Guidelines for the Application of Immersive Technology within Industrial Design Methodology

by

Ali Sattari

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Industrial Design

Auburn, Alabama
December 14, 2019

Keywords: Industrial Design, Immersive Technology, Virtual Reality, Augmented Reality, Mixed Reality, Extended Reality

Approved by

Benjamin Bush, Chair, Assistant Professor Industrial Design
Jerrod Windham, Associate Professor Industrial Design
Christopher Arnold, Associate Professor Industrial Design

Abstract

Immersive technology is the use of particular set of tools and technologies which bring an immersive experience to the user. This new technology can be considered as a new medium for communication and visualization. Industrial design, on the other hand, is a field that has a close bond with the new technologies in order to be efficient and take advantage of the new tools and capabilities that technology offers. Also, communication and visualization are two main parts of the design; therefore, immersive technology should be well considered by designers. This study researches different types of immersive technology, the capabilities and the advantages that they have for industrial designers. This study also provides a set of guidelines indicating when the immersive technology can be useful and beneficial for industrial designers and when it should be avoided.

Table of Contents

List of Figures

Abbreviations

AR: Augmented Reality

AV: Augmented Virtuality

DOF: Degree of Freedom

FOR: Field of Regard (the total area that can be captured by a movable sensor)

FOV: Field of View

HBD: Head Based Display

HMD: Head Mounted Display

HMPD: Head Mounted Projective Displays

IDSA: Industrial Designers Society of America

MR: Mixed Reality

VR: Virtual Reality

XR: Extended Reality

Chapter 1: Introduction

Problem Statement

Technology is growing rapidly and offering new tools and features every day. This acceleration, however, is not always easy to keep with. Therefore, it is necessary to better understand the new technologies, determining whether they are useful in a certain field thus making the process more efficient. Industrial design has a close bond with technology. Technology is incorporated in the early stages of design process to the final presentation. While certain technologies can be applied to every areas of the design process, it is not beneficial for every aspect. For example, digital drawing techniques can be used for quick ideation for early concepts in the development phase of the design process, and can be used to explain and communicate the final drawing, but it is best to use in early stages which are quick and iterative. Oppositely, 3D modeling which shows details with a great accuracy, can be used in every phase of design process but it is more effectively used when you need multiple views for prototype building.

Immersive technology, including VR, AR and XR, is an area that has already empowered the design process with new tools and capabilities in communication, simulation, feedback and presentation. These benefits come with their own cost though. Similar to digital sketching and digital modeling, they have the tendency to be useful at different places of the design process. But since the technology is still developing, no one knows exactly where it is most effective. By developing guidelines for the prescriptive use of immersive technology for industrial designers, opportunities can be created for them to take advantage of the benefits of this technology and demystify its operation and implementation.

Need for Study

The impact of technology on design, and industrial design particularly, is undeniable. it helps us to do the job more quickly and efficiently. It also provides us with new tools for enjoyment and professional productivity. Immersive technology is one of the latest technologies that allows the designers to explore new fields and experiences and push their capabilities to the next level.

Immersive technology, including Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR) and Augmented Virtuality (AV) is a computer-generated simulation of reality that immerses the user into a virtual environment. This technology, with the current state of the definition of the term, is new, and growing relatively rapidly. Therefore, the capabilities and advantages of the technology is improving fast as well.

There are many benefits this technology may enhance for daily use in the design process or profession:

- Improve ability to examine and explore 3D data;
- Cost savings;
- Enhance marketing;
- Convey ideas as artistic expression;
- Convey ideas as informative expression;
- Enable noninvasive experimentation and other simulation techniques;
- Improve safety.

(Sherman & Craig, 2019)

Although this technology has many benefits, its advantages might not be always beneficial to every phase of the design process; therefore, it is critical to know when to use it. This study will focus on creating a set of guidelines for industrial designers for the application of immersive technology, detailing the scope of immersive technology, and establishing what circumstances it should be used for, all while considering how to use it effectively within the industrial design discipline.

Objectives

The objectives of this study are as follows:

- Introducing the immersive technology and the different types of it to the designers.
- Suggesting when it should and when it should not be used during the design process.
- Showing how it can be effectively used in order to improve efficiency.

Assumptions

For this study it is assumed that the design processes and tools need to be updated with the latest technology in order to get more efficient through time. Also, it is assumed that designers are willing to use new tools and technologies during the design process in order to get a better result.

Scope and limitation

Industrial design is a broad field of study, consisting of a large area for exploration and a wide range of projects and products that can fit in this field of design. However, there are too many design processes, tools and methodologies that designers can possibly use. In this study two different design processes (double diamond and circular design process) and the IDSA design tools are going to be used to indicate proper areas for application of immersive technology. In terms of technology application, everything that is going to be claimed in this study is based on the most recent state of the immersive technology. New tools will provide additional technological opportunities as well as significant development of industrial design methodologies. This thesis will also include a broad scan of both technology and the applications of immersive technology into the design processes. While this section is broad it becomes increasingly important to elaborate through case studies where the application is not clear. These situations are referred as “Maybes”.

Anticipated outcome

Immersive technology covers a broad range of technologies that are improving rapidly, and it is getting even broader while it is improving. The end result of this study will be providing a set of guidelines for industrial designers, guiding them whether immersive technology can be useful and beneficial at different phases of design process or if it should be avoided in order to focus on using other technologies. Aside from the guidelines, the readers of this study will learn the current state of the immersive technology, different types of this technology, terms and boundaries between them, as well as the use cases of each type in order to enable them to use it properly and efficiently.

Chapter 2: Literature review

Immersion

Immersive technology is a computer-generated simulation of reality with physical, spatial and visual dimensions. Immersion is the state of consciousness where an immersant's awareness of physical self is diminished or lost by being surrounded in an engrossing total environment; often artificial. This mental state is frequently accompanied with spatial excess, intense focus, a distorted sense of time, and effortless action. (Handa, Aul & Bajaj, 2012).

In this study the term “Immersive Technology” is going to be used as an umbrella for addressing all the technologies and areas that bring an immersive experience to the user. Those areas are including Virtual Reality (VR), Augmented Reality (AR), Mixed reality (MR), and Augmented Virtuality (AV). In some sources, they use the term “Extended Reality” (XR) to address these areas; however, the term Extended Reality is lacking the concept of immersion, and these technologies are all about having an immersive experience. Therefore, in this study the term “Immersive Technology” is going to be used for that purpose. As a reference though, Extended Reality is going to be discussed as well later in this chapter, so that the audience of this study will have a comprehensive knowledge and perspective of this field. At this section different types of immersive technology, definitions, boundaries and capabilities are going to be reviewed. It is worth to mention that most of this information comes from an authoritative guide. The second part of this chapter though is dedicated to design methodologies and tools so that they can be employed to create the guidelines.

Virtual reality (VR)

VR is a computer-simulated reality that simulates a fully artificial environment that does not physically exist. Users within VR are closed off from the real world (Mealy, n.d.) Broadly speaking, VR technology platforms can be grouped into three paradigms:

1. **Stationary displays:**
   - Fishtank (aquarium) VR display
   - Surround VR display
2. **Head-based displays:**
   - Occlusive HBDs
   - Nonocclusive HBDs (optical see-through and video see through)
   - Smartphone-VR display
   - Head-based (mounted) projective displays (HBPD)
3. **Hand-based displays:**
   - Handheld-VR/AR display

(Sherman & Craig, 2019)

1. Stationary Displays

"Stationary VR" displays are those where the *"hard- ware is not worn or carried by the participant."* The implication then is that the screens are in the space around the participant, and also that they aren't moved by the participant and thus are stationary or fixed in place. That is not to say that the screens cannot be reconfigured; many CAVE-style systems can open and close the side walls to different stopping points to accommodate different purposes and different-sized audiences. Usually the reconfigurability is only engaged between applications, though it is possible to move the "wings" of the display while engaged in an application, and indeed with instrumentation the application could adjust to the movement as it happens (Sherman & Craig, 2019).

Fishtank (Aquarium) Virtual Reality Display

The simplest form of VR visual display utilizes a standard computer display (which might be a single 3D TV panel, perhaps even 4K resolution) and is called monitor-based VR, or more often, fishtank VR. For larger flat surface (planar) VR displays, we might consider them more of a large-scale (Oceanarium scale) aquarium rather than a ~50-gallon fishtank that more closely matches the viewing factor of a large monitor, but except for affecting FOV and FOR there isn't much of a difference. As a result, there is a tendency to also refer to larger planar screens as fishtank.

The name fishtank comes from the similarity of looking through a small aquarium glass to observe the 3D world inside (Fig 01-A). Viewers can move their heads from side to side and up and down to see around, over, and under objects, but they cannot enter the space. Treating the screen as a barrier is the norm in fishtank VR; however, since this is VR, the experience creator needn't adhere to this constraint-objects can also be displayed on the near (external) side of the screen, When this outside-the-tank effect is done, care must be taken to avoid the screen edge cutting off these objects and breaking the frame.

Fishtank VR differs from generic interactive 3D graphics displayed on a monitor, because a VR system tracks the user's head, and the rendered scene changes in response to the tracked head movement. The fishtank paradigm is classified as stationary display VR because, even though a computer display might be somewhat portable, it is unlikely that the display itself would move during use (Sherman & Craig, 2019).

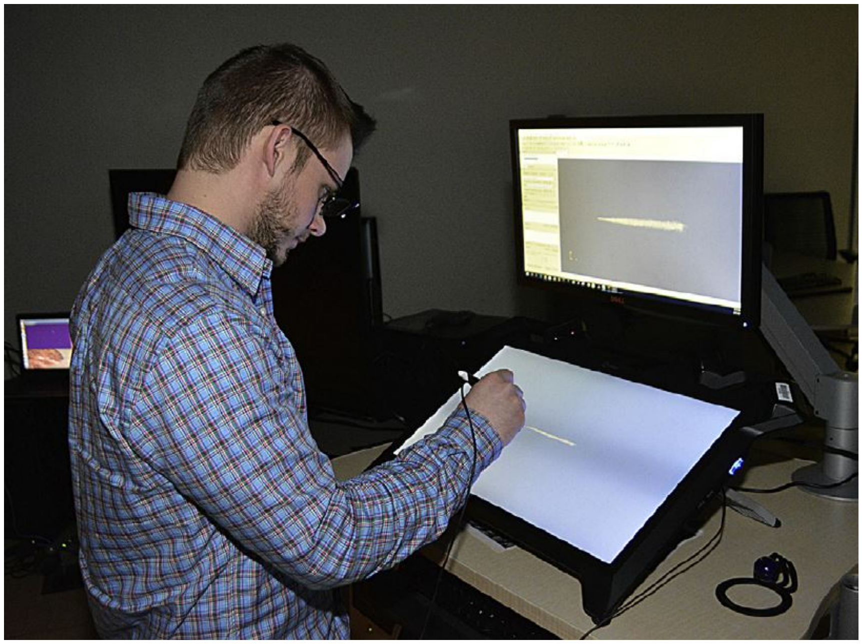


Figure 01-A The Z-space product is a commercial Fishtank VR style display with a stereoscopic view, head tracking, and a tracked hand-controller. The participant is able to see and look about a 3D world that appears to exist within the confines of the monitor. (Photograph courtesy of Simon Su.)

Surround Virtual Reality Display

Surround visual displays are another class of stationary devices. The screen may be much larger than the typical fishtank VR display, thereby filling more of the participants' fields of view and regard and allowing them to roam more freely. The size of the display certainly influences the interface to the virtual world. However, the key difference with fishtank (or large aquarium) displays is that the participants have screens on multiple sides of them, usually including the floor and three walls, sometimes the back wall, and occasionally the ceiling too.

Prior to the advent of flat-panel displays, surround-style displays relied exclusively on projection systems to provide the image display and thus were often referred to as "projection-based VR." Although large display walls are now typically created by setting several flat-panel displays side by side, projection systems can create frameless adjoining displays, making the scene more seamless. The choice between tiled flat-panels and projection raises three tradeoffs: (1) flat-panels (for the moment) have bezels producing a mullion effect in the view (bad); and (2) flat-panels are generally more convenient to fit into smaller spaces and install (good); and (3) it will usually take more flat-panels to cover the same surface area, which also provides higher resolution (bad/ good).

Another tradeoff to be considered when designing a surround VR system that when considering a projection method is whether to project from behind the screen (rear-projection) or use front-projection (projector on same side of the screen as the participant). Most surround VR systems are rear-projected to avoid the participants casting shadows on the screen. However, ultra-short throw projectors can be front-projected and only cast shadows as the user gets exceptionally close to the screen surface. Sometimes front-projection can work reasonably well simply by mounting the projectors sufficiently high above the floor. Indeed, in most surround systems, the floor is projected from above. (When the ceiling is also involved, the floor is projected from beneath, which leads to multiple logistical issues.) In fact, the DISH system designed by Walt Disney Imagineering uses high-mounted front- projection on a smooth, curved surface to entirely eliminate seams through projection overlap and blending for an extremely high sense of immersion (Fig. 01-B) (Sherman & Craig, 2019).

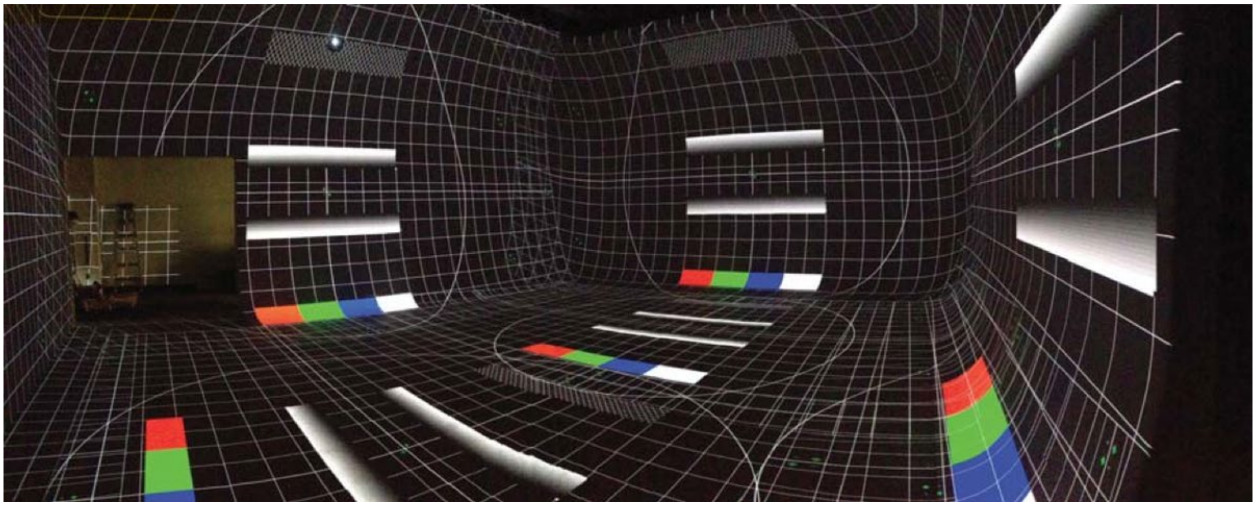


FIGURE 01-B The DISH by Walt Disney Imagineering is a large-format stationary VR display that front projects images onto all four walls and the floor of a very large room providing a 360-degree view of the virtual world. Here a configuration pattern reveals how the corners of the walls are curved to avoid any apparent discontinuities. (Photo by Disney.)

There is a trend to move away from rear-projection screens and projectors toward large, flat-panel displays. Flat-panel displays have higher resolution, require less maintenance (alignment calibration and bulb replacements), and take up less room than typical rear-projected systems. They do not require the additional distance between the projector and the screen necessary in rear-projected systems. However, until flat-panels are either large enough to span a wall-sized space, or have zero-space abutment, systems that are produced with tiled panels will have a problem with bezels breaking up the frame and making negative parallax images difficult to view.

Stationary VR displays are not the display paradigm that leaps to mind when most people discuss VR, which is exacerbated now that the price of HMDs is less than a single panel of a tiled display. HBDs were the first technological method used to put a viewer into another world (Sutherland, 1968) and HMDs are more frequently portrayed in the popular media. Recently, low-cost HBDs have once again made the general public aware of VR. However, the use of projection-based display for applied VR is substantial. Myron Krueger (1982) has been using projection displays in his virtual environments for decades, but their widespread use began in about 1992 when the EVL *CAVE* and Sun Microsystems' *Virtual Portal* were demonstrated at the 1992 SIGGRAPH computer graphics conference in Chicago. (Of course, flight simulators had been using projector technology for decades but were not then considered a VR display.) Thereafter, several single-screen stationary displays were introduced: (1) a table-top configuration, the *Responsive Workbench;* (2) a drafting table style, the *ImmersaDesk;* and (3) a high-resolution, single-screen, multiple-projector sys-tem, the *Infinity Wall.* All of these would be classified as fishtank style VR.

Again, size requirements of the various stationary displays influence the venue in which they are typically experienced. Fishtank displays can generally be placed in an office environment, allowing access without time constraint during the day. Larger, single-screen displays move into the domain of scheduled resources, leading to less frequent use. Nevertheless, these displays are not excessively obtrusive and can be added without too much difficulty to research environments, museum displays, and like venues.

Large, surround-projected displays, like EVL's *CAVE,* tend to be more of " an architectural statement," as cocreator Tom DeFanti would point out, often literally requiring architectural changes to the venue to accommodate them. Accordingly, surround-projected displays are more of a limited-access device, at least until large-scale flat-panel displays become available. However, many facilities in universities and corporate research centers accustomed to providing state-of-the-art laboratories have established that there are sufficient benefits to providing such higher-end displays using projectors for their researchers. Similarly, design centers in other large-scale production centers have found these larger-scale, walk-in immersive systems to help reduce costs and improve product designs.

Using flat-panel screens that are not quite the size of a wall has also been shown to work as an acceptable alternative, if ultimately not yet the perfect solution. In addition to not yet being able to walk on flat-panels, there is the geometric challenge of using rectangular units to surround the user both horizontally and vertically. The team that created the original CAVE has explored different configurations of tiling flat-panels, including the NEXcave, which overlaid panels in depth in order to reduce the large bezels of the era (an effect that worked better than one might assume) "DeFanti et al., 2011" (Fig. 02): the CAVE-2 which horizontally curved panels around the viewer (Fig. 03); and the WAVE (Wide-Angle Virtual Environment), which vertically curved the panels (Fig. 04); and the SunCAVE, which advances the design to curve the tiling over both dimensions (Fig. 05) (Sherman & Craig, 2019).

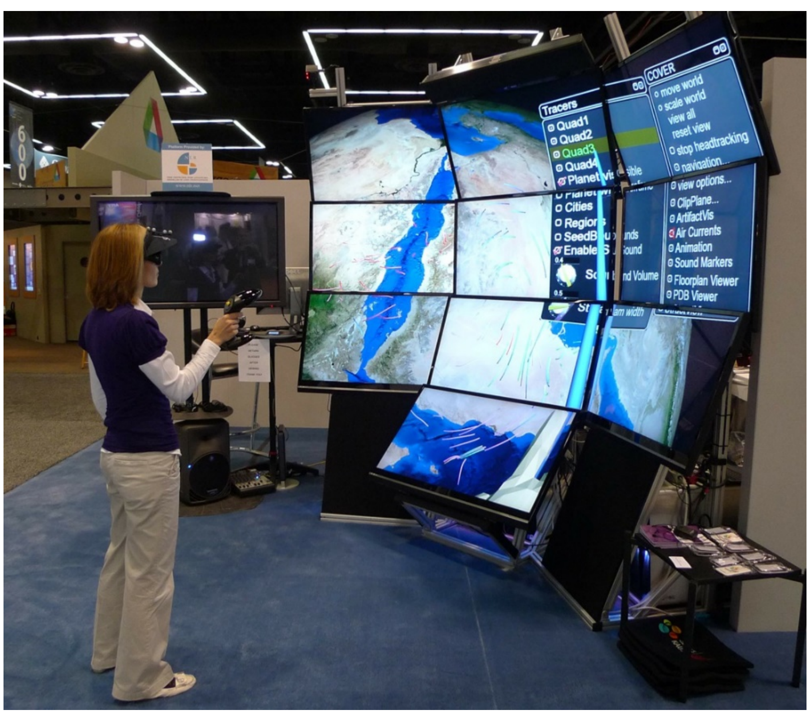


FIGURE 02 The NexCAVE Using multiple passive stereo screens creates a curved surface.

(nexCAVE, 2009)

FIGURE 03 CAVE 2

Students having an immersive meeting in CAVE2. The space can comfortably accommodate from five to seven individuals with chairs and tables. CAVE2 can be used to effectively juxtapose 2D, 3D, and abstract data, as well as text documents. It features a 320-degree panoramic view at 20/20 visual acuity. With a total of 72 thin-bezel, stereoscopic LCD panels, it has 10 times the resolution of the original CAVE at half the cost. (Reda, 2013)

FIGURE 04 The Qualcomm Institute' s WAVE provides the ability to look up and down in the virtual world bycurving tiles around the horizontal axis. (Ramsey, 2015)

FIGURE 05 The Qualcomm Institute' s SunCAVE

(Ismael, 2019)

2. Head-Based Displays

Unlike fishtank and surround visual display paradigms, the screens in HBDs are not stationary; rather, as their name suggests, they move in conjunction with the user's head (Fig. 06). Styles of HBDs include HMDs, counterweighted displays on mechanical linkages (e.g., the *BOOM),* small screens designed to display a virtual image several feet away (e.g., the *Private Eye* and *Google Glass),* experimental retinal displays (which use lasers to present the image directly onto the retina of your eye), and slightly movable, kinetoscope-type displays that the user puts their head up to (e.g., the Fakespace *PUSH* discussed in the next side-bar). Ultimately, and indeed already, this type of display is shifting to hardware that is more appropriately referred to as *head-worn* rather than *head-mounted*- approaching something on the order of a device similar to a pair of glasses in weight and size yet conveying high resolution and wide FOV (Sherman & Craig, 2019).

FIGURE 06. By attaching displays to the head, screens stay fixed relative to the user' s eyes. (by Oculus)

Again, the four subcategories that we will discuss are: (1) HBDs that occlude the real world from the participant; (2) HBDs that reveal the real world to the participant and thereby augment the real world with virtual objects or annotations; (3) HBDs that make use of mobile computing technology such as smartphones or tablets; and (4) head-worn systems where the images are projected from the head and reflected back (HMPD) (Sherman & Craig, 2019).

Occlusive Head-Based Virtual Reality Displays (HMDs)

As we've discussed, head-based VR visual displays are probably the equipment that most people associate with VR. In this section, we will talk about occlusive head-based VR-displays that block out the real world in favor of the virtual (Sherman & Craig, 2019).

