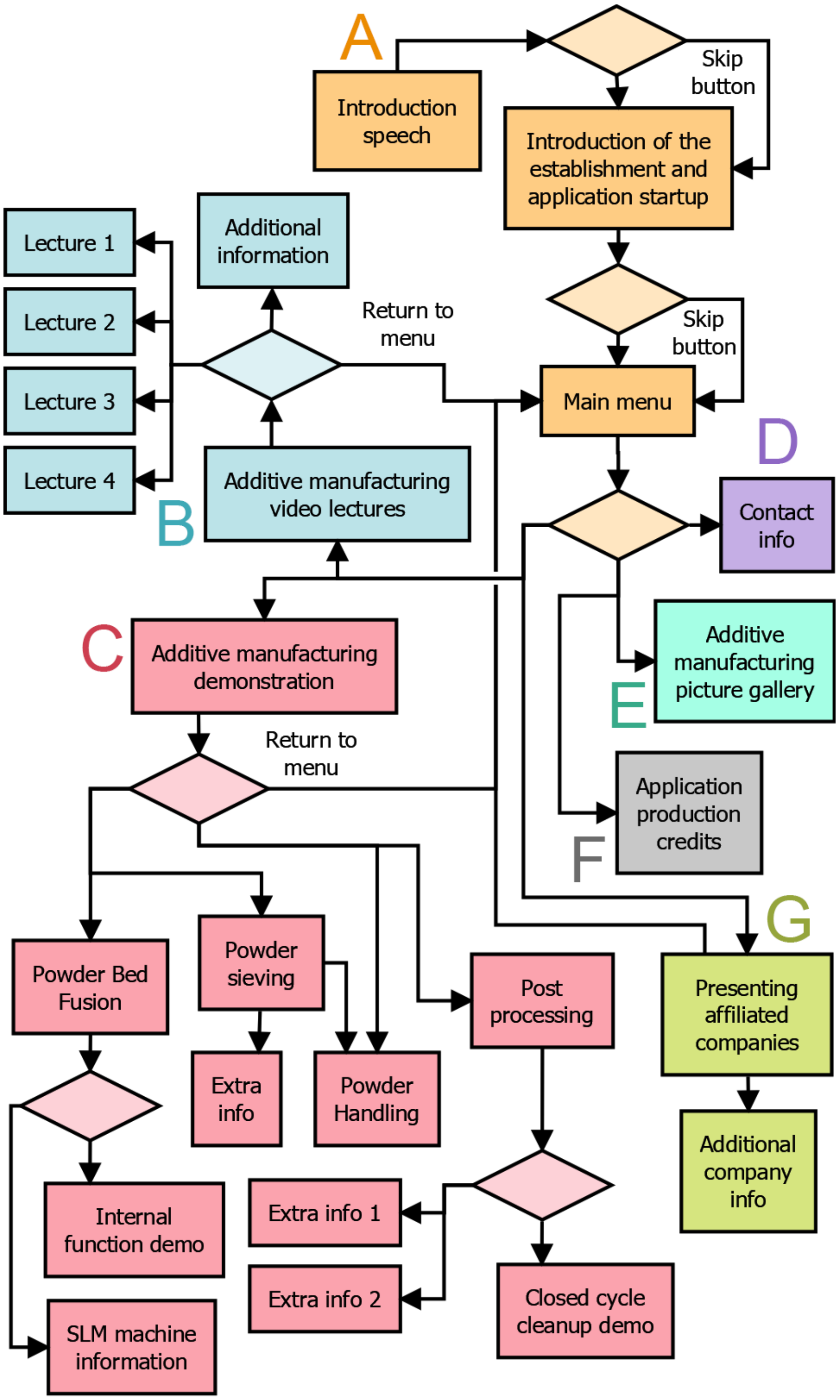
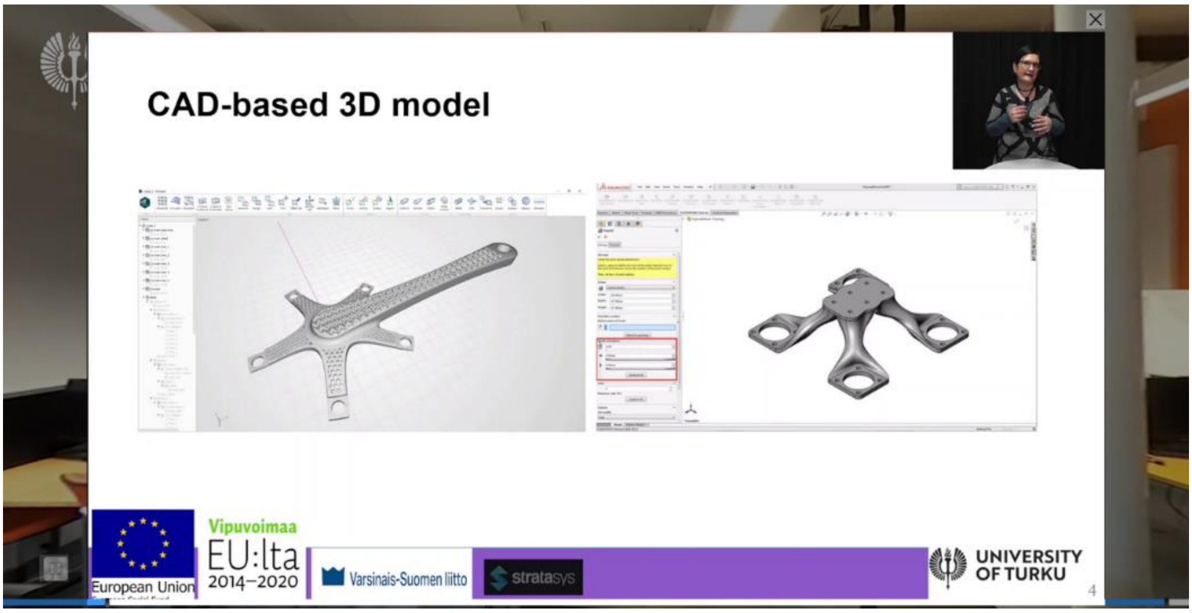