Nonocclusive (See-Through) Head-Based Displays

See-through HBDs are primarily designed for applications in which the user needs to see an augmented copy of the physical world-AR applications. There are two methods used to implement the "see-through" effect of these displays via optics or video (including depth camera capture). The optical method uses lenses, mirrors, and half-silvered mirrors to overlay an image from a computer onto a view of the real world (Fig. 07). The video method uses electronic mixing to add a computer image onto a video image of the real world, which is generated by cameras mounted on the HBD “Rolland et al. 1994”. The depth camera method mixes a real-time 3D point cloud of the real world into the proper collocated area of the virtual world, such that the participant can see the worlds mixed. This might be done for user safety, or to enable the participant to do real-world manipulations while immersed.

FIGURE 07. The Darqi Smart Helmet provides an augmented reality tool that uses optics to combine the real world with augmentation. (Mortice, 2017)

Annotating the real world is another type of AR application. The annotation can be simple text boxes with pointers to particular parts of an object, more detailed instructions that explain the next step of a task, arrows or other graphics showing where parts should be placed, and so on. These effects can be useful for training or performing actual procedures (Fig. 08), for example, performing procedures in a factory, such as manipulating valves to a proper setting could be done with a smart helmet indicating the proper position of the valve and ensuring that the correct value is in view.

Another reason for using an HBD with see-through capabilities is to reveal aspects of the real world to the user for their safety, or simply to be able to interact with real world objects while immersed. For example, the HTC Vive's camera view can be used to show real, physical hazards to an immersed participant while they are otherwise fully engaged in a virtual World (Sherman & Craig, 2019).

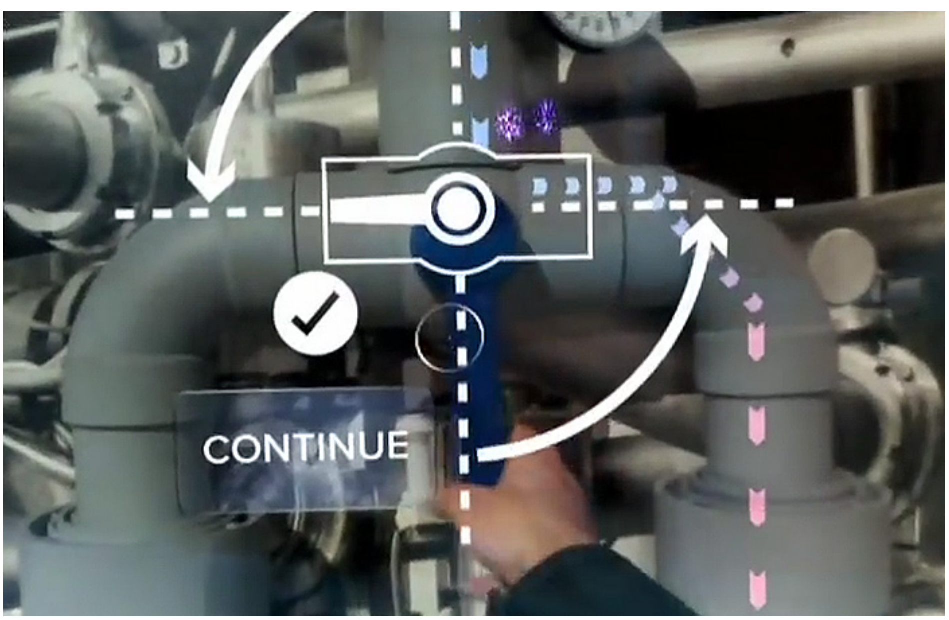


FIGURE 08. This image shows the view through an AR display instructing the user on the proper procedures for adjusting the flow through the pipes. (by Darqi)

Smartphone-Virtual Reality Head-Based Displays

Smartphone technology has been a major catalyst for the resurgence in interest in VR. The production of millions of small flat high-resolution screens at a very low cost became the means by which consumer-priced HMOs could be manufactured, beginning with the Kickstarter-funded Oculus DK-1. Plus, the proliferation of inertial / MEMS (micro-electro-mechanical systems) tracking units that are integrated into all mobile computing platforms (phones and tablets) was critical for VR. Given that these devices are also computers that can render 3D computer graphics as capably as a desktop computer of a few years ago, it makes sense that the phone itself (or tablet) could be used as the main component of a VR display. For many, smartphone-VR will be their first personal exposure to a VR experience; and for others, it may be the way they most frequently experience VR.

There are many precursor VR displays that share aspects of smartphone-VR, some of which may have directly inspired the concept. In VR (and AR), the idea of holding a visual display to the face ("held-to-the-head" apparatus donning style) goes back to the nVis virtual binoculars, and the University of Washington HitLab's viewer. Prior to VR are the stereoscopic viewers going all the way back to Wheatstone's 1938 invention (Fig. 09). Likely the first commercially available smart phone-VR holder was the Hasbro My3D device, which worked with Apple iPhones and iPods of that era (2010· iPhone-45 and earlier) and provided some simple VR game experiences. The US Institute for Creative Technologies' MxR Lab brought this idea to the "Maker" concept and created foamcore foldable holders with inexpensive lenses to create a DIY smartphone-VR holder (Fig. 10). Shortly thereafter Google released their wildly popular Google Cardboard smartphone holder, along with a magnetic "button" and some demonstration applications, and the concept went viral (Fig. 11). Later, Samsung teamed up with

OculusVR to create a more advanced notion of this: the GearVR, which had a more substantial housing and incorporated additional electronics for improved tracking as well as a 2D touch interface and some buttons (Fig. 11) (Sherman & Craig, 2019).

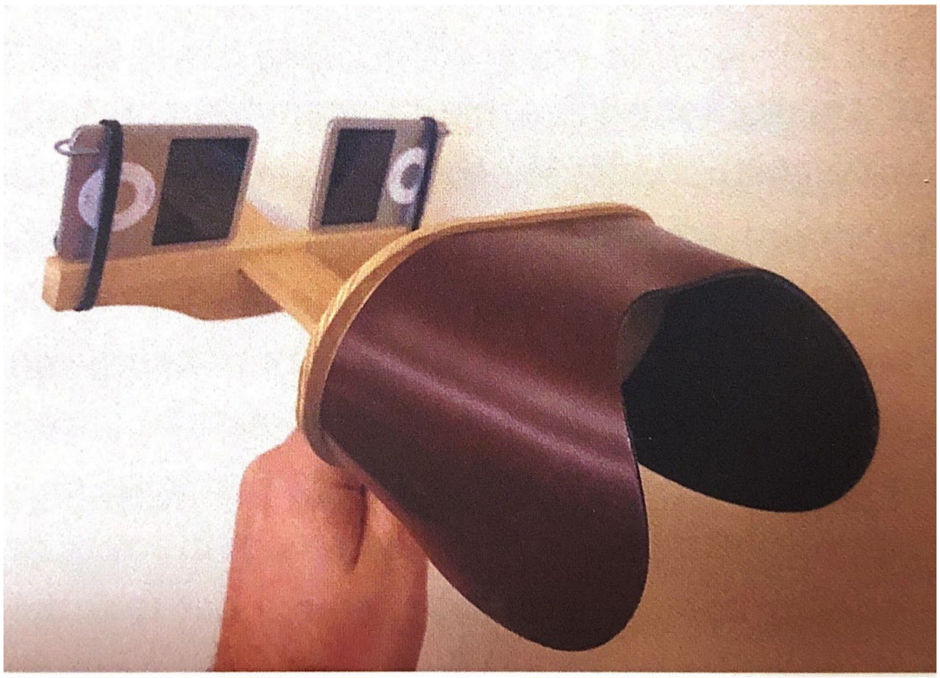


FIGURE 09 This mockup of a "classic" Wheatstone stereoscope mounts two small iPod displays synchronized to show stereoscopic pairs. (iPod Wheatstone viewer by Albert William, Chauncey Frend, Jeff Rogers, and Michael Boyles.)

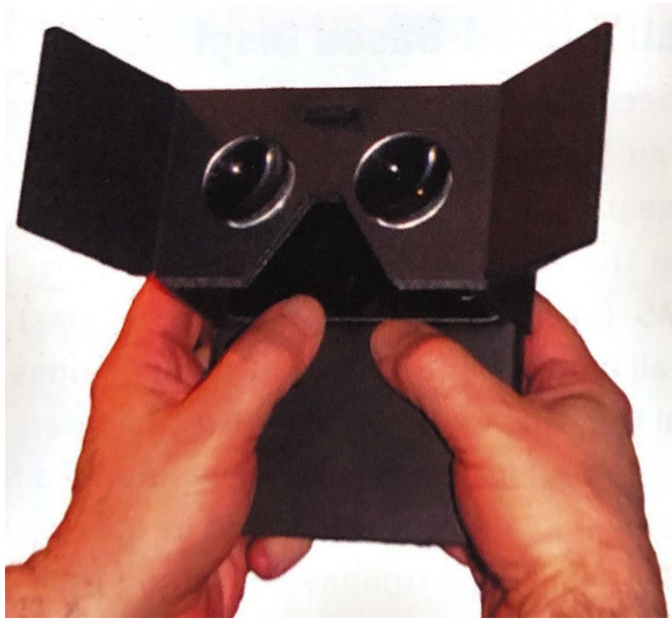


FIGURE 10 The advent of smartphones with inertial tracking-enabled devices, such as the OV2GO, to provide a low-cost 3-OF head-tracked VR experience. (Photograph courtesy of MxR Lab, Institute for Creative Technologies.)

FIGURE 11 Samsung Gear VR (by Samsung)

Head-Based (Mounted) Projective Displays

A rare class of VR display is one with many interesting features-a system where the virtual world is projected onto surfaces surrounding the user in such a way that they too appear to be located not at the screen but in 3D space. Thus far, the primary implementation of this style has been to use retro-reflective materials as the surfaces onto which the virtual world is projected, and to place the projectors in alignment with the user's eyes. This alignment requirement thus means that the projectors are " mounted " on the user's head-and so are head-mounted projective displays (HMPD). They might also be referred to as head-based retro-reflective displays.

A patent for probably the first instance of an HMPD was filed by James Fergason in 1994 (issued in 1997). Another early implementation of an HMPD was the "SCAPE" system created as a research system at the Beckman Institute at the University of Illinois where application areas and improved optics were explored (Fig. 12). In 2013, the company Technical Illusions ran a successful crowd- sourcing campaign on Kickstarter for their "CastAR" HMPD system. However, despite the Kickstarter funding as well as additional venture capital funding, the project was unable to deliver a product and the company was liquidated in 2017 (Sherman & Craig, 2019).

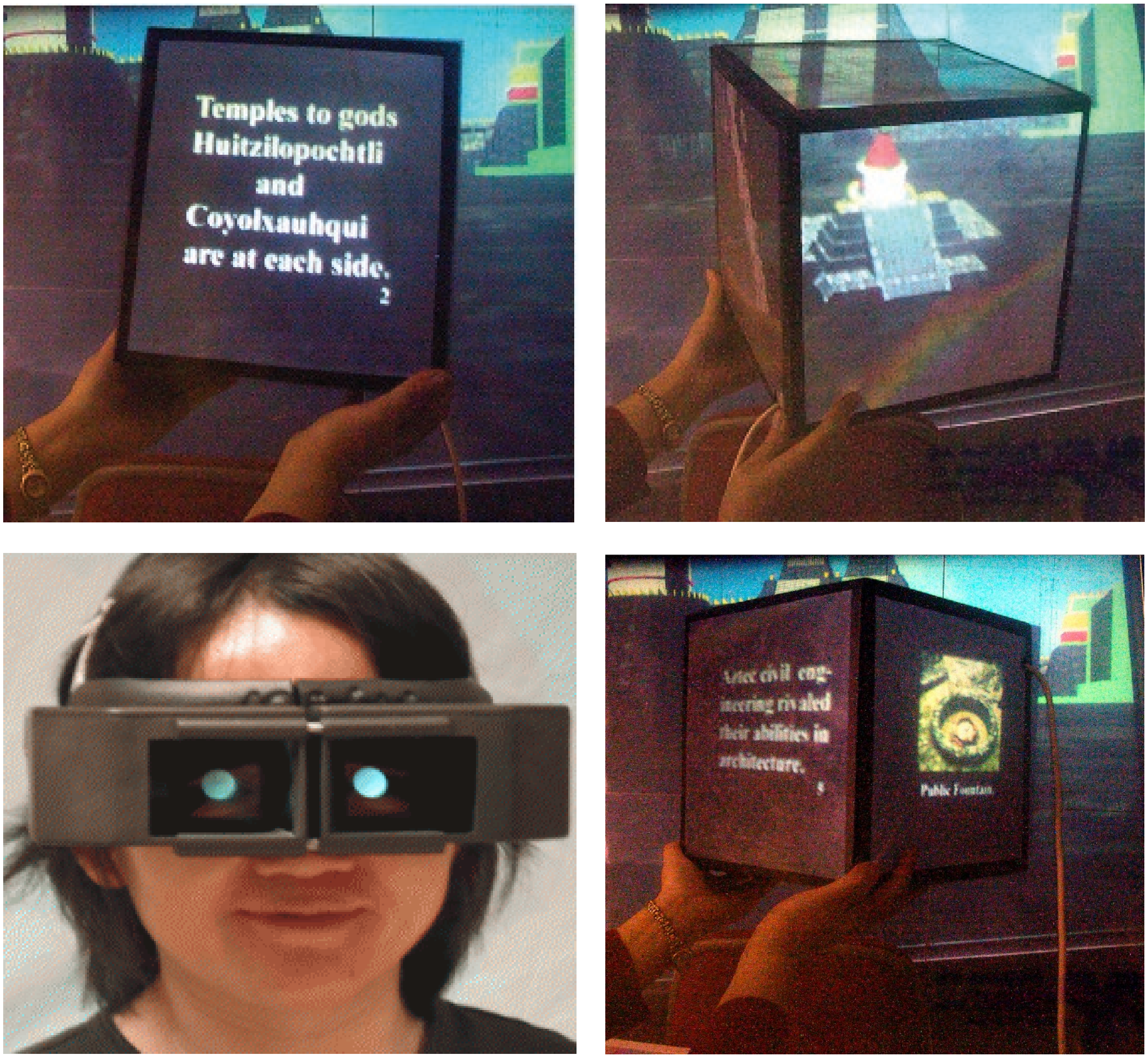


FIGURE 12 Using optics to map projector output to emanate from a user's line of sight, a virtual or augmented reality can be created using retroreflective material that bounces exactly the desired image back to the user. Multiple users will see the image from their own projectors. Here a cube is covered with the material and so objects can be made to appear inside the cube. (Photographs of the SCAPE project courtesy of Hong Hua.)

3. Handheld Virtual/ Augmented Reality

Another visual display paradigm that works well as an AR display is the handheld VR (or palm-VR) display. As the name suggests, a handheld VR display consists of a screen small enough to be held by the user. Of course, for it to be considered VR, the image on the screen must react to changes in the viewing vector between it and the viewer; that is, it must be spatially aware "Fitzmaurice, 1993".

The handheld display paradigm has developed at a rapid pace in the recent past. As computing devices have become increasingly miniaturized, and as people continue to take their devices on the road, handheld VR displays have become more common, particularly for AR applications. An early prototype, predating mobile computing technology, the Chameleon project from the University of Toronto prototyped a system using a portable television "Buxton and Fitzmaurice 1998". Their work focused on the use of physical objects as anchors in an information space that would help users locate data of interest-a simple example was to use a map of Canada to view weather or demographic data by holding the hand-held device over a particular region of the map.

A decade later, all this could be accomplished on some of the first smartphones that included cameras and had reasonably fast CPUs to do computer vision processing. For example, the Studierstube Tracker library from the Graz University of Technology was developed as a means of adding fiducial marker tracking technology to camera-equipped smartphones "Wagner et al., 2008". As the camera and computing technology on mobile phones continually improved, as well as the addition of inertial tracking, plus the mainstreaming of larger tablet displays beginning with the release of the Apple iPad in 2010, more and more could be accomplished on mobile platforms.

Now, there is a plethora of handheld-based "magic lens" AR applications that have become popular in recent years. By using embedded fiducial markers (which can be the diagram or image itself) diagrams can be augmented with 3D instructions, toy boxes with animated toys, and crayon drawings can come to life.

Another use of a handheld display is to augment the terrain surrounding a user. A farmer in the field might use the display to overlay a visualization of soil information about that particular spot in the field. A soldier could be given "X-ray vision" enabling them to see the structures that are beyond the next ridge (Sherman & Craig, 2019).

FIGURE 13 Augmented reality

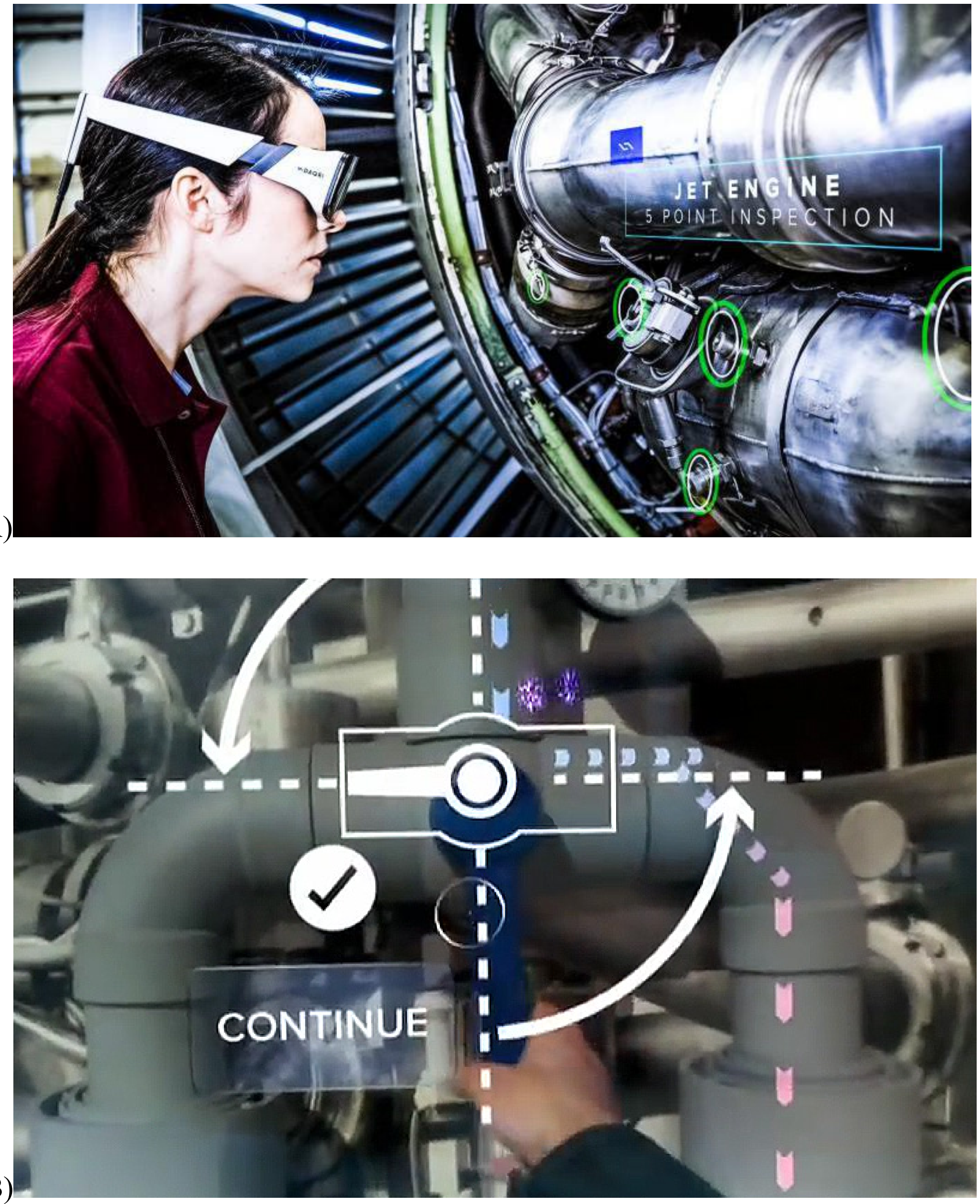
Augmented reality (AR)

AR is a medium in which real-time interactive digital information is overlaid on the physical world that is in both spatial and temporal registration with the physical world (Sherman & Craig, 2019).

Some VR applications are designed to combine virtual representations with perception of the physical world. The virtual representations can give the user additional information about the physical world not perceived by unaided human senses (such as pipes hidden behind a wall) or can add virtual objects to represent imaginary objects and characters. This type of application is referred to as augmented reality (AR), and sometimes as "mixed reality." In AR, the use of special display technology allows a user to perceive the real world with an overlay of additional information (Fig. 14). This term stems from Webster's (1989) definition of augment: "to make larger; enlarge in size or extent; increase." With augmented reality, we are typically increasing the amount of information available to the user in comparison to their normal perception, though there are cases where the " augmentation" is the digital removal of real-world information to reduce the complexity of the scene.

AR can be considered a type of VR. Rather than experiencing physical reality, one is placed in another reality that includes the physical along with the virtual. Conversely, VR can be considered a special case of AR in which the real world has been occluded.

Typically, it is the visual sense that is being augmented. For example, contractors who need information about the mechanical systems of a building might display the location of pipe and ductwork on the computer-connected HBO they wear as they walk through the building. Physicians might use AR to see the internal organs of a patient while simultaneously maintaining an external view of the patient's body (Sherman & Craig, 2019).

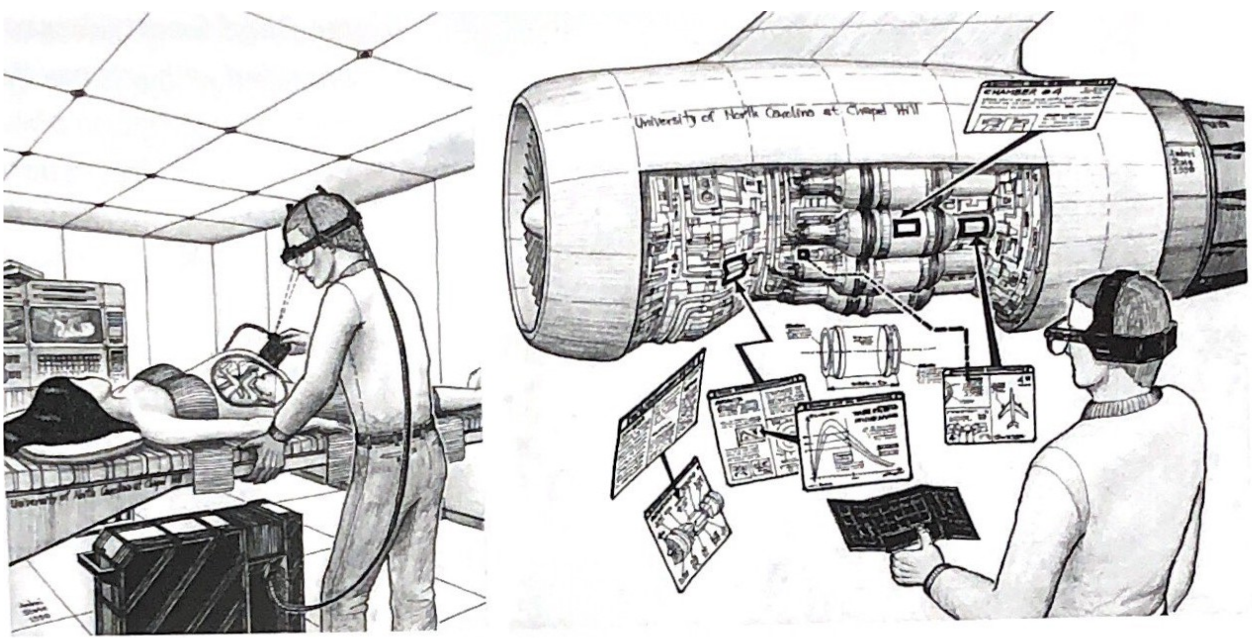


(A)

(B)

FIGURE 14 (A) A user wearing Daqri Smart Glasses is provided with in formation and documentation about a jet engine as she prepares to make an inspection. (B) Looking through a Smart Helmet, a user can see the direction of flow within the pipes, and the directions for and consequences of turning a valve-control lever. (Images courtesy of Daqri.)

Many possible AR applications focus on the concept of repairing the internal components of a living or mechanical system (Fig. 15). An example of one application of AR to medicine might be to allow students to manipulate and experiment with a digital cadaver in a real-world space. For example, the application could allow the student to preview their lab exercise while at home, and then to aid them when they are in the actual laboratory with the real cadaver. Note that similar examples can be devised for repair of mechanical systems, such as jet aircraft (Sherman & Craig, 2019).



(A) (B)

FIGURE 15 Augmented reality can be used to view systems that require investigation or repair.

(A) A physician is able to view 3D representations of ultra sound data of a baby aligned with its actual position within the mother. (B) A jet maintenance engineer is shown which parts need to be investigated and can refer to the documentation without moving away from the work area. (Drawings courtesy of Andrei State.)

Mixed reality (MR)

MR may take your view of the real world and integrate computer-generated content that can interact with that view of the real world. Or it may take a fully digital environment and connect it to real-world objects. In this way, MR can sometimes function similarly to VR and sometimes function similarly to AR. You'll often hear the terms being used interchangeably, which can be confusing. Here's a quick glance at the differences.

In MR, you may have a view of the real world, and a digital basketball may appear to bounce off the real-world floor and walls, or a digital rocket ship may appear to land on your coffee table. This is AR-based MR, and you'll often just hear these experiences referred to as AR.

In other MR instances, you may only see a completely digital environment with no view of the real world, but that digital environment is connected to real-world objects around you. In your virtual world, real-world tables or chairs may digitally appear as rocks or trees. Real-world office walls may appear as moss-covered cave walls. This is VR-based MR, sometimes called augmented virtuality.

Mixed reality is gaining traction in the industry, especially AR-based mixed reality. Remember that it is not uncommon for the terms augmented reality and mixed reality to be used synonymously (Mealy, n.d.).

FIGURE 16 SketchUp Viewer App for Microsoft HoloLens (by Skarredghost, 2017)

Case Study of making photorealistic mixed reality demo by Varjo and Volvo

(The content below is courtesy of Varjo.)

Mixed reality means blending virtual content with the real world. So far mixed reality has been accomplished with optical see-through, where the user sees digital objects augmented on top of reality through a pair of glasses. This is fine for portraying infographics or playing games, but for realistic scenes, it offers little value. Optical see-through devices can't display black or opaque content on top of the real world. Everything appears hazy and holographic.

We at Varjo wanted to get rid of this limitation and be able to render photorealistic, opaque content – where it is impossible to distinguish between what is real and what is virtual. Our mission was to make photorealistic mixed reality possible with video pass-through. Video pass-through means using cameras to digitize the world in real-time, and then showing the combined result of real mixed with virtual to the user.

Before we could achieve this, we first needed a VR headset capable of displaying the real world in human-eye resolution. That is why we released our first human-eye resolution product VR-1 (Fig. C1), targeted for professional users, to the market in February 2019.

And at Augmented World Expo 2019 in Santa Clara, we showed a glimpse of the magic that can be accomplished with video pass-through. We publicly demonstrated our new headset XR-1 Developer Edition (Fig. C2) for the first time with a joint demo with Volvo, made with Unity. With XR-1, you can blend virtual content seamlessly with reality with extremely low latency and integrated eye-tracking, in superior resolution (Davis, 2019).

Figure C1 Varjo VR-1

Figure C2 Varjo XR-1

Here's how the world's first photorealistic mixed reality demo was created:

Developing the XR-1 demo with Volvo and Unity

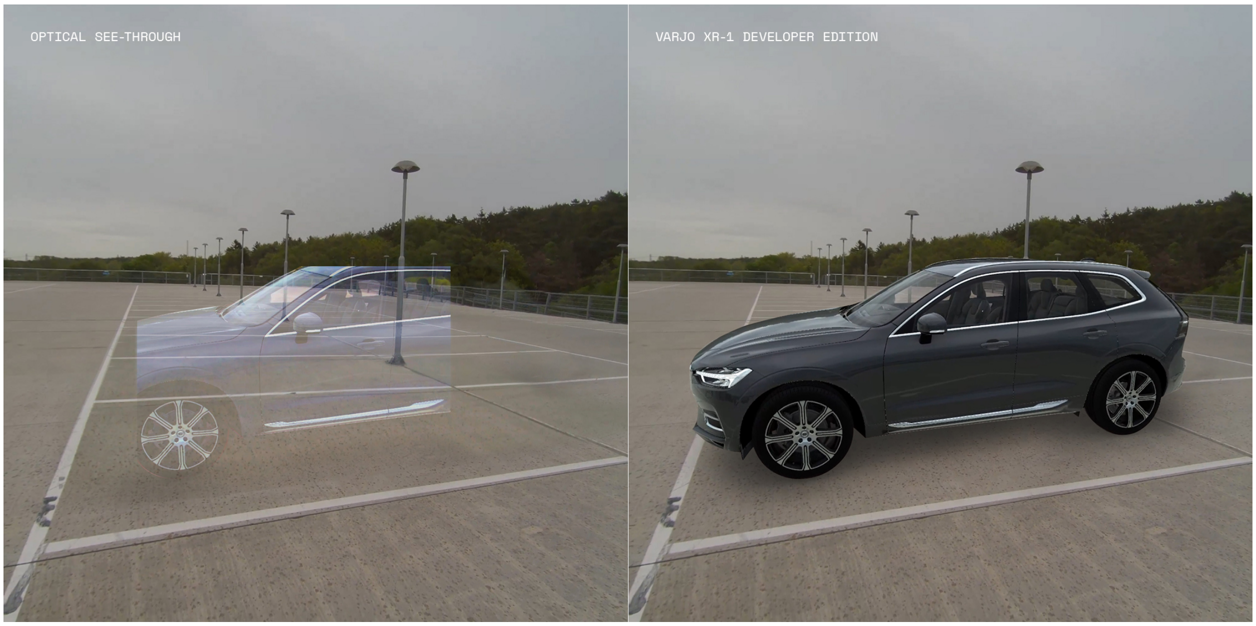


Figure C3 XR-1 demo by Varjo

Varjo began working on a video-pass through mixed reality headset in early 2018. The collaboration between Varjo and Volvo also started in spring 2018, as Volvo outlined the need for an XR headset that would allow them to test various elements of future cars – such as heads up displays, new materials, and UI for infotainment systems – inside a real car while driving on a real test track. The high requirements on readability and low-latency needed to drive a car on a test-track pushed Varjo to succeed in product development.

Given how well Unity already worked for the VR-1, it was a natural choice to try out how the virtual objects would appear in mixed reality. The fact that Unity is easy to integrate and extend with C++ libraries, such as our own Varjo plug-in, made it possible for us to extend our plug-in to support mixed reality. By simply defining the empty background in a VR scene to be replaced by the video-pass-through signal, we were quickly able to see virtual objects in a real environment.

The close collaboration and fast iterations were made possible by Unity's ease of use, as our team was developing and improving pass-through simultaneously while working hand in hand with our customer. A year later, the first public demonstration of XR-1 brought to life the capabilities of our technology, combined with Volvo's superior models and photorealistic Unity graphics (Davis, 2019).

The demo illustrates the power of video pass-through mixed reality as opposed to optical see-through. In this demo, you have the following steps:

1. Experience real reality

You see the real world around you through the XR-1 headset. The real world is streamed with <10ms latency via the high-res cameras in the front plate. You see the world in a full field of view and at a high resolution with a 90Hz framerate, which gives a sensation of not wearing any headset at all (i.e., seeing the real world with your own eyes). You can walk around and explore the real world freely (Davis, 2019).

2. Enter photorealistic mixed reality

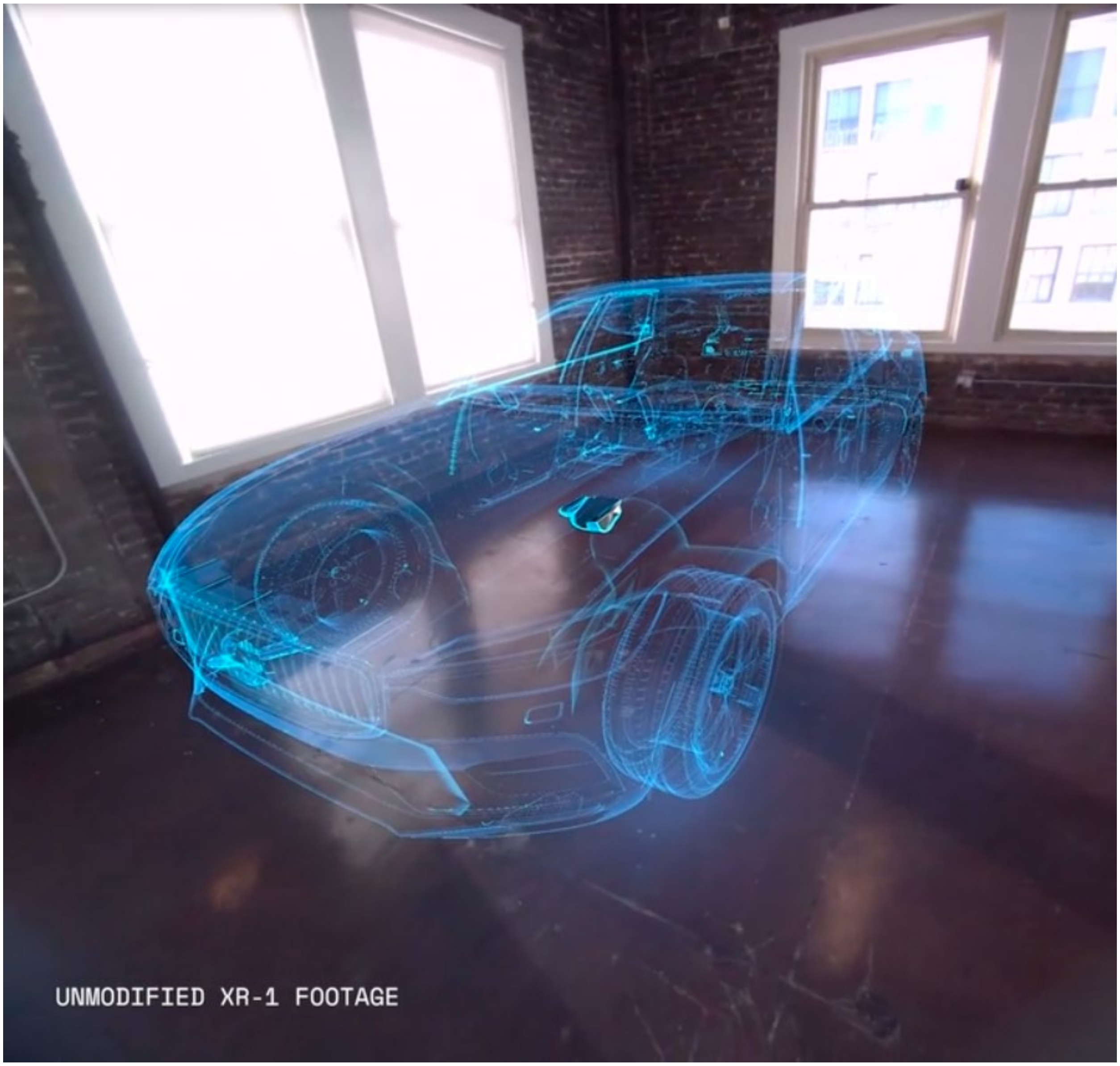


Figure C4 Volvo XC60 in XR

The Volvo XC60 builds up in front of you (Fig. C4). It first appears as a stylized transparent blue wireframe. The virtual car is anchored to the real floor in the room around you and oriented so that the chair in the booth is aligned with the driver's seat of the virtual car. The viewer can take a seat in the real chair and is still able to see the real surroundings through the wireframe.

The car now turns into a solid model, and the surfaces goes from transparent to opaque. The virtual car casts shadows on the floor of the real world, and looking on the car's surface, it is possible to see that the real world is reflected in the car's surfaces. The reflections come from an HDR cube map that was taken during setup on the exact spot of the car. The same cube map is also used for ambient lighting.

This is the first time the viewer sees opaque mixed reality, and the effect is stunning. You can still see the real world and your colleagues through windscreens (Davis, 2019).

How it was accomplished:

The car model was provided to Varjo by Volvo. Because the resolution of the headset and the car was so high, we needed to do as much pre-processing as possible. The lighting was baked in the DCC to textures and multiplied in custom shaders. The baked textures only dealt with occlusion and the shading is still affected by the skybox.

Mattias Wilkenmalm from Volvo handled asset creation and wrote custom car paint shaders that delivered superior results. We simply modified them to get the look and transitions we needed. The final model is around 7 million polygons and has around 150 4K textures (Davis, 2019).

3. Switch seamlessly into virtual reality – and back.

The viewer is then asked to step outside the car, and we transition to Venice. The last pieces of the real world around the viewer are now disappearing in a unique transition as the reality transforms into a virtual scene of Venice, where the car is parked in one of the alleys. The reflections in the car are now those of Venice, and the shadows of the car are now landing on the streets of Venice.

After a while, we transition back from virtual to the real world. The user can now go around the virtual car and see all the details and reflections. This shows that XR-1 offers the ability to still interact with others and select only the parts you want to virtualize (Davis, 2019).

How it was accomplished:

To make the transitions visually pleasing, Volvo’s Timotei Ghiurau, Lead, Virtual Experiences, and XR Research, used world space 3D noise with alpha cutouts to bring in the car and the environment. This is fast to do in the fragment and it looks very cool. It was a perfect combination when dealing with tight deadlines. Noise functions can be fetched from Unity’s Keijiro’s repository (Davis, 2019).

To get the smooth transition for the car reflections, the Venice environment was added to a separate layer so that the real-time reflection probe was only rendering the minimal amount of geometry. The reflection probe was rendered at 30 frames per second while the scene renders at a much higher frame rate. Having the transition visible in the reflection probe added much more immersion to the scene (Fig. C5) (Davis, 2019).

Figure C5 Reflection Setting, Unity

The fact that XR-1 is a first-of-a-kind headset to offer the ability to seamlessly switch from real reality into mixed reality onwards into full VR and back to reality again makes for a very impressive demo. It is a Matrix-like moment to see the surrounding reality disappear and replaced by a virtual scene and then traveling back (Davis, 2019).

Augmented virtuality

A term that has yet to gain much traction within the industry, augmented virtuality (AV), also sometimes called merged reality, is essentially the inverse of typical AR. Whereas AR refers to predominantly real-world environments that have been augmented with digital objects, AV refers to predominantly digital environments in which there is some integration of real-world objects. Some examples of AV include streaming video from the physical environment and placing that video within the virtual space or creating a 3D digital representation of an existing physical object.

Figure 17 shows an example screenshot of AV through Intel's recently defunct Project Alloy. Using 3D cameras, Intel was able to bring in interactive imagery of physical real-world objects (such as your hands) into its virtual environments (Mealy, 2018).

FIGURE 17 an example of AV from Project Alloy by intel. (Bruder, 2009)

Extended reality

Extended reality (XR) is the umbrella term for the entire spectrum of technologies discussed thus far (including VR, AR, and AV).

The virtuality continuum is a scale used to measure a technology's amount of realness or virtualness. On one end of the scale is the completely virtual, and on the other end is the completely real. XR spans the full spectrum of this scale, from end to end.

Figure 18 shows where these terms fall on this scale developed by technology researcher Paul Milgram in the 1990s. Remember, though, that MR and AR, while separated in this chart for definition's sake, are often used synonymously to refer to the spectrum that MR is shown covering here (Mealy, 2018).

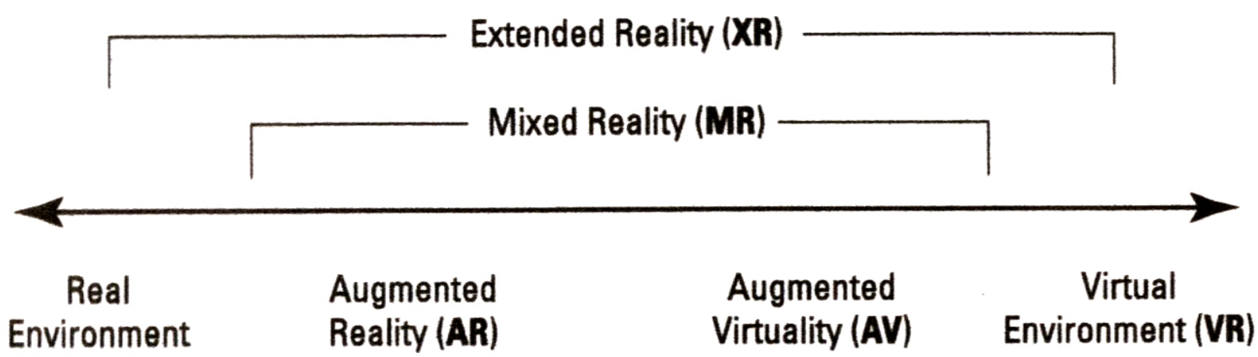


FIGURE 18 Paul Milgram's reality-virtuality continuum

As mentioned earlier in this chapter, in this study, the term "Immersive Technology" has been and will be used to address all the areas mentioned above. The purpose of discussing Extended Reality in here was only to clarify that in some sources this term might be used.

History

It is important to have an overview of the history of the technologies, ideas, and influences from which this new medium has evolved. By exploring some of the milestones that have led to the advent of VR technology, the source of many current interface ideas becomes evident. We look at how content has sometimes been driven by technology and technology by content. The rapid progression of technology has increased our expectations of what will be possible with VR in the not-so-distant future (Sherman & Craig, 2019).

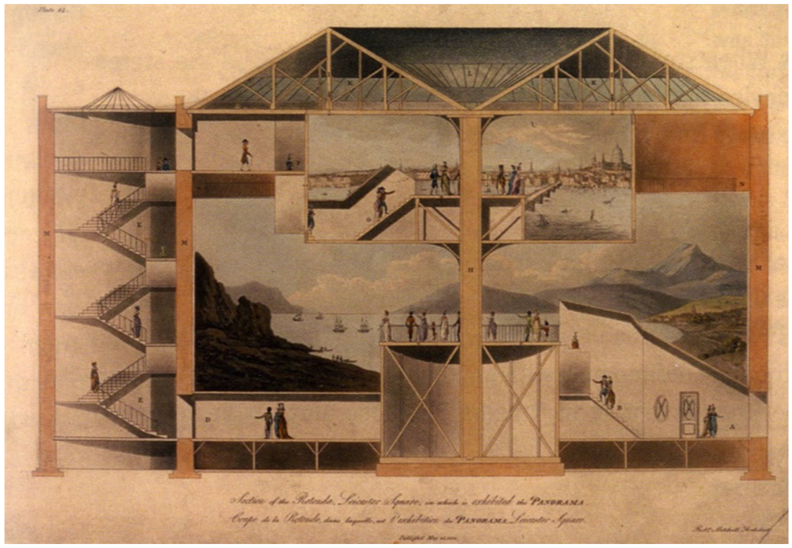
1435/36

Leon Battista Alberti first published the mathematics of linear perspective (single-point) rendering. Though we know painters and artists had been exploring the concepts of perspective in their renderings over the millennia (and not just linear perspective, but also oblique and isometric). Plus, it is very likely that Brunelleschi worked out the mathematics of linear perspective for his baptismal perspective experiment, but without publishing the methods (Sherman & Craig, 2019).

1787

In England, Robert Barker patents "Apparatus for Exhibiting Pictures," wherein the pictures were 360-degree paintings and the "apparatus" is a special building designed to house and exhibit these "panoramas" (Fig. 19). He would first publicly display his work in1788 in Edinburgh, moving it to London in1792 (Sherman & Craig, 2019).

(A)



(B)

FIGURE 19 (A) A cross-section of the London building where Robert Barker displayed his panoramic paintings. (B) Panoramic painting "Edinburgh from The Crown of St. Giles" (1972) attributed to Robert Barker from (1739-1806) and Henry Aston Barker (1774-1856) is one of the original views used by Barker in his360-degree displays. (Image A public domain; image B courtesy of City Art Centre, City of Edinburgh Museums & Galleries.)

1838

Sir Charles Wheatstone researches stereopsis and invents the stereoscope-a device that presents two separate photographs to the viewer, each photo taken from an offset to produce left and right views of a scene (Sherman & Craig, 2019).

1915

The first anaglyphic 3D movie film experiments were conducted by Edwin S. Porter and W.E. Wadell (Sherman & Craig, 2019).

1916

US Patent 1,183,492 for a head-based periscope display is awarded to Albert B. Pratt (Fig. 20) (Sherman & Craig, 2019).

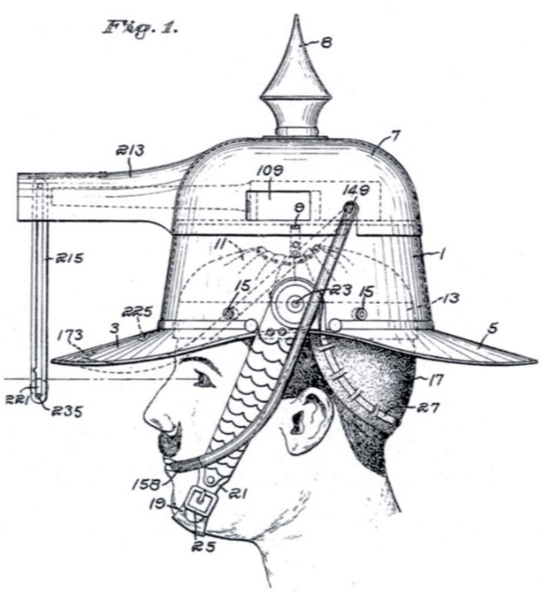


FIGURE 20 The first head mounted display (a periscope) is patented in1916. (Image courtesy of United States Patent & Trademark Office.)