Figure 16: Application structure

6.2.2 Theory presentations

Some of the fundamentals of additive manufacturing are explained in a virtual classroom setting via the use of short, narrated presentations, each being a duration of approximately 5-10 minutes. This adheres to the principles of micro learning. As was explained in Chapter 2, micro learning is based on dividing the learning topics to short individual lessons that the learner can consume at their leisure. The structure of this part of the application is illustrated in Figure 16 B. The presentations consist of simple full-HD (1080p) video recordings of slide shows with the narrator shown in the corner of the slides. Studies have shown that visualizing the instructor of video tutorials helps with the learning process [51]. The narrator goes through the slides and explains the topics in a short and concise manner. An example can be seen in Figure 17.



CAD-based 3D model

Figure 17: AM theory presentation

6.2.3 Practical demonstrations

The main content of the application is a selection of 360° videos. The structure of this segment of the application is illustrated in Figure 16 C. The videos in this part of the application demonstrate the various technologies and techniques in an authentic setting. Experts narrate these demonstrations as they are engaging with these technologies. These videos are also formatted based on the micro learning principles discussed in Chapter 2, so they are limited to approximately 5-10 minutes per video. During the video playback, elements appear in the field of view of the user, as shown in the VR screenshot in Figure 18.

Figure 18: Practical demonstrations menu

The elements in Figure 18 consist of link to further content, lists about important topics, figures, and links to examples or specialized use cases. Users also have access to an interface that allows them to skip to different parts of the demonstration. Micro learning relies on a trainee having immediate access to the info they need in an easily consumable format, so having short videos with the ability to re-watch specific segments is important. In the end of a demonstration, the user is given a prompt to continue to the next phase of the process being demonstrated. There can also be a prompt to enter a special video giving a closer look at the technology. The video content demonstrates the entire workflow of the use of the technology in question, but there are also additional links to more in-depth content for users who wish to learn more.

6.2.4 Technology showcases

Some of the companies in co-operation with the project are providing demonstrations of their own technologies and these are implemented into the application, which is illustrated in Figure 16 G. These mostly take the form of standard videos as opposed to 360° videos. However, some representatives of companies also conduct an introduction speech in the company premises on 360° video.

6.2.5 Stereoscopic footage

The author of this thesis recorded 360° stereoscopic footage to be used in a separate secondary user test. The footage was recorded in Koneteknologiakeskus Turku, and the subject was wire arc additive manufacturing (WAAM). The camera was positioned approximately two meters away from a welding robot arm that was additively manufacturing an object. The resulting footage displays the three-dimensional depth of stereoscopic footage. The author edited the same footage into a secondary version that is entirely monoscopic, displaying the same image to both eyes of a VR headset user.

6.2.6 Hardware

The training application was produced for use on generic VR headsets as well as on PC and mobile platforms, but the primary focus was to make it operable on a Pico G2 4k 3DOF standalone VR headset. This headset has built-in processor hardware and allows VR applications to be installed directly on it, without the need to have the headset connected via cables to a PC. The three degrees of freedom are also a simple enough interaction to allow VR applications to be used without externally installed beacons or explicit definition of the playing area that regulate the control within the virtual environment. Users only need to be able to turn their heads to look around and to be able to select buttons rendered in the VR environment. A standalone 3DOF headset fulfils those requirements. [52]

The sub-contractor team at Elomatic Oy used a GoPro Max 360° camera to record the content of the application. [53] The device uses two camera elements, one facing forward and another facing backward, to record monoscopic videos with a field of view of 194°. During processing, the video recorded by the two camera elements is algorithmically stitched together at the seams, producing a spherical 360° video at 4k resolution. Audio for the videos was recorded using clip-on microphones carried by the person speaking in a video.

The separate stereoscopy test used an Insta360 Pro camera to record the experimental footage. [54] The device has six camera elements spaced 60° apart. Each camera lens has a circular field of view of 200° so they overlap. During processing, the video recorded by all the camera lenses is algorithmically stitched together. The process analyses the perceived 3D-depth of the footage in order to produce separate views for two eyes, correlating details in the recorded footage in order to determine their stereoscopic depth within the image. The resulting video includes a 6k 360° recording for both the left and the right eye and can be viewed through a VR headset as a stereoscopic spherical video. When using the internal microphone of the camera, it also captures spatial audio that plays from appropriate directions when the footage is viewed in VR.