1929

After several years of flight training via "penguin" trainers (aircraft with shortened wings unable to generate enough lift to get off the ground), Edwin Link develops a mechanical flight simulator to train a pilot at a stationary (indoor) location (Fig. 21). The trainee can team to fly and navigate using instruments via instrument replicas in the cockpit of the Link Trainer (Sherman & Craig, 2019).

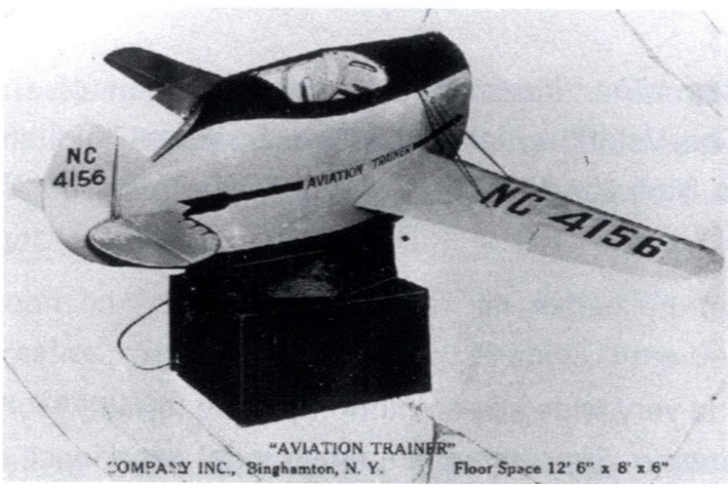


FIGURE 21 Flight simulation was an early form of "virtual reality'" technology. Pilots con train in synthetic environment that behaves as if they were actually flying. Early simulators used mechanical linkages to provide control and feedback Although flight simulators predated the modern digital computer; today they use highly sophisticated computers, simulation programs, tracking, and display technology. (Photo courtesy of the Roberson Museum.)

1935

“Pygmalion's Spectacles”, a short story by Stanley G. Weinbaum is published in Hugo Gemsback's *Wonder Stories* periodical “Weinbaum 1935” (Fig. 22). The story is about a device one wears that makes "dreams" become reality. “Fools! I bring it here to sell to Westman, the camera people, and what do they say? 'It isn't clear. Only one person can use it at a time. It's too expensive.' Fools! Fools!" (Sherman & Craig, 2019).

FIGURE 22 This illustration for the short story "Pygmalion's Spectacles" conveys how by wearing a pair of special glasses, the wearer is immersed into a virtual world.

1961

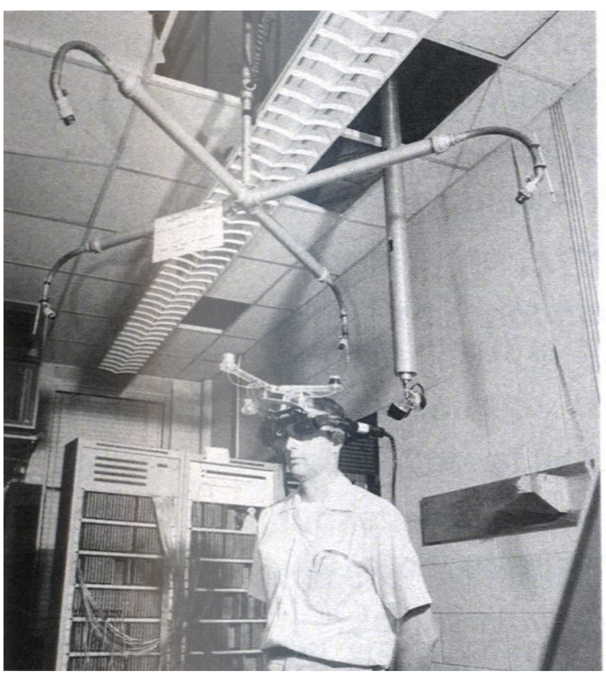
Philco engineers Comeau and Bryan (1961) create an HMD for use as a head-movement-following remote video camera viewing system. Head tracking and remote-camera movement were only about the yaw axis, with an electromagnetic coil mechanism to sense head rotation. They went on to start the company Telefactor Corp. based on their research in telepresence (Fig.23) (Sherman & Craig, 2019).

FIGURE 23 Early example of an HMO-based telepresence system. (Image courtesy of Electronics, VNU Business Publications, New York.)

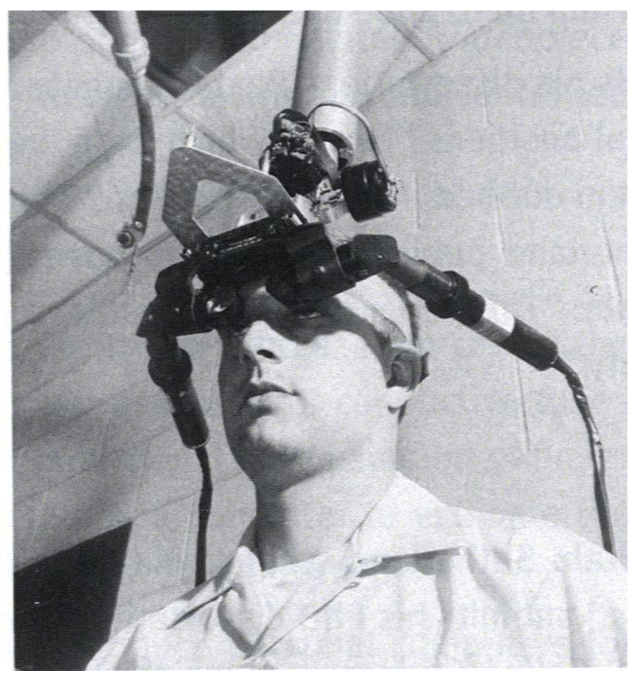
1968

Evans and Sutherland Computer Corporation is founded in 1968 by University of Utah computer science professors David Evans and Ivan Sutherland.

In his paper "A Head-mounted Three-Dimensional Display", Ivan Sutherland (1968) describes his development of a tracked stereoscopic HMO at Harvard University (and brought with him to Utah University) (Fig. 24). The display, which Sutherland first encountered at Bell Helicopter as part of a telepresence experiment for helicopter pilots, uses miniature cathode ray tubes (CRTs), similar to a television picture tube, with optics to present separate Images to each eye and an Interface to mechanical (nicknamed "The Sword of Damocles") and ultrasonic trackers. Sample virtual worlds include a stick representation of a cyclohexane molecule and a simple cubic room with directional headings on each wall (Sherman & Craig, 2019).



(A)



(B)

FIGURE 24 Ivan Sutherland created a viable head mounted display in 1968. The display provided stereoscopic visual images, mechanical and ultrasonic tracking, and a demonstration of the potential of virtual reality. (A) The mechanism for ultrasonic tracking places emitters at the end of four pipes. (8) Quintin Foster wears the HMO connected to the ceiling via a mechanical linkage (known as The Sword of Damocles) used to track the position of the wearer. (Photographs courtesy of Ivan Sutherland.)

1972

Developed by Atari, Pong brings real-time, multi person interactive graphics to the public (Fig.25). (Magnavox beat Atari to the home market with their Odyssey system, but Atari's coin operated version of Pong was the game that initiated the revolution.) In 1981, Atari would create a Research Labs division under Alan Kay, bringing together a cast of many future VR pioneers: Fisher, Bricken, Foster, Laurel, Walser, Robinett, and Zimmerman, among others (Sherman & Craig, 2019).

FIGURE 25 Atari brought interactive computer graphics to the mass market with the introduction of their Pong game. (Photograph courtesy of Atari Historical Society.)

1977

The Sayre Glove is developed at the Electronic Visualization Lab at the University of Illinois at Chicago. This glove uses light-conductive tubes to transmit varying amounts of light proportional to the amount of finger bending. This information is interpreted by a computer to estimate the configuration of the user's hand “DeFanti & Sandin, 1977”.

Commodore, Radio Shack, and Apple introduce personal computers for off-the-shelf use at home (Sherman & Craig, 2019).

1983

At MIT, Mark Callahan develops an early HMD which is one of the first university research projects involving HMO-styleVR outside Sutherland's work at Harvard, then Utah (Sherman & Craig, 2019).

1989

On June 6, VPL announces a complete VR system-RB-2 (Reality Built for 2) introducing the phrase ***virtual reality*** (Fig. 26).

Also, on June 6, Autodesk, Inc. announces their *Cyberspace* project, a 3D world creation program for the PC.

Division, Ltd. begins marketing VR hardware and software. They later drop their "transputer" hardware design efforts and license the *Pixel Planes* technology from the University of North Carolina at Chapel Hill. Division later sold the hardware component to Hewlett Packard to concentrate development on their software toolkit-ProVision VR.

Mattel introduces the *Powerglove* glove and tracking system for the *Nintendo* home video game system. It fails as a video game product but becomes a popular device for low-cost VR facilities and "garage" (i.e., DIY) VR enthusiasts.

Sorenson et al. (1989) publish on their work on "The Minnesota Scanner," which they call "A prototype sensor for three-dimensional tracking of moving body segments," and where body segments can be of a human, or of a robot. This concept is the one around which the HTC Vive Lighthouse tracking system works (Sherman & Craig, 2019).

FIGURE 26 This user experiences and interacts with a virtual world using the VPL Eyephones and Datagloves. (Image courtesy of NCSA.)

1992

Stationary (projection) VR is introduced as an alternative to the head-based paradigm at the SIGGRAPH '92 computer graphics conference in W Chicago. The main attraction of the Showcase '92 venue at SIGGRAPH was the CAVE (Fig. 27), conceived and developed by Tom DeFanti, Dan Sandin and their team at the Electronic Visualization Lab at the University of Illinois at Chicago with a variety of scientific and artistic applications demonstrating the technology "Cruz-Neira et al.1992".

Also, at SIGGRAPH '92, Sun Microsystems, Inc. introduces a similar display, The Virtual Portal. A major difference between these two displays is that the Virtual Portal was designed to accommodate only one individual within the immersive experience, whereas the CAVE allows up to 10 people to share the visuals, though with 1 person at a time having the optimal view.

Neal Stephenson's "Snow Crash" is published-a novel in which is described a multiparticipant virtual world with a VR interface (The Metaverse).

Logitech releases an integrated active-stereoscopic glasses and 3D mouse ("3D Mouse & Head Tracker") that are tracked via the ultrasonic method of tracking (Fig. 28). The ultrasonic receivers are integrated directly into the glasses and wand, making them ideal for desktop-sized fishtank VR systems "Logitech 1991".

Ascension Technologies releases the "Flock of Birds" system which provides for "long-range" (~6ft/2m) tracking of multiple receivers ("birds") using DC-pulsed electro-magnetic fields. This became a common system for CAVE and similar Stationary VR display systems (Fig. 29) (Sherman & Craig, 2019).

FIGURE 27 The CAVE, on display publicly for the first time at the SIGGRAPH '92 computer graphics conference in Chicago, generated long lines of people eager to see the new technology. (Image courtesy of the Electronic Visualization Lab at the University of Illinois at Chicago.)

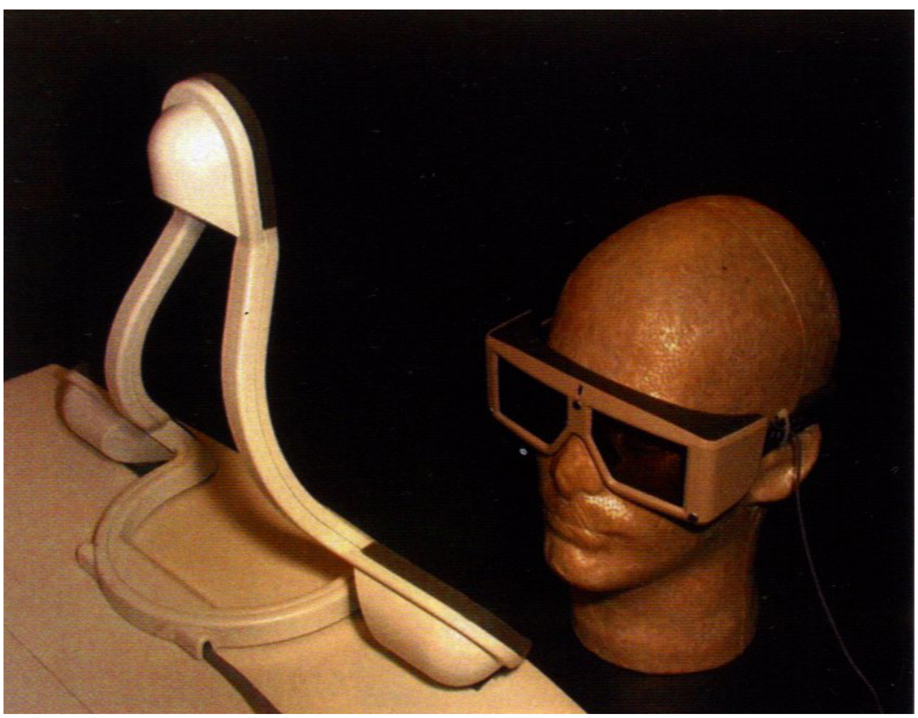


FIGURE 28 Logitech desktop 6-DOF tracking system based on ultrasonic signals which emanate from the three corners of the emitter and are transduced by microphones embedded in the active stereoscopic glasses worn by the user. (Photograph by William Sherman.)

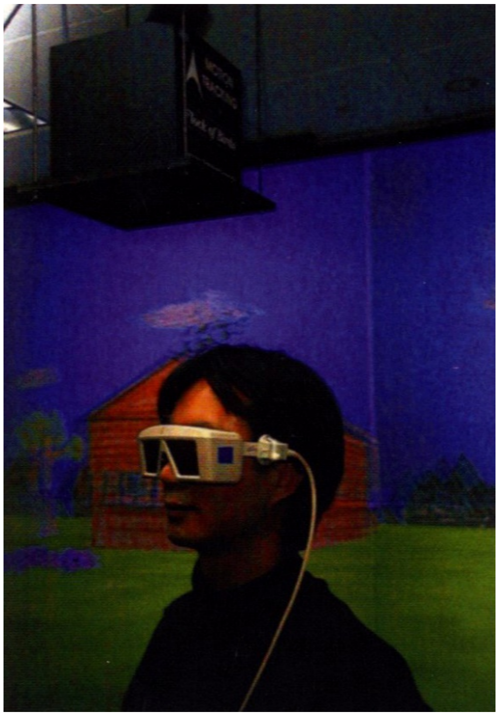


FIGURE 29 A user wears a pair of stereoscopic glasses onto which an Ascension Flock of Birds magnetic receiver has been attached to determine the relative position of the user from the emitter unit (black box) mounted near or within the VR system. (Photograph by William Sherman.)

1997

Virtual Technologies, Inc. introduces their *CyberGrasp* hand-based force feedback device (Fig. 30). This display allows the VR system to restrict the ability of the wearer to close individual fingers, enhancing the sense of touching and grasping in a virtual world (Sherman & Craig, 2019).

FIGURE 30 The CyberGrasp force feedback display (coupled with the CyberTouch input glove) uses a movement restriction technique to limit finger movement and thus provide feedback to the wearer's hand. (Image courtesy of CyberGlove systems Inc.)

2005

The Unity game engine is first released for the Apple OS/X operating system. It has since been ported to other platforms and is a popular choice for developing interactive experiences. Eventually, in addition to traditional game developers, Unity grew into a prevalent choice for VR and AR developers as well for quickly creating content for VR and AR applications (Sherman & Craig, 2019).

2012

The USC Institute for Creative Technologies (ICD MxR Lab releases the FOV2GO-a DIY HBD viewer that makes use of an individuals' smartphone with IMU as the tracker, computer, and display for VR. The viewer, made of foam-board and plastic optics, uses software developed at ICT to make use of a phone's internal inertial tracking and output a stereoscopic image pair based on the movement of the phone (Sherman & Craig, 2019).

Palmer Luckey, a student intern at the MxR Lab, runs a successful Kickstarter campaign for the Oculus Rift low-cost HMD (Fig. 31). A project sprouting from an interactive gaming student group at the University of Southern California, the Oculus Rift moves from prototype to production, with first-generation development units (DK-1) shipping in 2013, second generation (DK-2) shipping in 2014, and consumer units arriving in 2016.

The CAVE2 is introduced. The CAVE2 is based on consumer-grade flat panel HDTVs with passive stereoscopic capability. In conjunction with IMIU Omegalib and SAGE, it manifests a hybrid reality environment that integrates 2D data and meeting spaces with traditional VR (Sherman & Craig, 2019).

FIGURE 31 Funded through a Kickstarter campaign, the first Oculus Rift Development Kit (DK-1) reignited broad interest in virtual reality. (Photograph by William Sherman.)

2016

In 2016, after 50 years of progress, VR becomes an overnight success.

Oculus VR releases their first consumer-oriented VR display product (CV-1) through a preorder system. The initial system includes the HMD, a camera for video-based position tracking, and an untracked Xbox game controller for user input. Late in the year they release their Oculus Touch 6-DOF tracked hand controllers.

HTC and Valve release their first consumer-oriented VR display product (the Vive) through a preorder system. In addition to the HMD, the Vive system includes two "Lighthouse" tracking units as well as two fully tracked hand-held input controllers.

Daqri makes their "Smart Helmet" commercially available for industrial use. The Smart Helmet is an integrated AR system that includes a computational unit, a variety of sensors including thermal and EEG, in addition to those used for tracking. It is all contained within a personal protective equipment helmet to replace the traditional hardhat.

Microsoft releases their HoloLens development kit units for early exploration and development by research and consumer software organizations. The HoloLens is an all-in-one AR display that includes inside-out (SLAM) tracking, and a computational unit with rendering, in addition to the see- through optics.

Sony releases their "PlayStation VR" head-worn display, to be coupled with the PlayStation camera and Move controllers and used with the PlayStation 4 gaming console (Sherman & Craig, 2019).

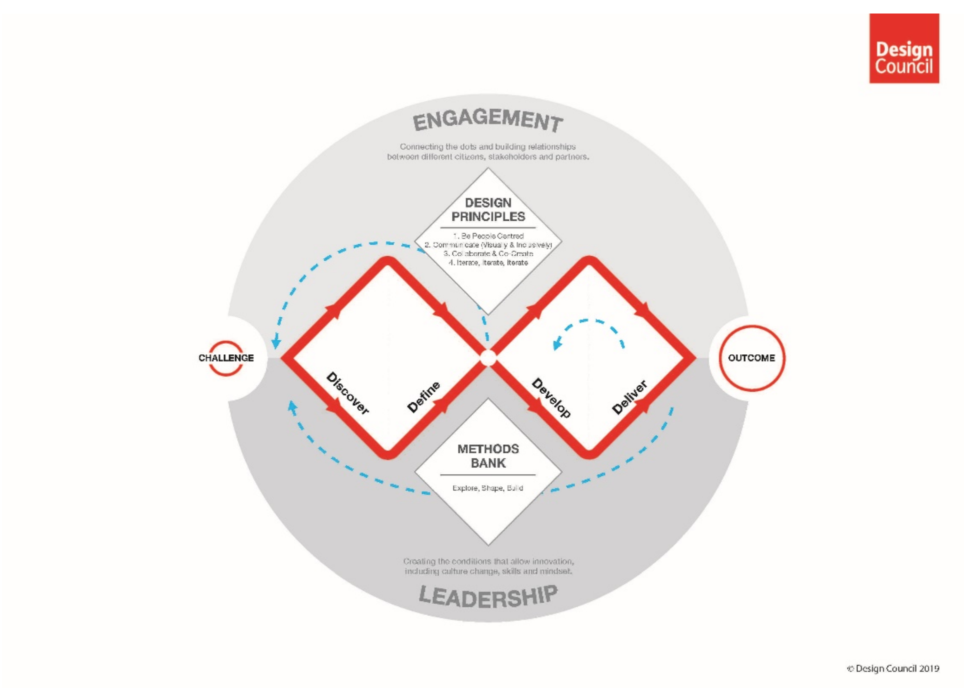
Design Process

Design is a problem-solving process. Through design history, there are many design processes and methodologies developed via organizations, design firms and even individuals. In this section, some of these processes which are more popular are going to be indicated so that later it can determine where Immersive Technology can be useful during the design process.

Double Diamond

Double Diamond design process, developed by British Design Council, is one of the most well-known and popular processes that is used by industrial designers, service designers and more recently UX designers. Design Council explains" Design Council's Double Diamond clearly conveys a design process to designers and non-designers alike. The two diamonds represent a process of exploring an issue more widely or deeply (divergent thinking) and then taking focused action (convergent thinking) (Design Council, n.d.).

FIGURE 32 Double Diamond design process by British Design Council



To show the details of the double diamond design process, we are going through the revamped version of double diamond, developed by Dan Nessler, which has more details and minor phases while keeping the core of the process.

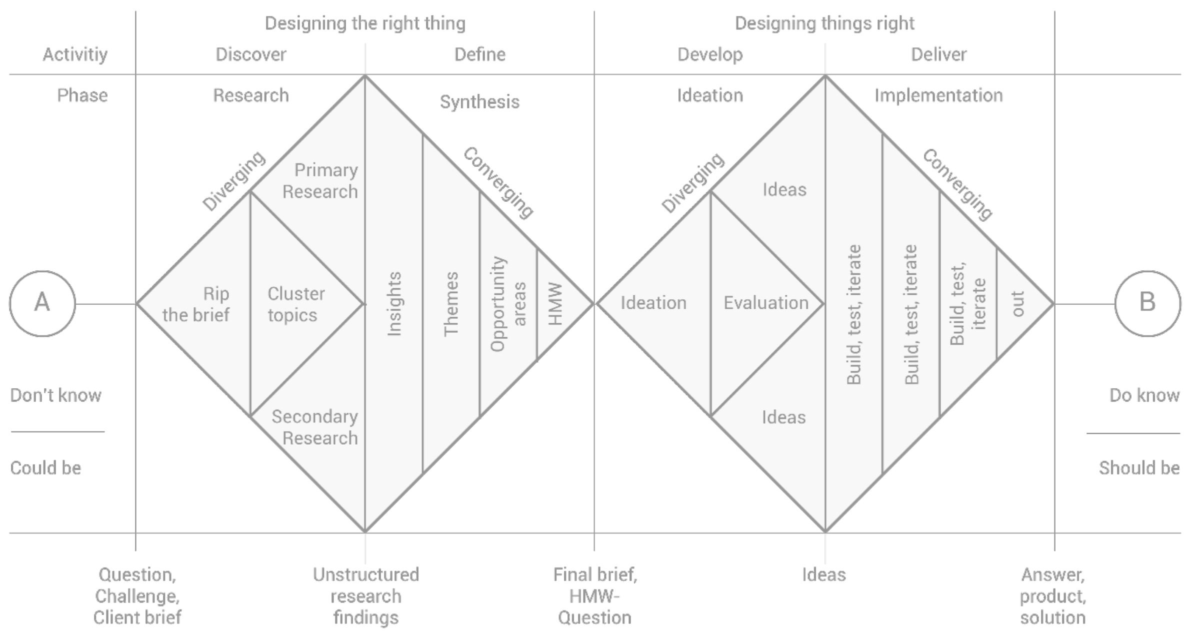


FIGURE 33 Revamped Double Diamond Design Process by Dan Nessler, 2016.

The Double Diamond is a structured design approach to tackle challenges in four phases:

1. Discover /Research— insight into the problem (diverging)
2. Define/Synthesis — the area to focus upon (converging)
3. Develop/ Ideation— potential solutions (diverging)
4. Deliver /Implementation— solutions that work (converging)

Phases of this process are either diverging or converging. During a diverging phase, you try to open up as much as possible without limiting yourself, whereas a converging phase focuses on condensing and narrowing your findings or ideas.

If you google the Double Diamond you are bound to find various interpretations and also varying wordings. I am going to stick to the version above as its wording allows flexibility and agility in its application in my opinion. Or in other words, it is the most appealing recipe to me.

The four phases of the Double Diamond may be simplified and merged into two main stages of the process.

Stage 1 — Doing the right thing (Diamond 1 — Discover and Define)

Whatever you do, you ought to look for the right problem to solve or the right question to ask before you try to do so. This is all about what you do.

Stage 2 — Doing things right (Diamond 2 — Develop and Deliver)

Once you have found the right question to answer or the right problem to solve, you want to make sure that you do this the right way. This is all about how you do it.

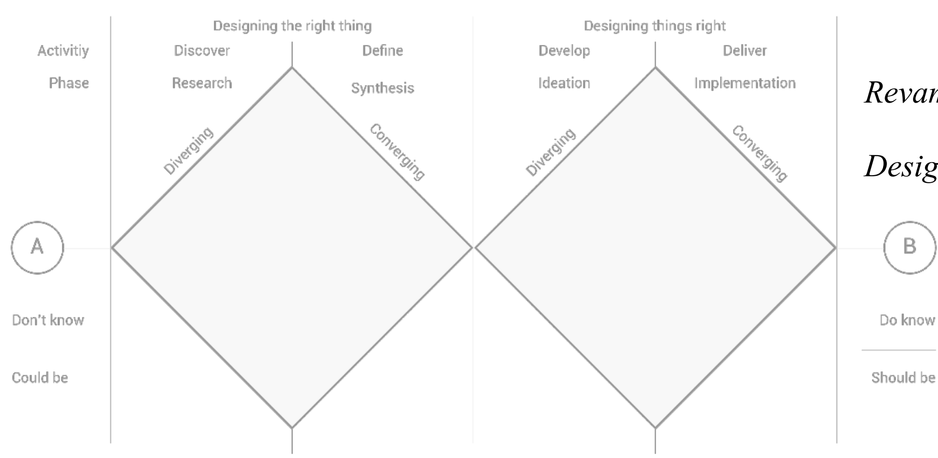


FIGURE 34

Revamped Double Diamond Design Process by Dan Nessler, 2016.

Stage 1 — Doing the right thing (Diamond 1 — Discover and Define)

This phase is split into Discover/Research and Define/Synthesis.

Discover / Research

1. **Rip the brief** (the usual starting point of your challenge) — Try to question the brief or your initial question by challenging every part of it and evaluating fields of interests.

List as many elements as you can, find characteristics, define areas of interest and extremes, list places, people (personas), experiences that are related and can be explored.

2. Before you dive into your research, **cluster your findings into topics** to get an overview and you might have to limit yourself in terms of the scope you want to research.

3. Dive into your **research**. Apply **primary** (field) and **secondary** (desk) research methods.

As a result, you ought to end up with a huge pile of unstructured research findings.

Define / Synthesis

In order to make sense of your findings, you want to synthesize your research by applying the following steps:

1. **Download** (summaries your raw findings and share them with your team) all your research.

2. **Cluster learnings** and similarities to themes.

3. **Find insights** (insights are the dormant truth about the consumer's motivations, wishes or frustrations regarding a specific topic)

build opportunity areas (a phrasing of the potential area of action).

4. **Create HMW questions** (A so called "how might we..." question that makes a tangible statement of what is to be done or solved within the area of action).

As a result, you ought to come up with a revamped brief (final brief, HMW-question) that either clarifies or details the initial brief challenge or even contradicts it.

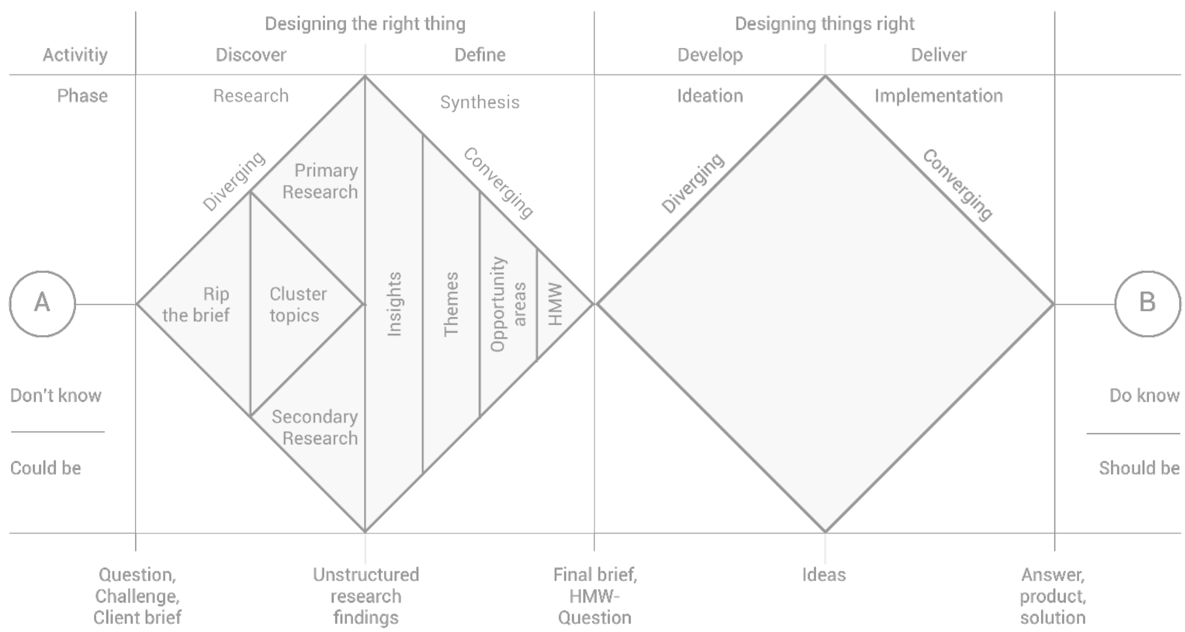


FIGURE 35 Revamped Double Diamond Design Process by Dan Nessler, 2016.

Stage 2 — Doing things right (Diamond 2 — Develop and Deliver)

This phase is split into Develop/Ideation and Deliver/Implementation.

Develop / Ideation

As you have deduced the actual question to solve or challenge, you start ideating.

1. **Ideation.** This is the fun part and as it is part of a diverging phase. You should restrain from limiting yourself and approach ideation with an open mind. Do not judge during ideation. Apply a "yes, and…" rather than a "no…" or "yes, but…" mentality. Let anything happen at this point and build upon each other's ideas.

2. **Evaluation.** Towards the end of an ideation phase, evaluate your ideas and select your favorite ones.

As a result, you ought to end up with one or a small number of ideas you want to later prototype and test, in order to find the best answer or solution to your initial question or problem.

Deliver / Implementation

Once you have come up with potential solutions (set of ideas), you want to evaluate the final one and the way it needs to be implemented or executed. In order to so, you may apply an agile approach consisting of three steps:

1. **Build/Prototype**
2. **Test/Analyse**
3. **Iterate/Repeat**

Aim for MVPs — minimum viable products/prototypes, that offer enough tangibility to find out whether they solve the initial problem or answers the initial question.

As a result, you ought to be able to go “out” with your final proposal, product, answer or solution (Nessler, 2016).

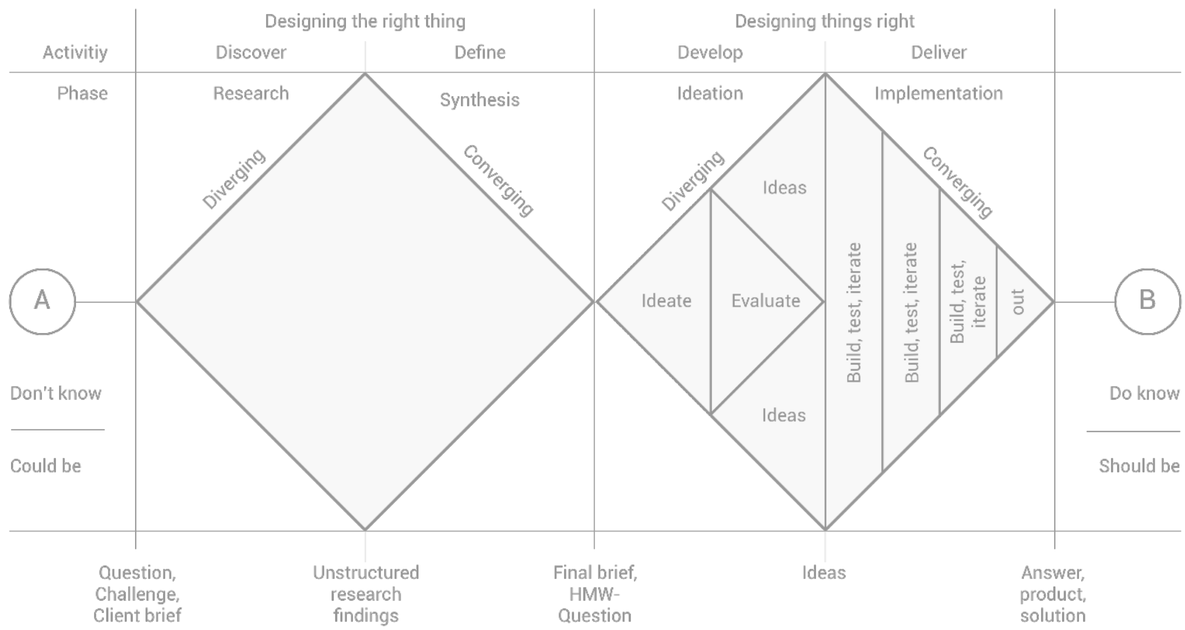


FIGURE 36 Revamped Double Diamond Design Process by Dan Nessler, 2016.

Circular Design Process by Walter Schaer

Schaer's method (Figure 37) is a cybernetic process, divided into three design phases; research (information), development (formation), and presentation (communication).

It was designed to be used by the industrial design students of Auburn University as a guideline for the formulation of a problem-solving process for design problems. The latest revision includes reference to problem-solving tools that may be used as an aid in satisfying the requirements of the steps within the process. It is one of the few design methods that provide this reference to the problem-solving tools and can prove to be an invaluable assistance in problem situations for the industrial designer. The steps within the process are presented in a logical sequential order and are self-explanatory. It is suggested that they be used as an outline in formulating a more specific process by the designer to fit his particular problem situation.

The general characteristics of this process leave it very flexible in terms of interpretation to various design techniques as well as serving as a logical statement of the design process for most any problem situation. One would be hard pressed to discover steps within this process that do not apply to any problem situation the industrial designer is required to solve. As a guideline, it is a valuable tool and thus played an important role in formulating the design method presented by the author (Borzak, 1974).

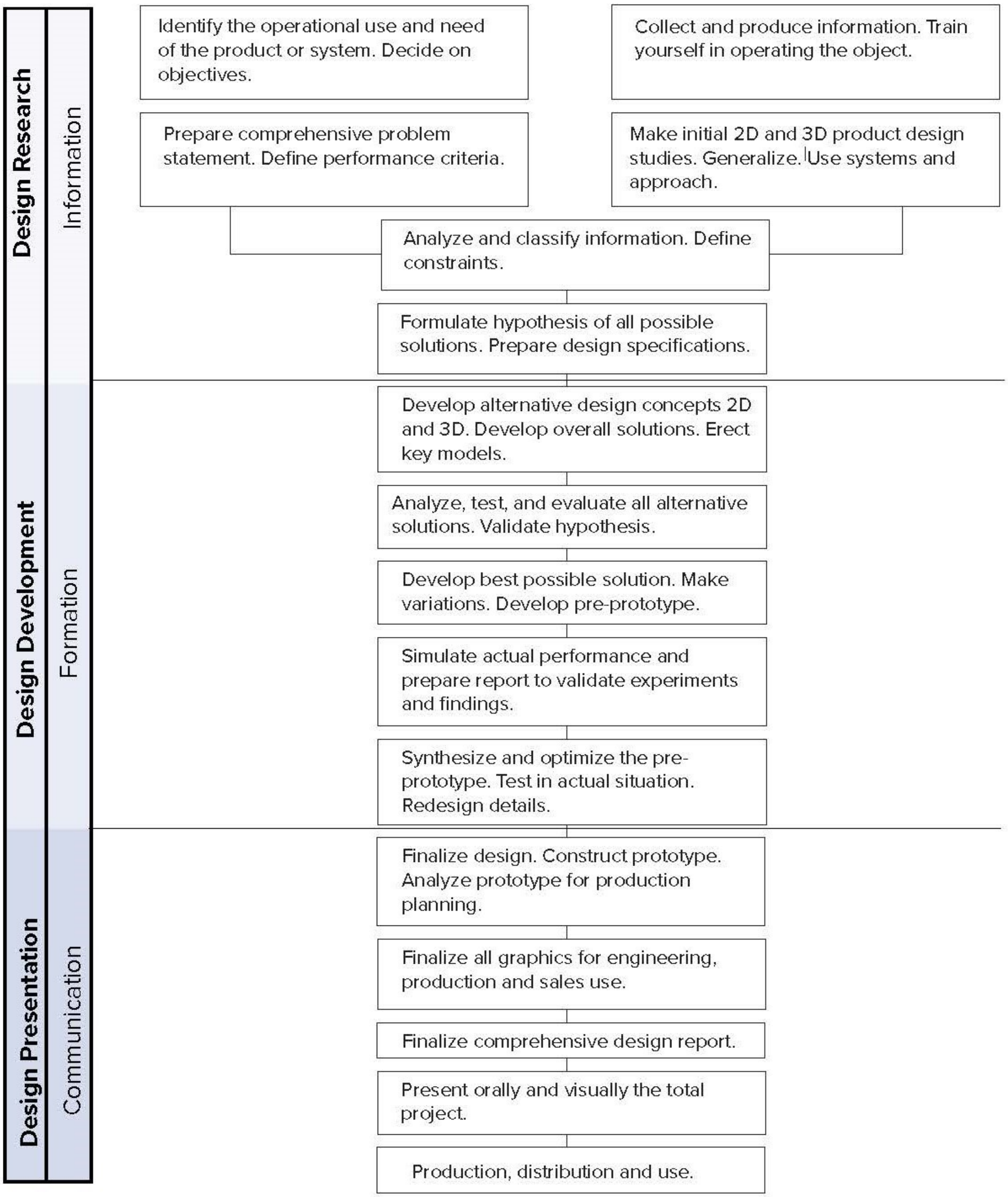


FIGURE 37 Walter Schaer's Circular Design Process

IDSA Design Tools

IDSA (Industrial Design Society of America) has provided a set of tools that designers can use through their design process.

1.IDEA SKETCH

Employed at a personal level to quickly externalize thoughts using simple line-work. Also known as Thumbnail, Thinking or Napkin Sketch.

2. STUDY SKETCH

Used to investigate appearance, proportion and scale in greater detail than an Idea Sketch. Often supported by the loose application of tone/color.

3. REFERENTIAL SKETCH

Used to record images of products, objects, living creatures of any relevant observations for future reference or as a metaphor.

4. MEMORY SKETCH

Helps expand thoughts during the design process using mind maps, notes and annotations.

5. CODED SKETCH

Informal coded representation that categorises information to demonstrate an underlying principle or scheme.

6. INFORMATION SKETCH

Quickly and effectively communicates features through the use of annotation and supporting graphics. Also known as Explanatory or Talking Sketch.

7. SKETCH RENDERING

Clearly defined proposal produced by controlled sketching and use of color/tone to enhance detail and realism. Also known as First Concept.

8. PRESCRIPTIVE SKETCH

Informal sketch for the exploration of technical details such as mechanisms, manufacturing, materials and dimensions.

9. SCENARIO & STORYBOARD

Describes interactions between user and product, sometimes in an appropriate context.

10. LAYOUT RENDERING

Defines the product, proposals as a third angle orthographic projection with precise line and color.

11. PRESENTATION RENDERING

Contains a high level of realism to fully define product appearance as a perspective view. Particularly useful for decision making by non-designers.

12. DIAGRAM

Schematic representation of the operating principle of relationship between components. Also knows as a Schematic or Diagrammatic Drawing.

13. PERSPECTIVE DRAWING

Descriptive three-quarter view produced using a perspective drawing technique. Created using line only without the application of color or tone.

14. GEN. ARRANGEMENT DRAWING

Exterior view of all components using line only and with sufficient detail to produce an Appearance Model if required. Usually drawn in third angle projection.

15. DETAIL DRAWING

Contains detail of components for the manufacturing product. Also known as Technical, Production or Construction Drawing.

16. TECHNICAL ILLUSTRATION

Communicates technical detail with a high degree of realism that is sometimes supported with symbols. Includes Exploded views.

17. SKETCH MODEL

Informal, relatively low definition 3D model that captures as the key characteristics of form. Also known as a Foam Model for 3D Sketch.

18. DESIGN DEVELOPMENT MODEL

Simple mock-up used to explore and visualize the relationships between components, cavities, interfaces, and structures. Usually produced using CAD.

19. FUNCTIONAL MODEL

Captures the key functional features and underlying operating principles. Has limited or no association with the product's final appearance.

20. OPERATIONAL MODEL

Communicates how the product is used with the potential ergonomic evaluation.

21. APPEARANCE MODEL

Accurate physical representation of product appearance. Also known as a Block Model as it tends not to contain any working parts.

22. ASSEMBLY MODEL

Enables the evaluation and development of the methods and tools required to assemble products components.

23. PRODUCTION MODEL

Used to evaluate and develop the location and fit a of individual components and sub-assemblies.

24. SERVICE MODEL

Supports the development and demonstration of how a product is services and maintained.

25. EXPERIMENTAL PROTOTYPE

Refined prototype that accurately models physical components to enable the collection of performance data for further development.

26. ALPHA PROTOTYPE

Bring together key elements of appearance and functions for the first time. Uses of simulated production materials.

27. BETA PROTOTYPE

A refined evolution of an Alpha Prototype used to evaluate ongoing design changes in preparation for the final specification of all components.

28. SYSTEMS PROTOTYPE

Integrates components specified for the production item without consideration of the appearance. Used to evaluate electronic and mechanical performance.

29. FINAL HARDWARE PROTOTYPE

Developed from the Systems Prototype as a final representation of the product's functional elements.

30. OFF-TOOL COMPONENT

Product using the tooling and materials intended for production to enable the evaluation of material properties and appearance of components.

31. APPEARANCE PROTOTYPE

Highly detailed representation that combines functionality with exact product appearance. Uses or simulates production materials.

32. PRE-PRODUCTION PROTOTYPE

Final prototype produced using production components. Manufactured in small volumes for testing prior to full scale production.

Chapter 3: Guidelines for using Immersive Technology

Overview

This chapter provides a set of guidelines that helps industrial designers implement Immersive technology into their design process. It is important to remember every design situation is different and presents its own challenges and that immersive technology is merely a tool and a communication medium; it cannot, and should not, be used in every situation.

This being said, the guidelines are designed to help answer when and how immersive technology can be applied within the context of the industrial design. However, that does not mean designers should apply the immersive technology at every applicable phase of design process that is named in these guidelines. Within these guidelines, the reader will also find an overview of common features of different types of immersive technology.

It is also important to remember that these guidelines have been formed based on the current state of the technology. This technology, with the current state of term, is fairly new and is improving rapidly. Therefore, there might be some new features and capabilities in the future that clearly could not be claimed in these guidelines.

Benefits and Features

In Chapter 2 we learned about different types of immersive technologies and how each type provides a different immersive experience to the user. Now, after a short review on the different types of immersive technology, we are going through benefits of each types and will see what capabilities and features each type has and whether that can be useful for the industrial designers or not.

Immersive Technology, generally, consists of Virtual reality (VR), Augmented reality (AR), Mixed reality (MR) and Augmented virtuality (AV).

Virtual Reality (VR)

VR is a computer-simulated reality that simulates a fully artificial environment that does not physically exist. Users within VR are closed off from the real world (Mealy, n.d.).

VR itself can be grouped into three paradigms:

- Stationary (fishtank and surround)
- Head Based (Occlusive, nonocclusive, smartphone, and projective)
- Hand Based

Each paradigm has its own benefits which can be named as the following:

Benefits of stationary displays (fishtank and surround)

- Good resolution (still better than most HMDs)
- Wider FOV (field of view)
- Longer user endurance (i.e., can stay immersed for longer periods)
- Higher tolerance for display latency
- Greater user mobility (fewer cables)
- Less encumbering
- Lower safety risk
- Better for group viewing
- Better throughput

- **Benefits of head-based displays (Occlusive, nonocclusive, smartphone, and projective)**
- Lower cost
- Greater portability
- Can be used for augmenting reality
- Can occlude the real world (required in some situations, e.g., as when using haptic [touch] displays in which the participant shouldn't see the haptic hardware)
- Less physical space required (compared with multiscreened stationary displays)
- Less concern for room lighting and other environmental factors
- Content development tools like Unity and Unreal Engine.

Benefits of hand-based displays

- Greater user mobility
- Greater portability
- Already in wide use as smartphones and tablets
- Well suited for "Magic Lens" AR
- Inexpensive
- Can be combined with stationary VR displays.

(Sherman & Craig, 2019)

VR can be considered as the broadest form of immersive technology since it has more background and older history comparing to other forms of immersive technology. Between different paradigms of VR, HBD (head-based display) is one of the most popular, if not the most popular paradigm and relatively there are more applications developed for that. There are many use cases in the fields of education, healthcare, military, communication, engineering, etc. already exist and they are getting more and more since the technology is growing rapidly.