6.3 Experimental procedure

Testing of the first version of the application was conducted by recruiting volunteers working in the SMEs that were consulted earlier in the project. The tests were conducted by the writer of this thesis and the Osuu & Uppoaa project team. The premises of participating companies were visited, and they were given the opportunity to test the training application using virtual reality goggles. Evaluation personnel were to remain in the room to answer any questions that might come up, but otherwise they were to remain as silent observers. The evaluation personnel were to listen to comments provided by the volunteer and to write them down as notes. After the volunteer was finished with the test, they were given a short survey to fill regarding various aspects of the application. The survey used a Likert scale evaluation method and only included 19 questions. The simplicity of the format and the small number of questions were chosen to ensure the willingness of participants to give overall feedback. A list of statements were to be evaluated based on how much the volunteer agrees with each statement on a 1 to 5 scale, 1 being “completely disagree” and 5 being “completely agree.” The survey also had space for additional notes regarding specific issues. Finished survey results were stored in a database anonymously, with only the company in question listed.

6.3.1 Stereoscopy experiment

The author of this thesis conducted a separate experiment regarding the difference in educational value between monoscopic 360° video and stereoscopic 360° video when viewed through VR goggles. Feedback was gathered on the viability of one over the other, in order to determine the importance of perceiving 3-dimensional depth in the video. The experiment was conducted by producing one short 360° additive manufacturing video using a stereoscopic 360° camera. During testing, there would be two groups of users. The first group would be tasked to view the video in VR goggles in a monoscopic format first, and then to view it again in the stereoscopic format. After both videos had been viewed, the testers were interviewed regarding which video was more suitable for the purposes of learning. The second group would view the videos in the reverse order and be prompted to give feedback in the same manner. Other concerns also had to be noted, such as potential cyber sickness issues originating from viewing stereoscopic footage. The stitching of footage from multiple cameras to a stereoscopic spherical video can cause various visual artifacts that can adversely affect the viewing experience. The impact of any such inaccuracies also had to be examined.

6.4 Results

6.4.1 Platform limitations

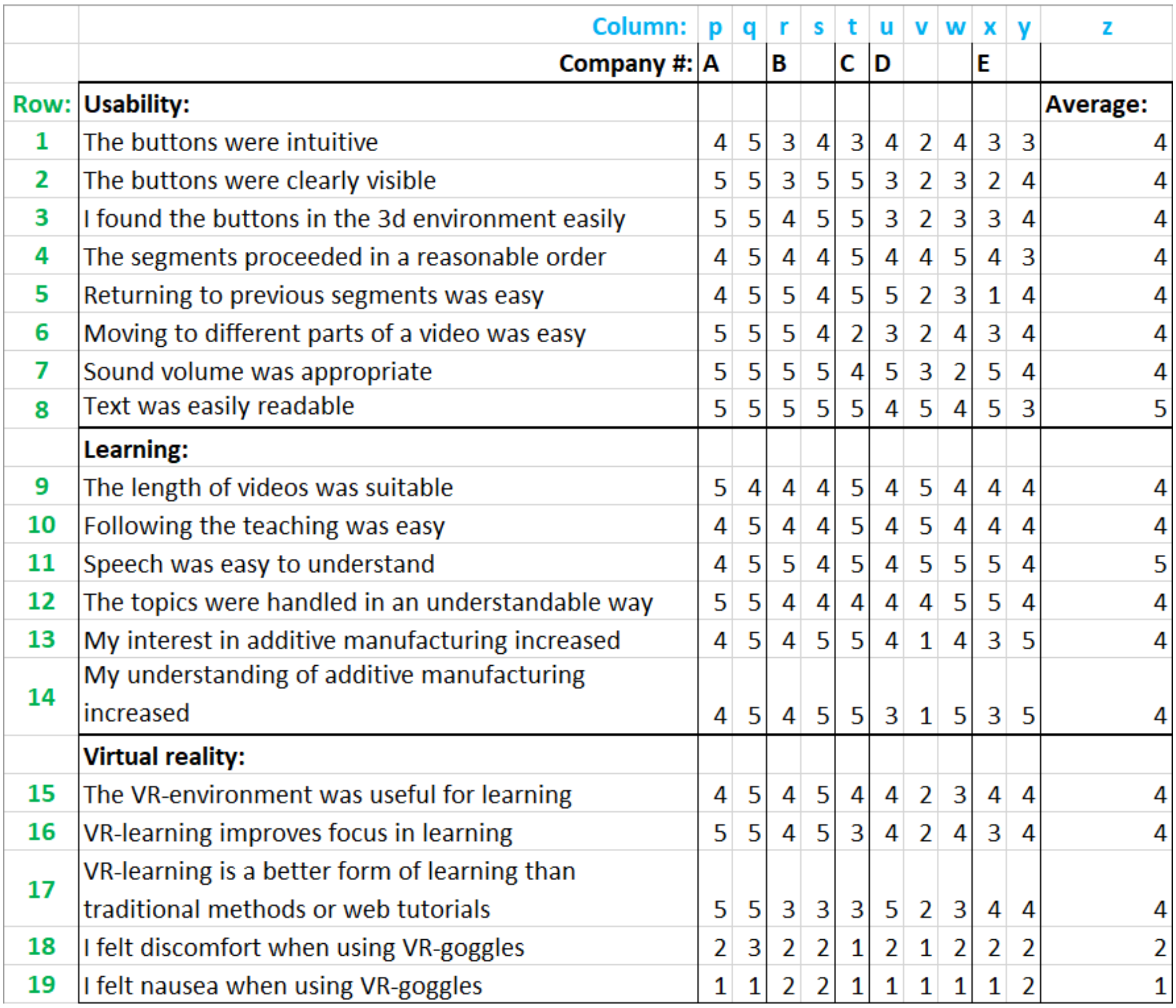
The 3dVista platform has some built-in limitations that pose some challenges for the production of this type of training application. For example, the use of videos within the virtual space was problematic in the context of micro learning because the implementation of a seek bar for video playback is not possible in the VR version. The user requires the ability to go back into previous segments of a video. However, even without a fully interactive seek bar, it was possible to implement an interface that allows the user to select pre-determined segments of a video. Also, additional content that provides deeper knowledge of subjects would be best implemented by links to externally hosted videos, but that approach is not compatible with the platform. Therefore, external content had to be implemented into the software in the same format as the first-party micro learning content. Another limitation regarding the integration of a browser-based and VR learning platform is the discrepancy between view orientation. This problem manifests when the user switches between scenes. The camera is meant to be pointing into a specific direction that allows intuitive continuation of the interaction, but that can differ between browser and VR implementations. The VR version also has a static field of view, whereas in the browser version the user can zoom the view in and out. Also, due to the 3dVista platform having originally been meant for virtual tours, the 360° scenes have a subtle spontaneous rotation around the vertical axis by default, which needs to be accounted for during production. When one leaves a 3dVista scene alone without input, it slowly rotates around that axis to show the entirety of the current scene. This is a hard-coded limitation that 3dVista developed with the assumption that their platform would only be used for one type of content, which is 360° virtual tours.