In the field of design, VR can be beneficial for communication, evaluation and development, which will be discussed in detail later in this chapter. VR chat (such as Rumii), VR sketching (such as Gravity sketch) and VR modeling/sculpture (such as Kanova) are some examples of useful applications that designers can benefit from.

Augmented Reality (AR)

AR is a medium in which real-time interactive digital information is overlaid on the physical world that is in both spatial and temporal registration with the physical world (Sherman & Craig, 2019).

Augmented reality has been already used in many areas such as education, gaming, navigation, etc. Almost all of them have something in common which is simulating the entire or some components of an experience that used to be tangible in most cases or did not even exist before this technology. In education, for instance, now we can explore human anatomy in a fully immersing experience via AR which used to be explored via images or tangible models that were not or could not be as detailed because of the production costs and limits.

AR 3D viewer is another capability that we are seeing the furniture companies taking advantage of. This technology has enabled them to present their products in an engaging way that let the user see the product in the real space before they buy it.

In the design process, this feature can be very useful when designers want to determine the right scale and the proportion for their product. It is also an alternative for presentation.

Mixed reality (MR)

MR may take your view of the real world and integrate computer-generated content that can interact with that view of the real world. Or it may take a fully digital environment and connect it to real-world objects. In this way, MR can sometimes function similarly to VR and sometimes function similarly to AR (Mealy, n.d.).

Mixed reality, as it sounds, is technically the combination of VR and AR. Microsoft Hololens can represent the MR very well since unlike the VR headsets it does not disconnect the user from the real world and at the same time the level of interaction and the immersive experience it provides to the user is beyond AR.

Jaimy Szymanski (2018) counts the following use cases for mixed reality in his article:

- **Engineering and Design Modeling**: Utilizing 3D modeling in engineering products is a tried-and-true method in most manufacturing environments. Reviewing designs in a collaborative VR space offers novel opportunities as traditional computer-aided design and modeling (CAD/CAM) technologies evolve.
- **Training and Employee Education**: Conducting training exercises in a VR environment offers many benefits over real-world programs, including increased safety; managing information transfer amidst high employee turnover; scaling trainers; and upskilling existing workers.
- **Real-time Information Overlay**: Primarily a use case meant for AR, real-time information is provided to a viewer utilizing wearable AR headsets or accessible

through a mobile device or tablet via an AR app, while simultaneously viewing real-world surroundings.

- **B2B Sales**: VR and AR can offer new, immersive opportunities to sell industrial products while simultaneously increasing portability and scaling salesperson efforts.
- **Marketing and Entertainment**: AR and VR content marketing are a growing field for digital marketers looking to reach audiences in new, engaging ways in order to compete with other online and mobile experiences (Szymanski, 2018).

From the design perspective some of these use cases, such as design modeling and Real-time Information Overlay, are directly related; the others however are still useful for designers to notice since it is beneficial for designers to have a business-oriented mind and recognize its tools and methods.

Artificial Virtuality (AV)

A term that has yet to gain much traction within the industry, augmented virtuality (AV), also sometimes called merged reality, is essentially the inverse of typical AR. Whereas AR refers to predominantly real-world environments that have been augmented with digital objects, AV refers to predominantly digital environments in which there is some integration of real-world objects.

The border line between these definitions are barely recognizable; however, with the current state of terms, artificial virtuality will be a big topic in the near future since the way the users interact with the virtual world is more natural. Some companies have already invested in hand tracking technology and used that as the controllers in their gadgets, such as Microsoft

Hololens and HTC Vive. The most recent one (by October 2019) was Facebook hand tracking for Oculus Quest, which was announced on September 2019 and is supposed to be released by the end of 2019.

Guidelines

Now it is time to see when Immersive technology can be beneficial in the design process. To do so, we are going through the two different design processes that are mentioned in Chapter 2 and the design tools provided by IDSA step by step and see at what phases immersive technology can be useful. For a better communication, we are going to use the words Yes, No and Maybe with their color code.

Yes means there is a lot of potential that already exist in this technology and it can be beneficial to use.

No means it is not suggested for immersive technology application, and it may offer less benefit than other technologies that are faster, more cost efficient, and require less effort overall

Maybe means that the application of Immersive technology is not clearly understood. There are opportunities where the application could be useful and there are opportunities where the application does not deliver a strong benefit. For this reason, explanation of MAYBE will be dealt with on a case to case basis.

The decisions of whether each step of design processes is a Yes, Maybe or No has been made through the Effort-Benefit chart. Implementing immersive technology into each step may take a certain amount of effort and will provide a certain amount of benefit as the result. Also, there is an area that the effort and benefit have almost equal ratio, in that area the outcome would be a Maybe. The area below that would be a Yes since the ratio of benefit is higher than the effort. The upper area of the chart (above the maybe area) would be No since it takes more effort than the amount of benefits it provides.

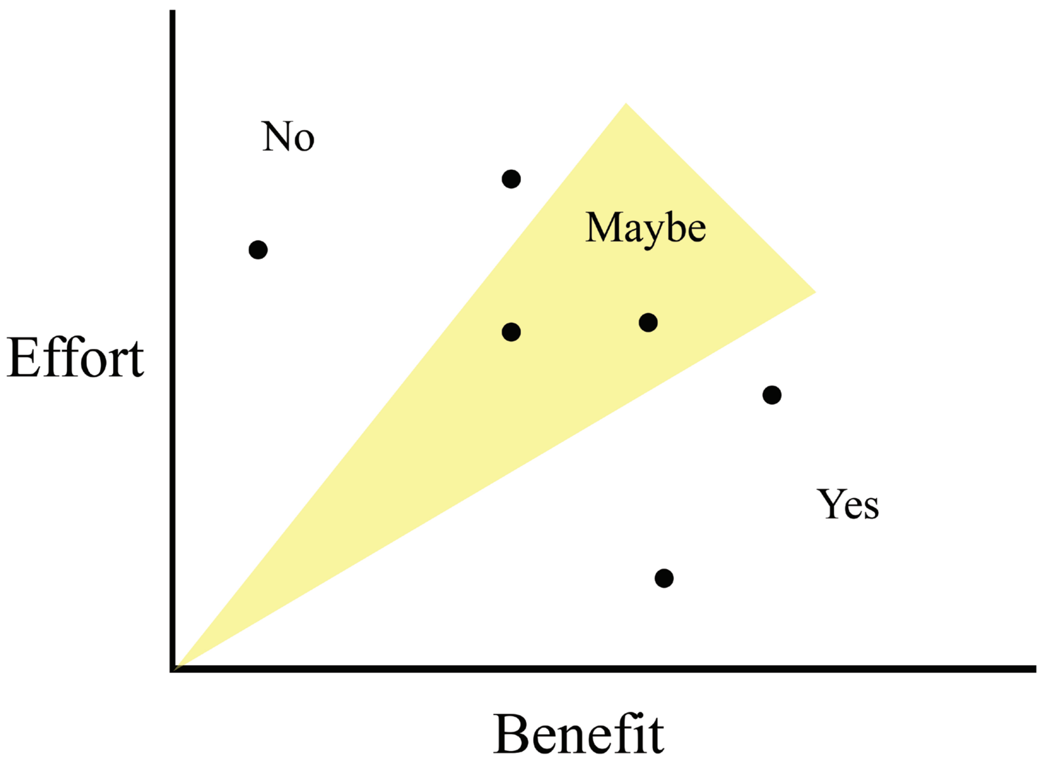


Figure 38 Effort-Benefit Chart.

Double Diamond

Double diamond is the first design process that we are going to investigate. As it mentioned before, double diamond is a popular design process that was developed by the British Design Council and it is getting used in different design fields such as industrial design, service design, user experience design, etc. In this section we are using the revamped version of double diamond, processed by Dan Nessler, since it's more detailed and comprehensive.

Stage 1 — Doing the right thing (Diamond 1 — Discover and Define)

This phase is split into Discover/Research and Define/Synthesis.

Discover / Research

- **Rip the brief** ⟶ No

  This is the starting point of the challenge, questioning the brief by challenging every part of it and evaluating fields of interests. As it discussed, immersive technology is a medium mostly for communication and visualization. Although it may have some tools for research, it would not be helping the process at this point to get more efficient (reference Effort-Benefit Chart).

- **Cluster your findings into topics** ⟶ No

  This is before diving into the research and it helps to narrow down the research area. Same as the previous step, using immersive technology would not be helpful in this phase either.

- **Primary research** ⟶ Maybe

  Depending on the type of research and the research method, immersive technology might be useful. In some cases, if some interview involved in the research process, VR chat would be a useful tool for communication. Otherwise note taking and audio recording would be better tools to use (reference Benefits and Features on page 80).

- **Secondary research** ⟶ No

  Secondary research (also called desk research) is a type of research that the researcher uses some already existing data. Immersive technology cannot be useful at this step.

Define / Synthesis

- **Download** ⟶ No

  Download is about summarizing all the raw findings from the research. Since it is processing the information, Immersive technology would not be a proper tool to use.

- **Cluster learnings and similarities to themes** ⟶ No

  Similar to download, cluster learning and similarities to themes is more about processing information and categorizing. Therefore, immersive technology would not be very helpful at this phase.

- **Find insights (opportunity area)** ⟶ No

  Find insight is building opportunity areas (a phrasing of the potential area of action). This is another step of synthesizing the research findings and immersive technology would not be a useful tool.

- **Create HMW (how might we…) questions** ⟶ No

    This is the last step of the Define phase and is about creating question that makes a tangible statement of what is to be done or solved within the area of action. Obviously immersive technology is not a tool for creating questions; therefore it should not be used here.

Stage 2 — Doing things right (Diamond 2 — Develop and Deliver)

This phase is split into Develop/Ideation and Deliver/Implementation.

Develop / Ideation

- **Ideation** ⟶ Yes

    This is the first step of idea development. At this stage, the designer approaches ideation with an open mind and without any limits.

    The goal is to let anything happen at this point and build upon each other's ideas. Ideation is one of those phases that immersive technology can be very helpful. There are already some very useful applications developed for sketching and sculpting via VR, which are very valuable for designers since they no longer need to communicate their 3D ideas in a 2D space (pen and paper sketching). Instead, they can easily sketch in a 3D space and evaluate it from different angles. Or without needing to know complex 3D modeling software, they can sculpt their idea very quickly. Having said that, it is very important to notice that immersive technology is not a replacement for pen-and-paper sketching and 3D modeling software. Rather, it is a complementary tool to enhance the process of design. The result of these two mediums are different; therefore the use cases should be different as well. VR sketching is for the time that the designer needs to evaluate the idea from different angles. And VR sculpting can be used when a rough and quick overview of the model is needed.

In addition to these applications, there are sometimes that designers want to share their ideas and evaluate them; in those cases VR chat can be a very useful tool for communication.

- **Evaluation** ⟶ Yes

This is towards the end of ideation phase and is evaluating the ideas and selecting the best ones. As mentioned before, VR sketching and VR chat are a good tool to use for this purpose so the user can evaluate ideas in a 3D space, put comments on them or make some changes if needed (reference Benefits and Features on page 80).

Deliver / Implementation

- **Build/Prototype** ⟶ Yes

Prototyping is another phase of design process that Immersive technology can be very useful. In some projects prototyping can be very time consuming and cost a lot. In such projects, immersive technology can play a huge role and save a lot of time and money resources as well as material resources since it can be fuly virtual. Since this is a broad use case, all different forms of immersive technology

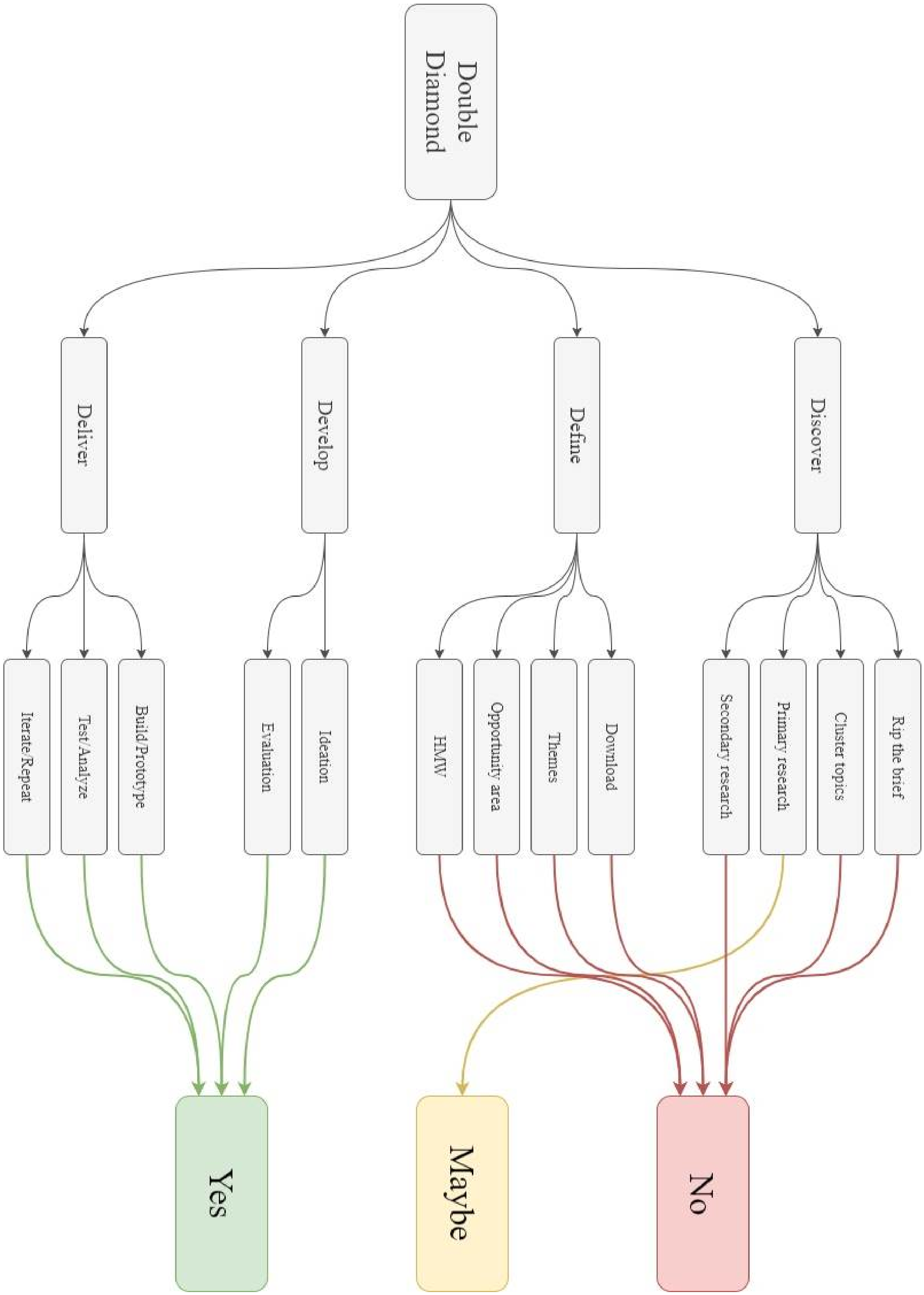
(VR, AR and MR) can be used in this phase. Volvo, the Swedish car company, has done a project with Varjo mixed reality goggles, which is a great example for this use case.

- **Test/Analyze** ⟶ Yes

  The next step is testing and analyzing. Similar to prototyping, Immersive technology can be useful in testing as well. If the prototyping process was done virtually, it can be easily tested through the same tools. Also, the eye tracking technology will help the designer to analyze the interaction between the user and the product and discover the weaknesses and.

- **Iterate/Repeat** ⟶ Yes

  The last step is to repeat the second diamond phases. Since immersive technology was beneficial for all the phases in the second diamond, this step (which is basically going through previous phases) was indicated as a Yes as well.



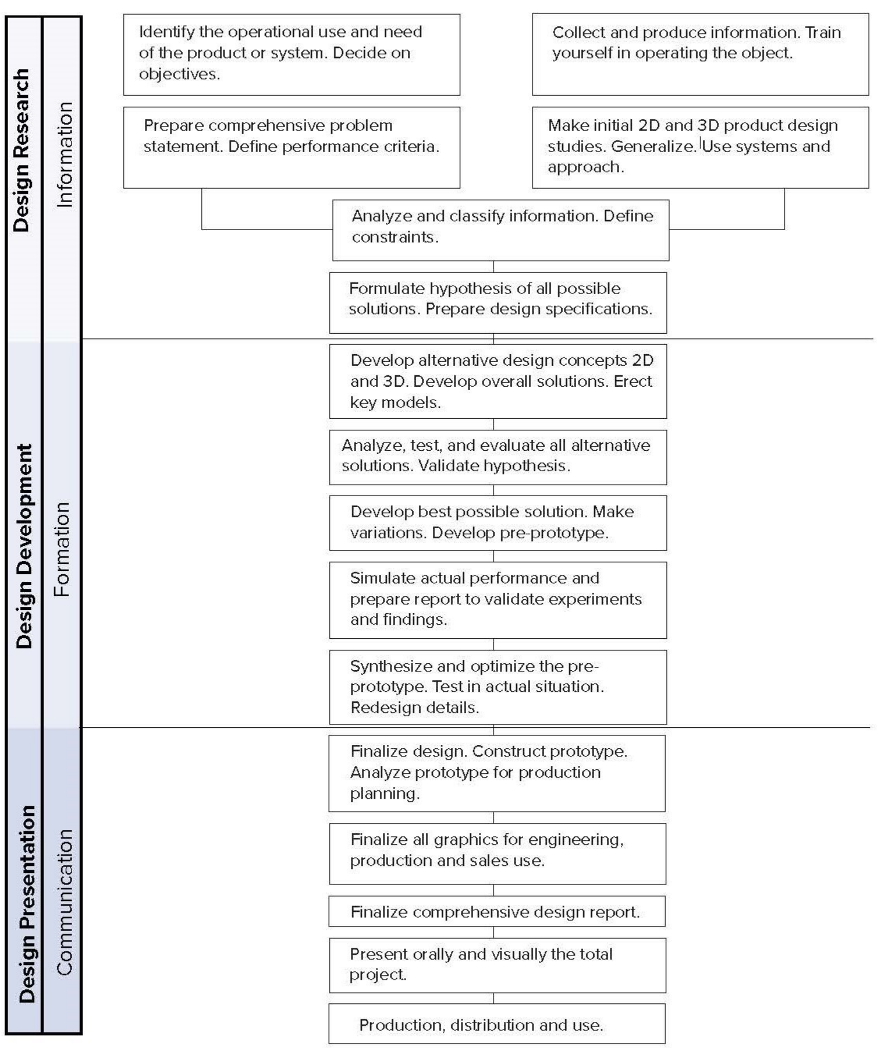
Double Diamond
Discover
Define
Develop
Deliver
Rip the brief
Cluster topics
Primary research
Secondary research
Download
Themes
Opportunity area
HMW
Ideation
Evaluation
Build/Prototype
Test/Analyze
Iterate/Repeat
No
Maybe
Yes

Circular Design Process by Walter Schaer

Circular design process was designed to be used by the industrial design students of Auburn University as a guideline for the formulation of a problem-solving process for design problems. The latest revision includes reference to problem-solving tools that may be used as an aid in satisfying the requirements of the steps within the process (Borzak, 1974).

Schaer's method is a cybernetic process, divided into three design phases;

- **Research (information)**
- **Development (formation)**
- **Presentation (communication)**



Research (information)

- Identify the operational use and need of the product or system. Decide on objectives. ⟶ No

  The first step of the research phase is to investigate the objectives to determine whether we need a product or a service. As discussed, immersive technology is mostly for communication and visualization; therefore, it will not be beneficial to use it at this step.

- Collect and produce information. Train yourself in operating the object. ⟶ Maybe

  Depending on the project and the research methodology that are being used in the project, immersive technology might be useful for gathering the information through some interviews via VR chat application.

- Prepare comprehensive problem statement. Define performance criteria. ⟶ No

  Although immersive technology could be useful for gathering information, it is not beneficial for processing them. Hence, it should be avoided at this step of the design research.

- Make initial 2D and 3D product design studies. Generalize. Use systems and approach. ⟶ Maybe

  If some visualizing is needed at this point, immersive technology could be useful.

- Analyze and classify information. Define constraints. → No

  As discussed, immersive technology is not a tool for classifying information; therefore, it should not be used at this step.

- Formulate hypothesis of all possible solutions. Prepare design specifications. → No

  This is the last step of the research; since it is still working with the information, pulling out the data for the design specification immersive technology cannot be useful.

Development (formation)

- Develop alternative design concepts 2D and 3D. Develop overall solutions. Erect key models. → Yes

  This is the first step of formation, which is generating 2D and 3D ideas. As mentioned, immersive technology could be a very useful tool for visualization. Designers can draw or sculpt their idea in VR sketching and VR modeling applications and explore them in a 3D space from different angels.

- Analyze, test, and evaluate all alternative solutions. Validate hypothesis. → Yes

  Since immersive technology offers an immersive experience of exploring concepts, it can be a very useful tool for evaluation. Designers can better understand 3D ideas in the 3D space. Hence the evaluation process would be improved. Depending on the project, different forms of immersive technology can be used, and it can be done through either the existing applications or making a new one from the scratch based on the requirements of the project.

- Develop best possible solution. Make variations. Develop pre-prototype. → Yes

  Developing the possible solutions is technically making adjustments or variations of the already developed idea. No matter if it is 2D or 3D, VR tools and applications are useful at this step.

- Simulate actual performance and prepare report to validate experiments and findings → Maybe

  As it discussed in the previous guideline, there are some projects for which prototyping or simulation process could be very expensive and time consuming, such as automotive prototyping or cockpit simulation. Therefore, immersive technology can be possibly a huge money and time saving tool at this step. Also, in some projects there is a need to simulate the user interface; in that case immersive technology can be used as well. However, in the most traditional industrial design projects that need tangible prototypes in order to simulate the performance, immersive technology cannot be beneficial at this phase.

- Synthesize and optimize the pre-prototype. Test in actual situation. Redesign details. → Yes

  In the projects that the tangible product is engaging with the user interface, AR and MR tools can be useful for simulating the UI.

Presentation (communication)

- Finalize design. Construct prototype. Analyze prototype for production planning. → Yes

  As discussed, immersive technology can be a useful tool for prototyping (depending on the project) and analyzing. The eye tracking technology can be very useful for analyzing.

- Finalize all graphics for engineering, production and sales use. → Maybe

  The communication between designers and the engineers has been always a big challenge and is a very important step. Through an immersive experience, engineers can fully explore the final product and the details via an exploded view. However, when we are talking about finalizing, it might be defined as a phase that the designer applies all the adjustments to the model, in that case immersive technology cannot be helpful since it needs to be done in an accurate tool such as Solidworks.