Issues regarding bandwidth and performance arise with the PC browser version and limited testing on these aspects was conducted by the author of this thesis. 360° videos have large file sizes, and even though the application can start immediately streaming a video while the later parts of it are still being downloaded, users without access to high-speed internet experience pausing as the download attempts to catch up with the video playback. Fortunately, while the browser session is active, all previously downloaded videos remain accessible, and replaying a video does not cause the application to download it again. Playing videos with such large resolutions also requires significant amounts of processing power despite the fact that the application can utilize multiple central processing unit (CPU) cores simultaneously, as well as the resources of the graphical processing unit (GPU). In fact, high CPU usage spikes coincide with pauses in playback. During live demonstrations of the VR application to various interested parties, a system to transfer the view of the VR goggles onto an external display was attempted. This is known as screen casting. Unfortunately, the high performance demands of the 360° video playback combined with the high performance demands of screen casting often caused the crashing of either the training application or the screen casting application. The Pico G2 4k standalone VR headset simply lacks the power to accomplish both simultaneously.

The audio used in the application was mostly recorded using clip-on microphones and thus does not include a spatial element, which would normally have a significant impact on the experience in a 360° environment, especially in VR.

6.4.2 Application feedback

Feedback given by test users was collected into a document. Average Likert-scale scores were calculated based on the values provided by the test users, as displayed in Figure 19, column z. Participants from five companies took part in the testing and numbered feedback. The feedback was divided into three categories evaluating aspects of usability, learning and virtual reality. The results were categorized into column sets based on the respective companies (Figure 19, columns p - y) and subdivided to columns based on feedback of individual participants. For example, company D had three different participants (Figure 19, columns u - w).



	Column:	p	q	r	s	t	u	v	w	x	y	z
	Company #:	A		B		C	D			E		
Row:	**Usability:**											**Average:**
1	The buttons were intuitive	4	5	3	4	3	4	2	4	3	3	4
2	The buttons were clearly visible	5	5	3	5	5	3	2	3	2	4	4
3	I found the buttons in the 3d environment easily	5	5	4	5	5	3	2	3	3	4	4
4	The segments proceeded in a reasonable order	4	5	4	4	5	4	4	5	4	3	4
5	Returning to previous segments was easy	4	5	5	4	5	5	2	3	1	4	4
6	Moving to different parts of a video was easy	5	5	5	4	2	3	2	4	3	4	4
7	Sound volume was appropriate	5	5	5	5	4	5	3	2	5	4	4
8	Text was easily readable	5	5	5	5	5	4	5	4	5	3	5
	Learning:											
9	The length of videos was suitable	5	4	4	4	5	4	5	4	4	4	4
10	Following the teaching was easy	4	5	4	4	5	4	5	4	4	4	4
11	Speech was easy to understand	4	5	5	4	5	4	5	5	5	4	5
12	The topics were handled in an understandable way	5	5	4	4	4	4	4	5	5	4	4
13	My interest in additive manufacturing increased	4	5	4	5	5	4	1	4	3	5	4
14	My understanding of additive manufacturing increased	4	5	4	5	5	3	1	5	3	5	4
	Virtual reality:											
15	The VR-environment was useful for learning	4	5	4	5	4	4	2	3	4	4	4
16	VR-learning improves focus in learning	5	5	4	5	3	4	2	4	3	4	4
17	VR-learning is a better form of learning than traditional methods or web tutorials	5	5	3	3	3	5	2	3	4	4	4
18	I felt discomfort when using VR-goggles	2	3	2	2	1	2	1	2	2	2	2
19	I felt nausea when using VR-goggles	1	1	2	2	1	1	1	1	1	2	1

Figure 19: Test feedback results

The numerical scores were relatively high across the board. None of the aspects that were evaluated received universal critique, and some outliers ended up significantly affecting the average (Figure 19, column v, rows 13 and 14, and column x, row 5). Audio aspects scored the highest, with only some outliers. The intuitiveness of buttons was the most divisive topic, producing very different impressions in different test users.