- Finalize comprehensive design report. → Maybe

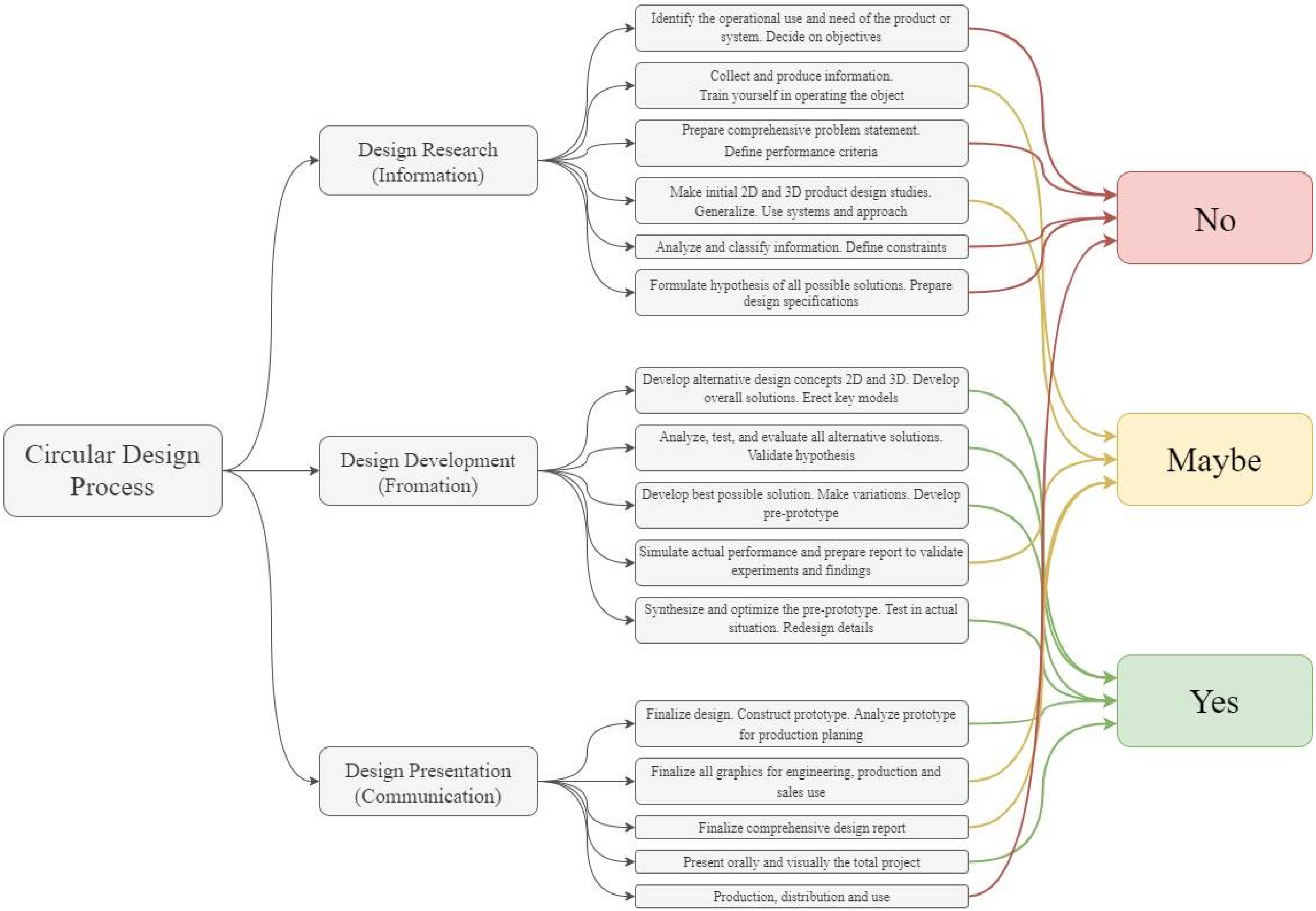
  Part of preparing a comprehensive design report is the observation and immersive technology can might be helpful in some cases. As an example, the eye tracking technology can be used to pull out some data of the interaction between the user and the product.

- Present orally and visually the total project. → Yes

  Presentation is all about visualization and communication which is the main functions of immersive technology; therefore, it can be a useful tool at this step. VR chat, and AR/VR customized applications are useful for providing an immersive experience for the audience.

- Production, distribution and use. → No

  These are production and post production steps which designers may not be involved in directly. Immersive technology cannot be very helpful at this phase.



Circular Design Process
Design Research (Information)
Design Development (Fromation)
Design Presentation (Communication)
Identify the operational use and need of the product or system. Decide on objectives
Collect and produce information. Train yourself in operating the object
Prepare comprehensive problem statement. Define performance criteria
Make initial 2D and 3D product design studies. Generalize. Use systems and approach
Analyze and classify information. Define constraints
Formulate hypothesis of all possible solutions. Prepare design specifications
Develop alternative design concepts 2D and 3D. Develop overall solutions. Erect key models
Analyze, test, and evaluate all alternative solutions. Validate hypothesis
Develop best possible solution. Make variations. Develop pre-prototype
Simulate actual performance and prepare report to validate experiments and findings
Synthesize and optimize the pre-prototype. Test in actual situation. Redesign details
Finalize design. Construct prototype. Analyze prototype for production planing
Finalize all graphics for engineering, production and sales use
Finalize comprehensive design report
Present orally and visually the total project
Production, distribution and use
No
Maybe
Yes

IDSA Design Tools

Unlike the two design processes that we investigated, these are the tools that designers are using within those processes in order to design a product. It is important to notice once again that immersive technology itself is a tool as well; therefore, it is wrong to think it can be replaced with other design tools. Rather, it can improve some of them and enable them to be more effective and efficient in the use cases.

1.IDEA SKETCH ⟶ No

Employed at a personal level to quickly externalize thoughts using simple line-work. Also known as Thumbnail, Thinking or Napkin Sketch.

Although VR provides some tools for sketching, the purpose of Idea Sketching is to record an instant idea and it is important to be quick and accessible at anytime and anywhere. Therefore, immersive technology would not improve this tool.

2. STUDY SKETCH ⟶ Yes

Used to investigate appearance, proportion and scale in greater detail than an Idea Sketch. Often supported by the loose application of tone/color.

Since the Study Sketching has greater details and is investigating proportion and scale, VR sketch can be very useful. Designer can explore ideas in a 3D space and also sketch in the real scale, which is rarely possible on paper (only if the object dimensions fit into the paper size).

3. REFERENTIAL SKETCH ⟶ No

Used to record images of products, objects, living creatures of any relevant observations for future reference or as a metaphor.

This is mostly for adding notes to a sketch or an image for later reference. Hence the traditional ways should be quicker and more efficient.

4. MEMORY SKETCH ⟶ No

Helps expand thoughts during the design process using mind maps, notes and annotations.

Similar to referential sketch, immersive technology could not be as quick and efficient as the traditional ways for the memory sketch.

5. CODED SKETCH ⟶ No

Informal coded representation that categorizes information to demonstrate an underlying principle or scheme.

As discussed before, immersive technology would not be the best tool for categorizing.

6. INFORMATION SKETCH ⟶ Yes

Quickly and effectively communicates features through the use of annotation and supporting graphics. Also known as Explanatory or Talking Sketch.

The purpose of information sketch is better communication through extra details and explanations. Since VR sketch is in a 3D space, it can be helpful for better understanding the concept and a better overall communication.

7. SKETCH RENDERING → Yes

Clearly defined proposal produced by controlled sketching and use of color/tone to enhance detail and realism. Also known as First Concept.

VR provides some useful tools for painting/rendering the drawings, as well as presentation tools which can be useful for this area.

8. PRESCRIPTIVE SKETCH → Yes

Informal sketch for the exploration of technical details such as mechanisms, manufacturing, materials and dimensions.

Technical details can be better communicated in a 3D space therefore, VR can be improving prescriptive sketching.

9. SCENARIO & STORYBOARD → Maybe

Describes interactions between user and product, sometimes in an appropriate context.

MR might be a useful tool for showing the interaction between user and the product since it can overlay the virtual media on the real world (the user in this case).

10. LAYOUT RENDERING ⟶ Maybe

Defines the product, proposals as a third angle orthographic projection with precise line and color.

Again, the 3D drawing capability of immersive technology; may improve the communication of this tool.

11. PRESENTATION RENDERING ⟶ Yes

Contains a high level of realism to fully define product appearance as a perspective view. Particularly useful for decision making by non-designers.

The challenge of this type of rendering is to be photo-realistic and nothing would be showing a 3D object as realistically as presenting it in a 3D space. VR and AR are useful tools for presentation rendering.

12. DIAGRAM ⟶ Yes

Schematic representation of the operating principle of relationship between components. Also knows as a Schematic or Diagrammatic Drawing.

The relationship between components would be well presented in a 3D space. In addition to that, exploded view or even simple animations might be helpful too. Therefore, immersive technology can improve this area.

13. PERSPECTIVE DRAWING ⟶ Yes

Descriptive three-quarter view produced using a perspective drawing technique. Created using line only without the application of color or tone.

Perspective drawing is basically a 3D drawing on a 2D paper. Drawing the concept directly in a 3D space can be a good improvement for this medium.

14. GEN. ARRANGEMENT DRAWING ⟶ Yes

Exterior view of all components using line only and with sufficient detail to produce an Appearance Model if required. Usually drawn in third angle projection.

Arranging the 3D components on a 2D paper will lose the thickness of the components; therefore, VR sketch can be very useful at this point.

15. DETAIL DRAWING ⟶ No

Contains detail of components for the manufacturing product. Also known as Technical, Production or Construction Drawing.

This type of drawing usually has its own language to communicate. It is very accurate and uses manufacturing codes for the production. Therefore, immersive technology may not be efficient to use in here.

16. TECHNICAL ILLUSTRATION ⟶ Yes

Communicates technical detail with a high degree of realism that is sometimes supported with symbols. Includes Exploded views.

Technical illustration, however, could be improved via immersive technology since through that designers can show the details of connections and exploded view accurately and in a 3D space, which improves the overall communication.

17. SKETCH MODEL ⟶ Yes

Informal, relatively low definition 3D model that captures as the key characteristics of form. Also known as a Foam Model for 3D Sketch.

VR sketching and VR sculpting applications can be useful here.

18. DESIGN DEVELOPMENT MODEL ⟶ Maybe

Simple mock-up used to explore and visualize the relationships between components, cavities, interfaces, and structures. Usually produced using CAD.

Depending on the project, if the actual model was needed then immersive technology cannot be beneficial. But if the purpose of this step was only to demonstrate the joint and connections, then immersive technology can be useful.

19. FUNCTIONAL MODEL ⟶ No

Captures the key functional features and underlying operating principles. Has limited or no association with the product's final appearance.

Function model needs to be tangible and functioning with the real components. Therefore, immersive technology cannot be used here.

20. OPERATIONAL MODEL ⟶ Maybe

Communicates how the product is used with the potential ergonomic evaluation.

Depending on different types of ergonomic evaluation that was needed in the project, immersive technology might be useful.

21. APPEARANCE MODEL → Yes

Accurate physical representation of product appearance. Also known as a Block Model as it tends not to contain any working parts.

Since this model is only for the appearance, with no working parts, immersive technology tools can be useful.

22. ASSEMBLY MODEL → No

Enables the evaluation and development of the methods and tools required to assemble products components.

The assembly model is better to be a tangible model since it is for production.

23. PRODUCTION MODEL → No

Used to evaluate and develop the location and fit a of individual components and subassemblies.

Similar to assembly model, production model needs to be tangible as well.

24. SERVICE MODEL → Maybe

Supports the development and demonstration of how a product is services and maintained.

Service model could be a virtual model since the its purpose is to demonstrate how the services and maintenances should be done, which could be done virtually (This can fit in the VR training category).

25. EXPERIMENTAL PROTOTYPE ⟶ Maybe

Refined prototype that accurately models physical components to enable the collection of performance data for further development.

Depending on the project, if the prototype was for the appearance use or testing the user interface, it can be done virtually.

26. ALPHA PROTOTYPE ⟶ No

Bring together key elements of appearance and functions for the first time. Uses of simulates production materials.

Since the function is important at this stage, this prototype cannot be virtual.

27. BETA PROTOTYPE ⟶ No

A refined evolution of an Alpha Prototype used to evaluate ongoing design changes in preparation for the final specification of all components (meet Effort-Benefit Chart).

Similar to alpha prototype, beta prototype is better to be tangible too.

28. SYSTEMS PROTOTYPE ⟶ No

Integrates components specified for the production item without consideration of the appearance. used to evaluate electronic and mechanical performance.

This prototype is only for the technical aspects. Therefore, it needs to be a tangible prototype.

29. FINAL HARDWARE PROTOTYPE → No

Developed from the Systems Prototype as a final representation of the product's functional elements.

Again, since this prototype is for technical aspects, it cannot be virtual.

30. OFF-TOOL COMPONENT → No

Product using the tooling and materials intended for production to enable the evaluation of material properties and appearance of components.

This is for the material decision making; therefore, it needs to be with actual material.

31. APPEARANCE PROTOTYPE → No

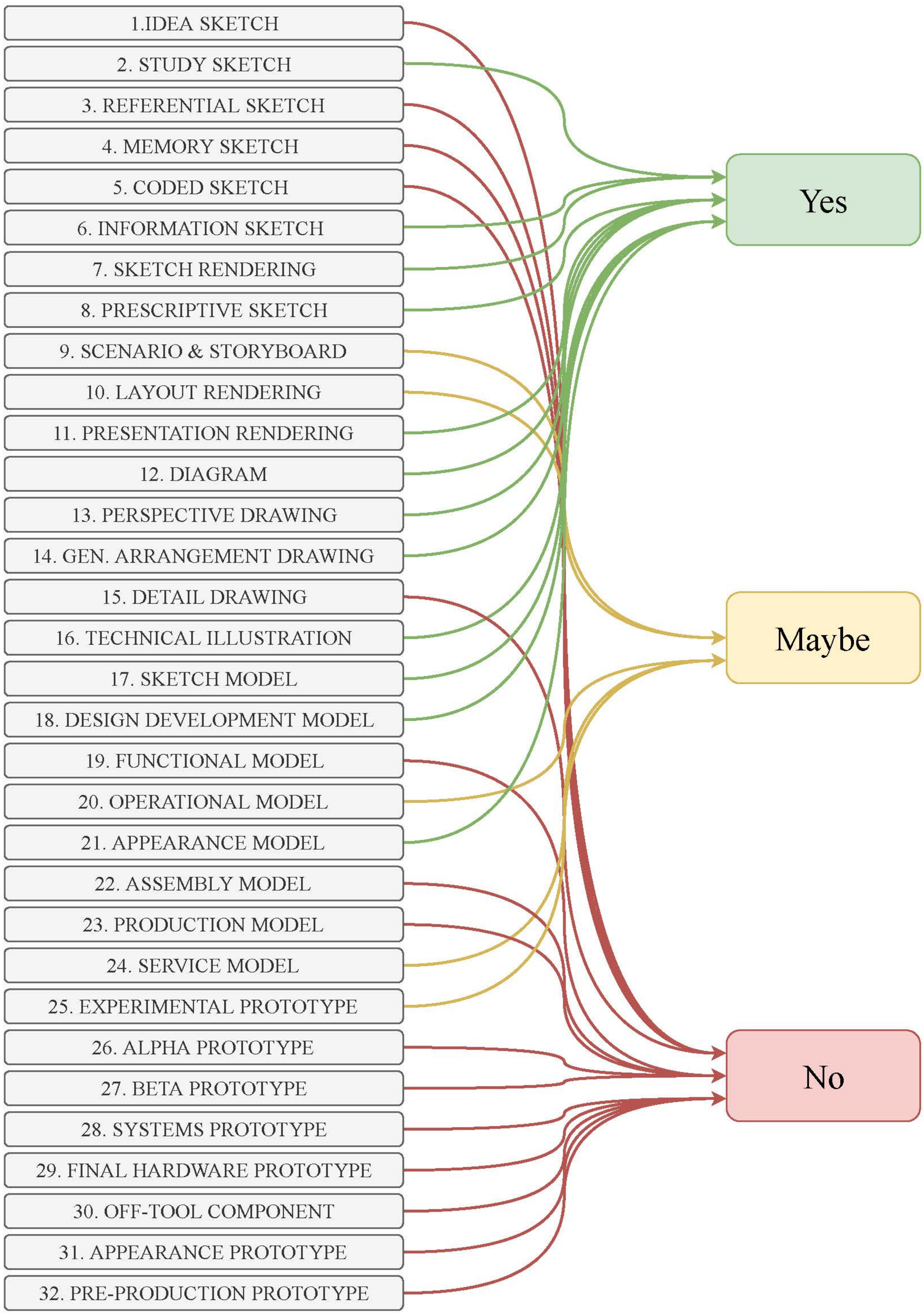
Highly detailed representation that combines functionality with exact product appearance. Uses or simulates production materials.

Regarding to the functionality aspects, it needs to be tangible.

32. PRE-PRODUCTION PROTOTYPE → No

Final prototype produced using production components. Manufactures in small volumes for testing prior to full scale production.

This is a manufacturing test. And it cannot be virtual (meet Effort-Benefit Chart).


1.IDEA SKETCH
2. STUDY SKETCH
3. REFERENTIAL SKETCH
4. MEMORY SKETCH
5. CODED SKETCH
6. INFORMATION SKETCH
7. SKETCH RENDERING
8. PRESCRIPTIVE SKETCH
9. SCENARIO & STORYBOARD
10. LAYOUT RENDERING
11. PRESENTATION RENDERING
12. DIAGRAM
13. PERSPECTIVE DRAWING
14. GEN. ARRANGEMENT DRAWING
15. DETAIL DRAWING
16. TECHNICAL ILLUSTRATION
17. SKETCH MODEL
18. DESIGN DEVELOPMENT MODEL
19. FUNCTIONAL MODEL
20. OPERATIONAL MODEL
21. APPEARANCE MODEL
22. ASSEMBLY MODEL
23. PRODUCTION MODEL
24. SERVICE MODEL
25. EXPERIMENTAL PROTOTYPE
26. ALPHA PROTOTYPE
27. BETA PROTOTYPE
28. SYSTEMS PROTOTYPE
29. FINAL HARDWARE PROTOTYPE
30. OFF-TOOL COMPONENT
31. APPEARANCE PROTOTYPE
32. PRE-PRODUCTION PROTOTYPE
Yes
Maybe
No

Chapter 4: Application of Guidelines

Overview

After indicating the guidelines, now it is time to see how these guidelines can be used in a project. In this chapter, we are going through an application as an example of how designers can use these guidelines in the design process and how these guidelines can benefit them. It is worth to mention, as it discussed in Chapter 3, these guidelines show all the applicable phases of design process that immersive technology can be possibly used. That does not mean designers must apply all the Yeses to their project. Although it is possible, they do not have to go through every phase and step of these guidelines.

It is also important to notice that the purpose of this study is not showing how to use the design process in order to design a product. Rather, it should be used as a guideline to show the user whether the immersive technology can be useful and beneficial at a particular phase of design process or not. on the other hand, the audiences of this study are designers who are assumed to know the design process and know how to design a product. Therefore, in this chapter while we are going through the design projects, some unnecessary and unrelated phases of the design process might be skipped in discussion in order to stay focused on the field of immersive technology and indicate how an industrial design project can turn into an immersive technology application.

Design Project

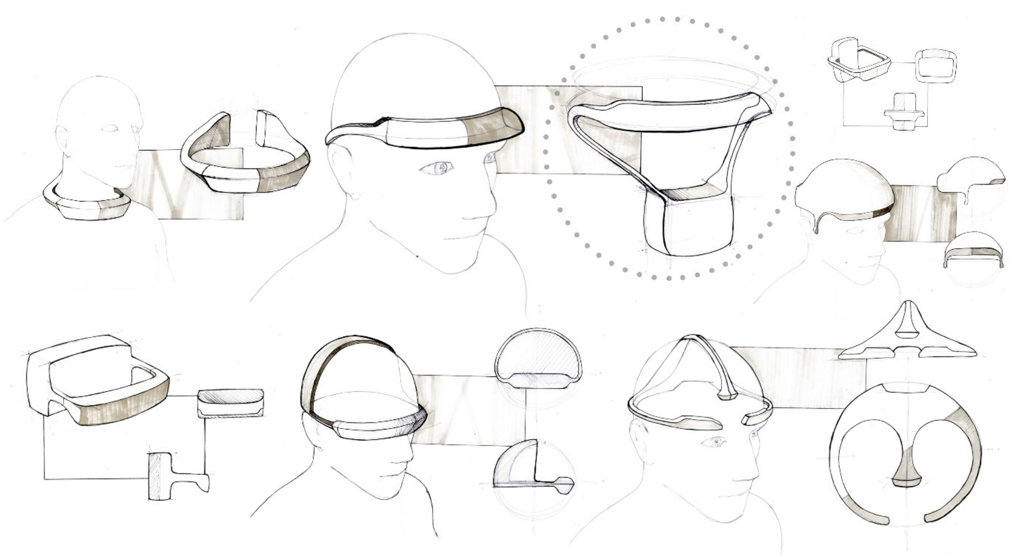
The design project we are going to discuss is called Musical Vision. This product was designed and developed by Jonathan Walden and Ali Sattari, partnering with the engineering team from Georgia Tech University. Musical Vision is an assistive device which utilizes echolocation to aid mobility for people who are visually impaired.

Design Process

In this project we used the circular design process. After the design research (Figure 39), we went through the ideation and developed some concepts through sketching (Figure 40)

Figure 39, Research

Figure 40, Ideation.



After developing alternative design concepts, we made some rough prototypes in order to analyze and evaluate the alternative solutions. (Figure 41)

Figure 41, Developing alternative design concepts. Analysing, testing and evaluating the alternative solutions.

The next step of the circular design process is "simulate actual performance and prepare report to validate experiments and findings". Now we want to take a deeper look at this phase to see if we can use immersive technology for this product.

According to Chapter 3, this phase is a Maybe and it depends on what type of design project we are working on.

In this project (Musical Vision) there are two requirements. First we need to embed all the electronics into the prototype for the simulation. Secondly, we need to test and evaluate the ergonomic factors of the headset. For this particular project, it is not advised that we leverage immersive technology while we could visualize the test fit and prototype. We are currently unable to gain accurate feed back on user comfort, weight balance upon the skull and fit or adjustability to match the users. Therefore, it is better to have a tangible prototype rather than a virtual one (Figure 42).