When it comes to the learning of additive manufacturing topics, the numerical feedback seems to indicate high rates of success. Test users expressed increased interest in and knowledge of the topic (Figure 19, rows 13 and 14). The average scores for these two factors were deflated by an outlier participant who was already an expert and an honest assessment of both factors resulted in the minimum score (Figure 19, column v, rows 13 - 14).

When it comes to the specific criticism that was provided by test participants, one of the most common criticisms of the application was the somewhat unpredictable calibration of the viewing angle. Users would be using the VR interface, and the viewing angle would change between scenes due to unknown reasons. The VR controller includes a button that allows the user to re-centre the view, but it should not be necessary to use it in the middle of viewing VR footage. Some test users also voiced their concerns over the lack of a video seek bar and the difficulty to jump into different parts, due to the fact that the video that is currently playing does not show the current time. For example, a user has the opportunity to jump to 2:00, but does not know how much that is forwards or backwards from where the user is currently. A suggestion by some test users was to divide the videos to smaller segments, allowing users to choose parts to skip to more precisely, and it would be helpful to see the current time of the video at some point on the screen. Some test users voiced concerns regarding the usefulness of the content being in VR, especially when it comes to the theory presentations. The narrow horizontal field of view of the VR headset caused issues for some users because they had difficulties in acquiring the interactive elements in the environment. It may be easier to find those elements if the FOV would be wide enough to display them in the peripheral vision of the user. An observation that is also reflected in the numerical scores is the intuitiveness of buttons (Figure 19, rows 1 - 3). Some of the main functions were implemented with buttons placed very low on ground level, and it made them difficult to find for some users. These buttons can be seen on the bottom of Figure 18. Some users also criticized the video resolution, saying that the low resolution of only 4k spread across a spherical video, in which only a small segment in front of the user is relevant, may obscure some important details in the practical demonstration. Embedded standard videos, such as the theory lecture slideshows were criticized as being too close to the eyes of the user.

A problem with gathering test feedback in general is the willingness of subjects to answer questionnaires at all. However, another issue is the fact that the results may be influenced by the novelty of the involved technology, as well as unwillingness of the subjects to provide harsh constructive criticism. With a small sample size, a majority if not all of the results may be skewed, and high scores across the board may simply indicate an excessively polite test audience. Therefore, numerical feedback on a Likert scale may be used to pinpoint which aspect of the application requires further refinement, but specific verbal feedback is more valuable for addressing the actual issues raised by test users.

6.4.3 Stereoscopic footage feedback

Test users were tasked to view the stereoscopic footage and a monoscopic equivalent through Pico G2 4k VR goggles. The total number of test users was 8. Feedback was gathered in the form of a short interview, allowing the test users to give prompted as well as open qualitative feedback. Prompted feedback involved the topics of comparative impression, comparative educational value, and comparative adverse effects. Half of the test users viewed the monoscopic footage first, and the other half viewed the stereoscopic footage first.

Regardless of whether a test user viewed the stereoscopic or monoscopic footage first, the feedback mostly leaned to one direction. Comparative impression, aka. how impressive the overall experience was, indicated that stereoscopic footage has a much stronger impact on the viewer overall. When it comes to educational value, the opinion of test users was that being able to perceive the depth in 360° video brings additional information value. Adverse effects from viewing stereoscopic video was only slightly felt by one of the test users.

A test user who viewed the stereoscopic footage first indicated that the footage seemed hazy or lacking in clarity when looking upwards. This was possibly caused by the combination of fluorescent lights in the ceiling producing glare and the stereoscopic stitching being unable to produce proper three-dimensional depth directly above the viewer. Several test users also commented on the footage having low detail at a distance, but the primary subject of the video, the welding robot, was displayed in clear detail and the three-dimensional depth made the details appear clearer than in the monoscopic equivalent. Two users commented on the fact that even small, fast-moving details appeared to have perceptible depth to them, and they really provided a convincing impression of presence. Two other test users who viewed the monoscopic footage first felt heightened immersion in the stereoscopic equivalent, and also felt like the footage was higher resolution in stereoscopic format despite the fact that both videos were in the same resolution. Only one test user felt slightly uneasy when viewing the stereoscopic footage, but suspected lack of experience in VR to be the culprit rather than the footage itself. This test user also felt slightly too tall in the scene, which was probably due to the user viewing the footage while sitting down, even though the footage was recorded with a camera at average standing eye level. The importance of 360° camera positioning is discussed in Chapter 3.1.1.

6.5 Discussion

Results from the testing of the VR training application indicate that there is moderate to high interest in this type of training and high educational value in the format. The micro learning approach was proven effective, and further application of micro learning principles in a more granular way might improve the learning value further. The educational content itself, be it the theory lectures or the practical demonstrations seems to have resonated with the test audience to a high degree, indicating that these formats should be utilized further in the future.

Tests regarding stereoscopic video indicate that three-dimensional depth provides additional value. It is unknown how this additional value would impact the educational potential of a VR training application, but the impressions of the test users indicate a heightened sense of presence when viewing stereoscopic footage, and previous studies have highlighted the value of that kind of immersion, as discussed in Chapter 3.2.

Further refinement of the usability aspects of this training app as well as the format of the micro learning aspects is needed to fully realize the potential of this type of learning. Adjustments to the duration of video segments may improve user experience, and user interface design consistency could improve usability and reduce confusion. The placement of interactive elements needs to be carefully considered so that the average user can intuitively interact with the functions of the application and find all the functions that they expect. The normal non-360° videos need to be adjusted so that they are viewed from a comfortable perspective in VR. Opting for stereoscopic 360° video in further revisions or future projects has the potential of improving the system, but using stereoscopic video requires additional care to be taken in order to ensure usable quality. The use and positioning of a camera while filming the footage must involve careful planning in order to ensure that the resulting video is suitable and causes no discomfort in users.

Quality assurance, including frequent user testing is necessary for iterating on the creation of an intuitively usable VR training interface. A short user interface tutorial segment should be designed and implemented to familiarize users with a standardized interface layout that remains consistent across the functions of the application.

7 Conclusions

The evolution in the way people consume information mandates change in the ways information is provided. The ubiquity of high-speed internet globally has led to the expectation of being able to acquire information and solutions to problems very quickly and easily. Concepts such as micro learning, e-learning, online tutorials, and gamified learning assessments have increased in popularity due to producing positive learning outcomes. Students have been more satisfied with their learning outcomes and their information retention has also shown improvement when engaging with these modern learning techniques.

Virtual reality technologies have shown major improvements in the last decade, allowing many types of users to engage with VR, and VR has also been slowly introduced into education. Fully interactive real time 3D-environments that utilize six degrees of freedom give users the ability to experience every part of the virtual world. However, in some cases, 360° video is enough to convey the necessary information and create a sense of presence without time-consuming and expensive production of 3D-assets to fill the virtual spaces. 360° cameras are becoming more advanced and more affordable, and the educational value of 360° video in VR with three degrees of freedom has shown some promise. With the addition of stereoscopic depth, 360° video approaches the immersive potential of real time 3D VR, and feature realistic visuals captured from the real world, as opposed to virtual 3D objects.

Industrial additive manufacturing using metal materials provides many advantages over traditional manufacturing methods. Several metal AM technologies have seen wide adoption in the manufacturing industry. Knowledge of these technologies and how they should be effectively used is needed in the industry. Designing parts for AM provides many new opportunities and introduces its own limitations and concerns that the utilizers of AM need to be made aware of. Some training resources for AM already exist online, as well as official certification authorities that can validate the knowledge of AM users.

Osuu & Uppoaa is a Turku School of Economics and the Faculty of Technology of the University of Turku research project taking place over two years. It is funded by the European Social Fund. The aim of the project is to produce a virtual reality training application in Finnish, to aid small- and medium-sized enterprises in Southwest Finland to integrate additive manufacturing into their businesses. The application was designed by the author of this thesis in co-operation with experts of the fields of education and additive manufacturing in the project team, and the technical production of the application itself was outsourced to Elomatic Oy. The application consists of a set of interactive menus in virtual reality, using 360° video. Users can watch theory lecture videos about various additive manufacturing topics and see actual AM machines in operation in 360° video environments, with their operation explained by experts. The learning materials were formatted to be in short segments, so that they follow the principles of micro learning.

The training application received largely positive feedback among test users, corroborating the findings of previous studies regarding VR training in general. The results also indicated a successful application of micro learning principles. Some usability issues were noted during the tests. The user interface was not intuitive enough for some test users. Feedback on the application is being taken into consideration when making improvements in a second iteration of the application that is in production. Stereoscopic 360° video also received positive feedback among test users. Feedback indicated heightened immersion and a perception of a sharper image when viewing stereoscopic footage compared to a monoscopic equivalent. Based on this feedback, the use of stereoscopic 360° video is also being considered for the second iteration of the training application that is to be produced.

7.1 Going forward

A second iteration of the training application is to be produced in the Osuu & Uppoaa project. The design of the application is informed by feedback gathered during the first phase of the project. Usability concerns are to receive special attention in order to ensure an intuitive interface that does not interfere with the learning potential, and a basic tutorial to familiarize users with the user interface is being planned. User interface design needs to be iterated and tested, and a consistent and intuitive interface needs to be implemented across the application. Further refinement of the micro learning aspects will require the segmentation of videos to even smaller individual parts, and the user interface needs to accommodate more granular control over the content so that it can be consumed by users in a more efficient way. The additive manufacturing experts of the project team have planned the inclusion of new learning topics such as AM work safety and advanced post processing. The inclusion of several other industrial AM technologies is also being planned, such as polymer AM and biomaterial AM. These technologies are to receive the same type of 360° video demonstrations using real hardware in an authentic setting as the laser powder bed fusion technology received in the first version. Additional theory presentations on new topics are also to be included. The possibility of the use of stereoscopic video is being taken into consideration for the second phase due to the positive feedback gathered during stereoscopic VR video user tests.

7.2 Further studies

Several aspects of industrial training systems such as the Osuu & Uppoaa VR training app would benefit from additional research. These include but are not limited to:

- Studies on the intuitiveness of various virtual reality user interfaces in order to determine what kind of interface would be most effective for a 360° video-based VR training application

- User tests to compare the educational value of 360° VR video in three degrees of freedom to real time 3D VR in six degrees of freedom in order to make a proper cost-benefit analysis

- Examination of the importance of the visual presence of an instructor in a video lecture, and how it affects the learning potential and information retention

- Analysis of the optimal duration of micro learning materials in order to maximize the ability of viewers to concentrate and absorb knowledge

- Examination of the value of video thumbnails to entice engagement with training

- Review of different VR headsets and affiliated technologies in order to determine which ones would be most suitable for use in training

- More user tests regarding cyber sickness when watching 360° video through VR goggles, with special attention paid to the difference between monoscopic and stereoscopic video

- Evaluation of the effect of video playback framerate when watching video through VR goggles

Taking the results of studies such as these into account when designing a virtual reality training application would help in ensuring optimal operation and the best possible potential for learning.

8 References

[1] M. Korpela, N. Riikonen, H. Piili, A. Salminen and O. Nyrhilä, Additive Manufacturing - Past, Present, and the Future, Palgrave MacMillan, 2020.

[2] T. Suomalainen, “Metalliosia 3D-tulostimella,” Newspool.fi, 2020. [Online].

[3] K. Schönberg, “3D-tulostuksen teollinen läpimurto saavuttamassa vihdoin Suomen – voi jopa tuoda tehtaita takaisin maailmalta,” YLE Uutiset, 11 February 2021. [Online].

[4] R. Gerbaudo, R. Gaspar and R. Gonçalves Lins, “Novel online video model for learning information technology based on micro learning and multimedia micro content,” *Education and Information Technologies,* 2021.

[5] F. Paas and J. Sweller, “Implications of Cognitive Load Theory for Multimedia Learning,” *Cambridge University Press,* 2014.

[6] E. Kaila, “Utilizing Educational Technology in Computer Science and Programming Courses - Theory and Practice,” *Turku Centre for Computer Science,* 2018.

[7] I. Jahnke, Y.-M. Lee, M. Pham, H. He and L. Austin, “Unpacking the Inherent Design Principles of Mobile Microlearning,” *Technology, Knowledge and Learning,* 2019.

[8] U. Zandbergs, J. Judrups, E. Plane and R. Uscins, “Improvement of Microlearning with help of Learning Analytics in Enterprises,” *Engineering for Rural Development,* 2021.

[9] S. A. Nikou and A. A. Economides, “Mobile-Based micro-Learning and Assessment: Impact on learning performance and motivation of high school students,” *Journal of Computer Assisted Learning,* 2018.

[10] Q. Qian, Y. Yan, F. Xue, J. Lin, F. Zhang and J. Zhao, “Coronavirus Disease 2019 (COVID-19) Learning Online: A Flipped Classroom Based on Micro-Learning Combined with Case-Based Learning in Undergraduate Medical Students,” *Advances in Medical Education and Practice,* 2021.

[11] P. James, “HTC Vive Review: A Mesmerising VR Experience, if You Have the Space,” Road to VR, 5 April 2016. [Online].

[12] A. Cannavò, G. Ministeri, F. Lamberti and G. F. Pratticò, “A movement analysis system based on immersive virtual reality and wearable technology for sport training,” in *ACM International Conference Proceeding Series*, Torino, 2018.

[13] A. Filimonov, J. Zeiger, D. Y. Goldrich, R. Nayak, S. Govindaraj, J. B. Bederson, R. Shrivastava and A. M. C. Iloreta, “Virtual reality surgical planning for endoscopic endonasal

approaches to the craniovertebral junction," *American Journal of Otolaryngology - Head and Neck Medicine and Surgery,* 2022.

[14] Valmet, "Valmet Virtual Mill - A virtual learning experience," 2021. [Online].

[15] Google Inc., "Rendering Omni-directional Stereo Content," 2016. [Online].

[16] C. Blair, C. Wlash and P. Best, "Immersive 360° videos in health and social care education: a scoping review," *BMC Medical Education,* 2021.

[17] L. M. Wilcox, S. Elfassy, C. Grelik and R. S. Allison, "Personal space in virtual reality," *ACM Transactions on Applied Perception,* 2006.

[18] T. Keskinen, V. Mäkelä, J. Hakulinen, P. Kallioniemi, J. Karhu, K. Ronkainen, J. Mäkelä and M. Turunen, "The Effect of Camera Height, Actor Behavior, and Viewer Position on the User Experience of 360° Videos," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Osaka, 2019.

[19] G. Lampropoulos, V. Barkoukis, K. Burden and T. Anastasiadis, "360-degree video in education: An overview and a comparative social media data analysis of the last decade," *Smart Learning Environments,* 2021.

[20] E. Davoodi, H. Montazerian, A. S. Mirhakimi, M. Zhianmanesh, O. Ibhadode, S. I. Shahabad, R. Esmaeilizadeh, E. Sarikhani, S. Toorandaz, S. A. Sarabi, R. Nasiri, Y. Zhu, J. Kadkhodapour, B. Li, A. Khademhosseini and E. Toyserkani, "Additively manufactured metallic biomaterials," *Bioactive Materials,* 2021.

[21] C. W. Hull, "Apparatus for production of three-dimensional objects by stereolithography". Patent 4,575,330, 1984.

[22] T. Rayna and L. Striukova, "From rapid prototyping to home fabrication: How 3D printing is changing business model innovation," *Technological Forecasting & Social Change,* 2015.

[23] Ecrimesa Group, "Metal Injection Molding: advantages and disadvantages," [Online].

[24] N. Hawaldar and J. Zhang, "A comparative study of fabrication of sand casting mold using additive manufacturing and conventional process," *The International Journal of Advanced Manufacturing Technology,* no. 97, 2018.

[25] W. Grzesik, "Hybrid additive and subtractive manufacturing processes and systems: A review," *Journal of Machine Engineering,* 2018.

[26] DEYUCNC, "What are the advantages of CNC small batch processing?," [Online].

[27] SANS Machining, "Design Parts For Small Batch CNC Machining," [Online].

[28] Enteknograte, "Additive Manufacturing: FEA Based Design and Optimization with Simufact, Abaqus, ANSYS and MSC Apex," [Online].

[29] "CATIA Function-Driven Generative Designer," Inceptra. [Online].

[30] S. Hendrixson, “How Fluid Dynamics, 3D Printing Delivered a Better Air Duct,” Modern Machine Shop, 2021. [Online].

[31] General Electric Inc., “Lung-Inspired 3D-Printed Heat Exchanger,” 2019. [Online].

[32] M. Mir, “Additive Manufacturing Simulation - Beat The Heat.,” AdditiveLab, 13 March 2019. [Online].

[33] A. Pikkarainen, “3D printing – creating learning environment for engineering students,” LUT University, 2017.

[34] M. Erfan, B. Sara, B. Michele and G. Mario, “Surface post-treatments for metal additive manufacturing: Progress, challenges, and opportunities,” *Additive Manufacturing,* no. 37, 2021.

[35] SLM Solutions, “SLM 280 - Robust Selective Laser Melting,” [Online].

[36] L. Scime, S. Devincent Wolf, J. Beuth, S. Mrdjenovich and M. Kelley, “Safety and Workflow Considerations for Modern Metal Additive,” *JOM: the journal of the Minerals, Metals & Materials Society,* 2018.

[37] M. Petretta, G. Desando, B. Grigolo and L. Roseti, “3D printing of musculoskeletal tissues: impact on safety and health at work,” *Journal of Toxicology and Environmental Health,* 2019.

[38] G. Costabile, M. Fera, F. Fruggiero, A. Lambiase and D. Pham, “Cost models of additive manufacturing: A literature review,” *International Journal of Industrial Engineering Computations,* 2017.

[39] S. D. Thomas and W. S. Gilbert, “Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion,” *NIST Special Publication,* vol. 1176.

[40] M. Baumers, P. Dickens, C. Truck and R. Hague, “The cost of additive manufacturing: machine productivity, economies of scale and technology-push,” *Technological Forecasting & Social Change,* 2015.

[41] R. E. Laureijs, J. Bonnín Roca, S. Prabha Narra, C. Montgomery, J. L. Beuth and E. R. H. Fuchs, “Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes,” *Journal of Manufacturing Science and Engineering,* 2017.

[42] D. Thomas, “Costs, benefits, and adoption of additive manufacturing: a supply chain perspective,” *International Journal of Advanced Manufacturing Technology,* 2015.

[43] I. F. Ituarte, J. Partanen and S. Khajavi, “Challenges to implementing additive manufacturing in globalised production environments,” *International Journal of Collaborative Enterprise,* 2016.

[44] 3DA, “Industrial Additive Manufacturing: Misconceptions & Stereotypes,” 2019. [Online].

[45] E. Pei, M. Monzón and A. Bernard, Additive Manufacturing – Developments in Training and Education, 2019.

[46] European Powder Metallurgy Association, “Introduction to additive manufacturing technology,” [Online].

[47] SME, “Additive Manufacturing Certification,” [Online].

[48] A. Tuomisto, A. Salminen, A. Helin, S. Parchegani, J. Susi and H. Piili, “Osuu ja Uppoaa,” University of Turku. [Online].

[49] 3dvista, “Virtual Tour Pro,” 3dvista. [Online].

[50] Elomatic Oy, “Virtual Prototyping References,” [Online].

[51] R. F. Kizilcec, J. N. Bailenson and C. J. Gomez, “The Instructor’s Face in Video Instruction: Evidence From Two Large-Scale Field Studies,” *Journal of Educational Psychology,* 2015.

[52] Pico, “Pico G2 4k: VR goes 4K.,” [Online].

[53] GoPro, “This is GoPro MAX: Tech, Specs + More,” [Online].

[54] Insta360, “Insta360 Pro,” [Online].