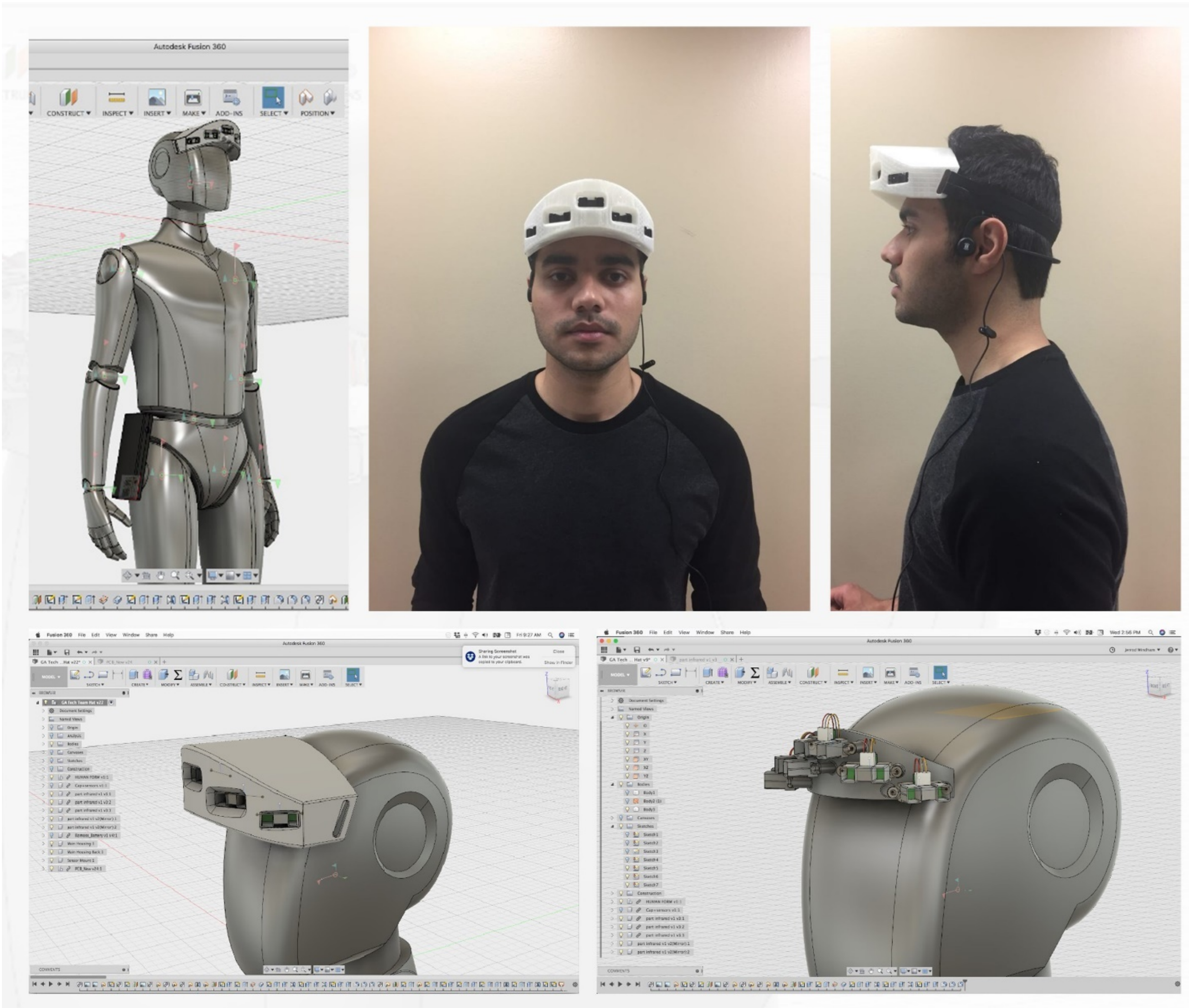


Figure 42. Tangible prototype for simulating actual performance

The next step of the process is Synthesizing and optimizing the pre-prototype, testing in the actual situation and redesigning the details (Figure 43). And after that would be finalizing the design, constructing the prototype and analyzing the prototype for the production planning (Figure 43).

Figure 43. Finalizing design and constructing the prototype.

The next phase of the circular design process is finalizing all the graphics for engineering, production and sales use. At this phase, once again we want to take a look to see if the immersive technology can be beneficial or not.

According to Chapter 3, this phase of circular design process is a Maybe, meaning that if finalizing is assumed as adjusting the details of the design and geting the outcome directly from that, immersive technology cannot be useful. However, if finalizing is assumed to be a decision-making process in order to finalize the details, then immersive technology can be very useful since it can be used as a communication tool and help the designers and engineers communicate more effectively.

For Musical Vision, we already developed some prototypes and adjusted the details in previous phases; also since this project involves both designers and engineers it would be beneficial to visualize the exploded view of the final model through immersive technology, in order to communicate with engineers. Now let's see how it can be done.

Alternative tools for making an immersive experience

It is already mentioned that there are multiple applications already built and developed such as VR chat, VR drawing etc., and they are growing rapidly since this technology is getting more popular and there are more companies investigating it. However, this is not the only way to have an immersive experience. In many cases, designers may need more freedom in order to customize their immersive experience and get the best result out of this technology. For that purpose, some software companies have developed some tools and added some features to their products which makes this process easier. Solidworks, Sketchup and Autodesk Inventor are some of these softwares. However, if we want to make an immersive experience from scratch there are two softwares, Unity and Unreal, that are very popular and used the most.

These are gaming engines that developers are using to develop games and applications. In this project, we are going to use Unity to show the step by step process of making an application for an immersive experience.

Unity application

In this application we want to make an exploded view of our product (musical vision) in Unity and present that in VR. Let's start off with the software itself and its user interface to get more familiar with that (Figure 45).

As mentioned, Unity is a gaming engine that developers are using it to develop games and applications. It is good to notice that when we are saying it is a game engine it does not necessarily mean that it is only for entertainment. Since Unity allows the user to add coding to their components, such as 3D models, animations, graphics etc., that gives the user the freedom of having all sorts of interactivity. Since this feature is mostly used for making games, they call that a gaming engine. Otherwise it can be used for all kinds of applications.

Unity interface

In order to create a new project, the first step is to select what type of project we want to create (Figure 44) then after loading and setting up the scene, the default page will show up (Figure 45).

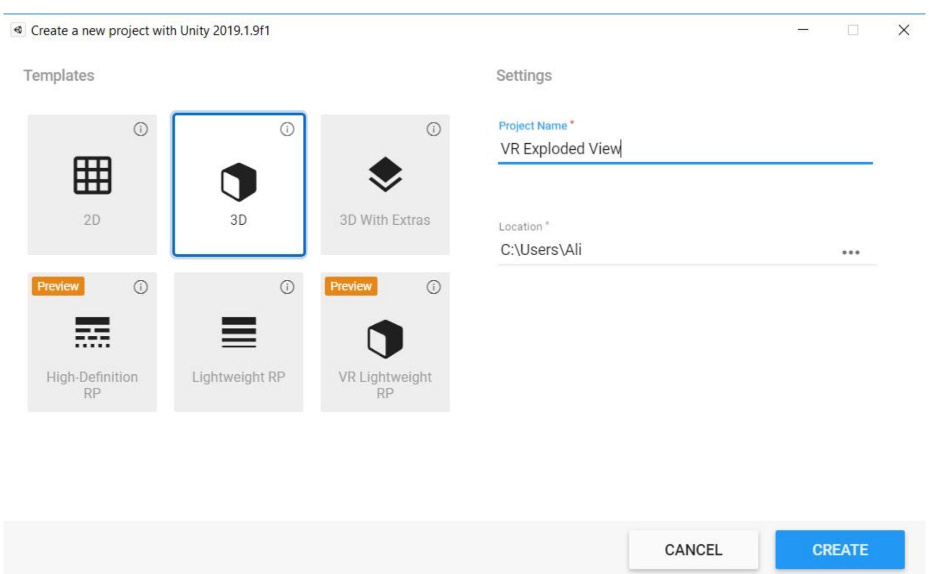


Figure 44. Unity start up page.

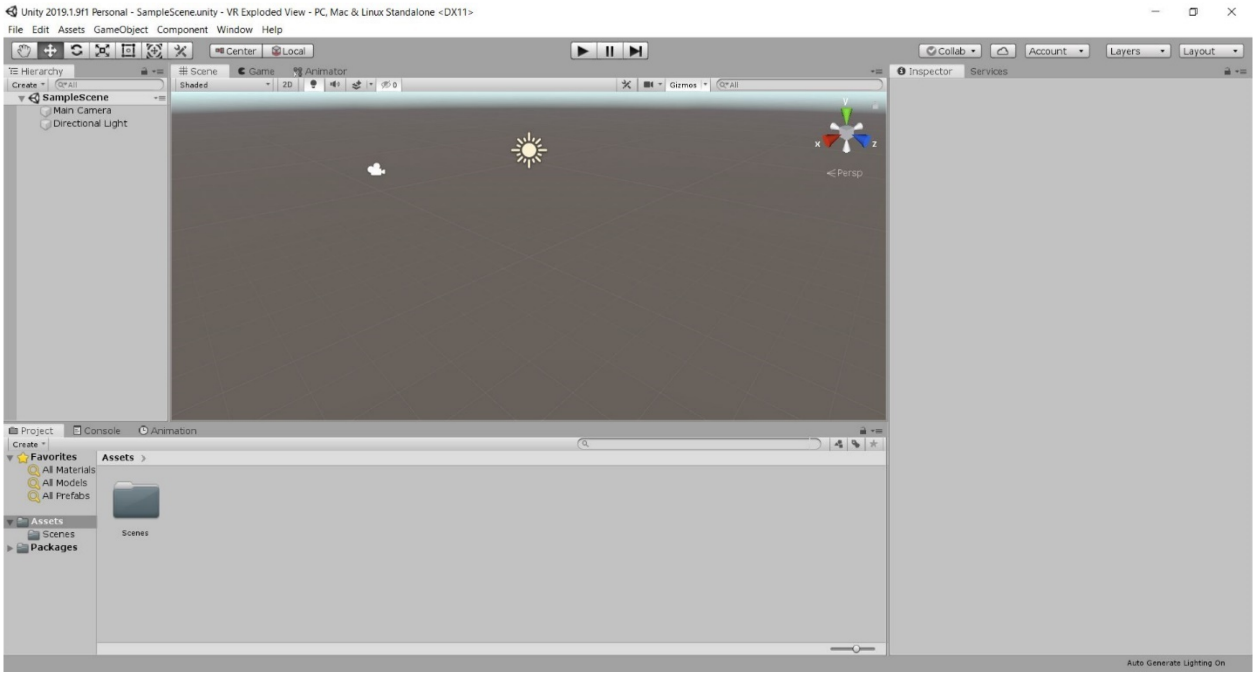


Figure 45. Unity Interface.

Importing model

The next step is to import our model into the scene. Unity takes the standard 3D formats such as "3ds", "obj", "fbx" and also SketchUp models. In this project we are going to use "fbx" format in order to keep all components all clear and separate (Figure 46) (depending on the native software, layers and components of the model are usually getting mixed up in "obj" and "3ds").

In order to import the model to our scene, first we need to add the model to our asset folder, which can be done easily by clicking and dragging to the asset box below the active area. After that we can adjust the setting of the model by clicking on it and changing the values, such as the scale and other features that it provides with the model. When we are done with the model setting, we can click and drag the model from the asset box to the hierarchy list on the left side of the screen, called Sample Scene (Figure 46).

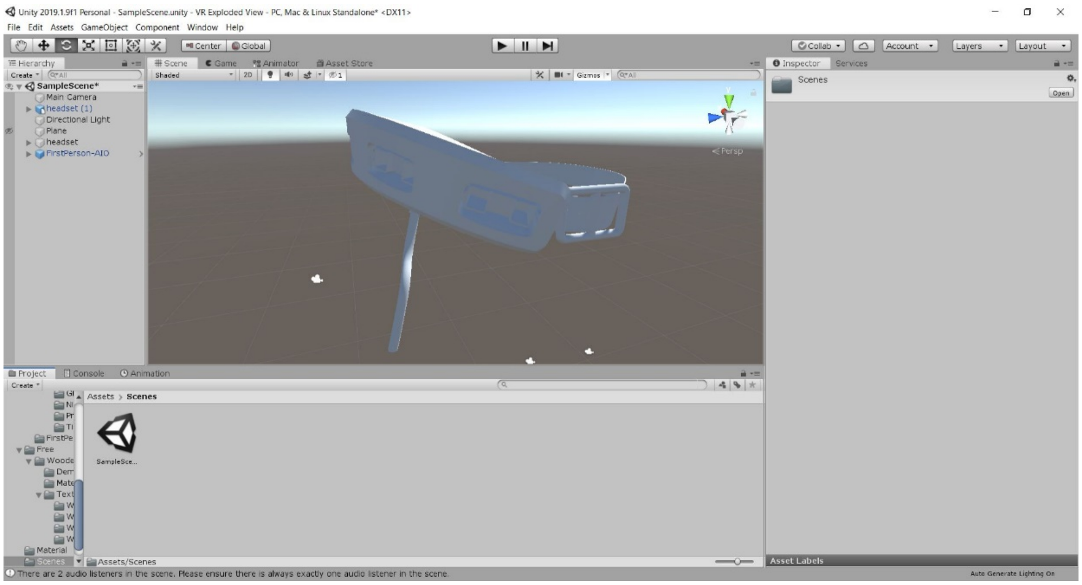
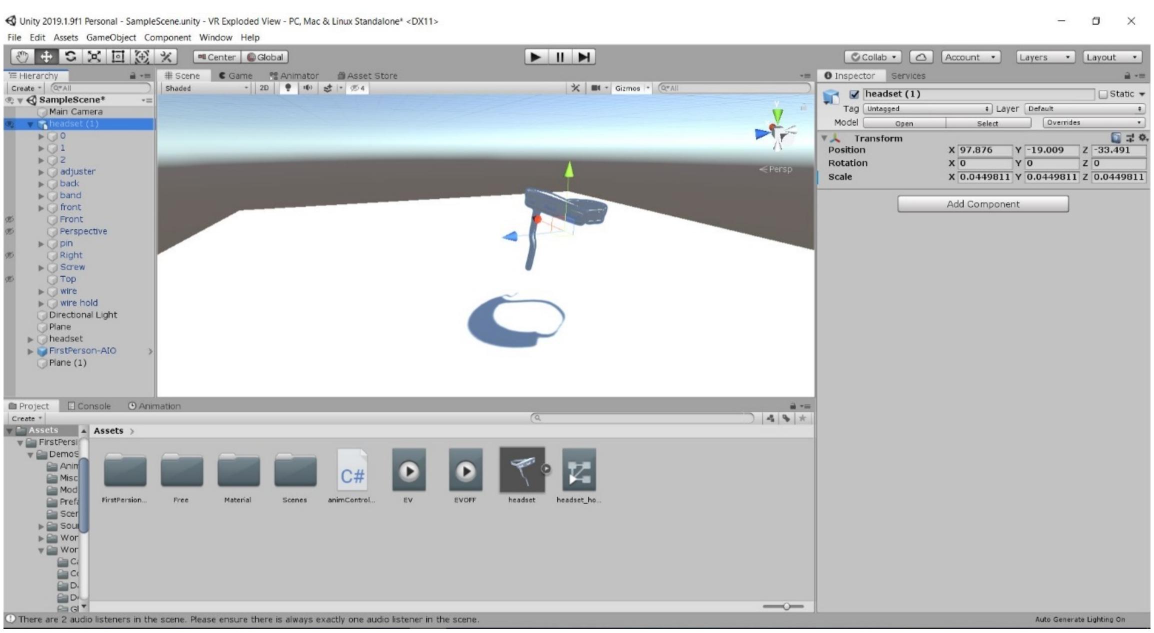


Figure 46. Importing 3D model

Adding Ground

Other than importing the model, we also need to add a plane to the scene as the ground. It can be done through GameObject > 3D Object > Plane. (Figure 47)

Figure 47. Adding a plane



Adding material

After we import the model, we need to add some material to the model, material adding process in Unity might be different with the Keyshot (Keyshot is a rendering software which most of industrial designers are using to render their products). Although there is a possibility to buy and download some material packs from the unity asset store, we can also create our own material, which we are going to do now.

In order to create a new material, right click somewhere on the asset box area, go to Create tab and then select Material. After creating a new material, we can add textures to it and change the values of it within the Inspector tab on the right side of the screen (Figure 48) (in order to keep all the components more organized, it is better to create a new folder first and create all the materials in there. A new folder can be created through right clicking on the asset box > create > folder, and then you can rename the folder.).

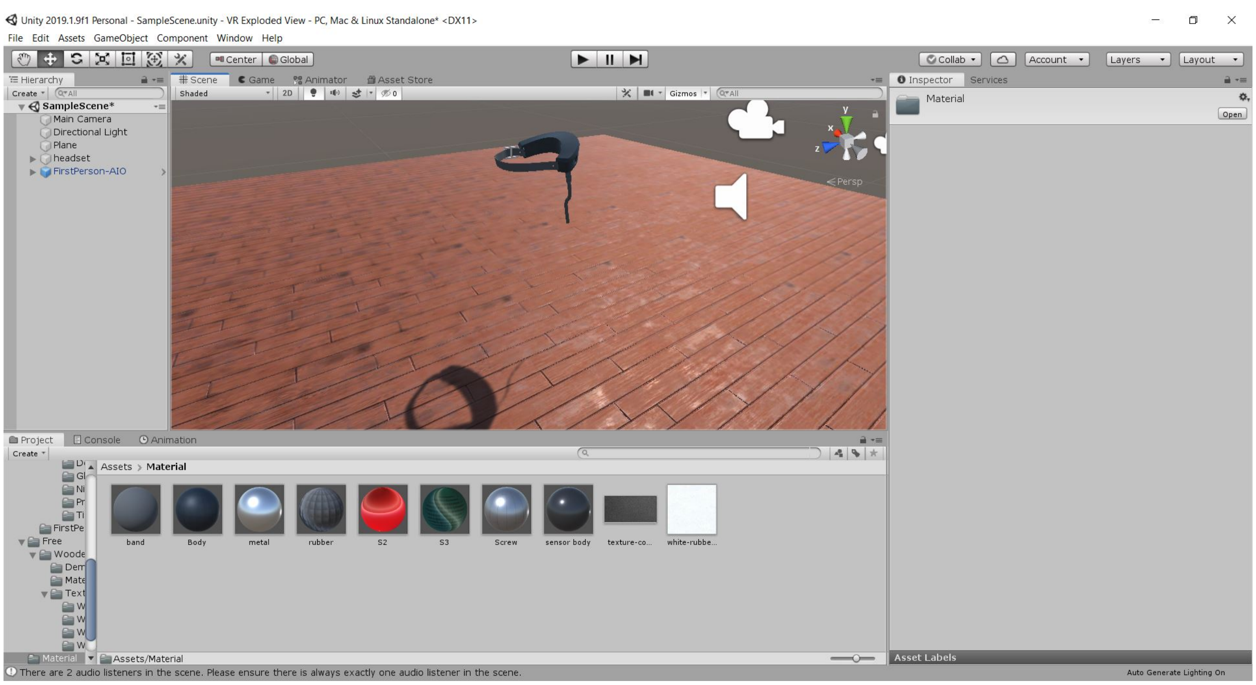


Figure 48. Creating and Adding material to the model.

Creating Animation

In order to have a smooth exploded view, we need to make an animation showing all the components getting apart and then getting them all back together. an animation can be created by right clicking on the project box > Create > Animation. Then by double clicking on the animation asset that we just made it goes to the timeline where we can set the key frames and animate our model (In case the animation tab is not on your toolbar, it can be added through Window > Animation > Animation. or use the shortcut Ctrl+6). In order to indicate which model or component we want to make that animation for, we can either click and drag the animation asset to that component on the hierarchy list or simply select that component while having the animation tab open and create an animation asset for that component. The last step is to animate the model by adding a property ("transform" in our case) and setting the keyframes for each movement we want to have (Figure 49).

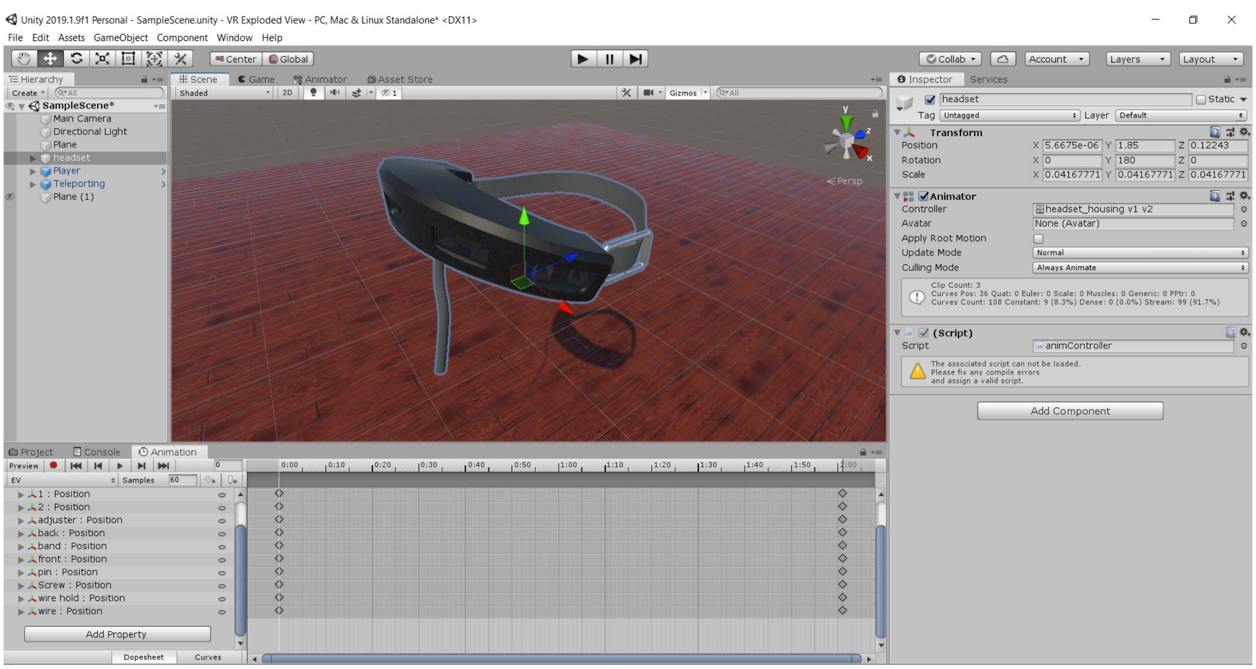


Figure 49. Creating an animation

Adding the VR player

Now that we have our model all set up, we need to add a VR player in order to be able to interact with the model in the VR. Depending on what type of VR equipment we are using, there are multiple assets available in the Unity asset store that are already developed and ready to use. The process of running a scene and interacting with models in VR requires some programming skills and may get complicated. These assets are available in order to enable non-programmers (like designers) to use this technology.

For this project we are using an HTC Vive Pro headset, so we need to download Steam VR prefab from the asset store and import it into our project (Figure 50).

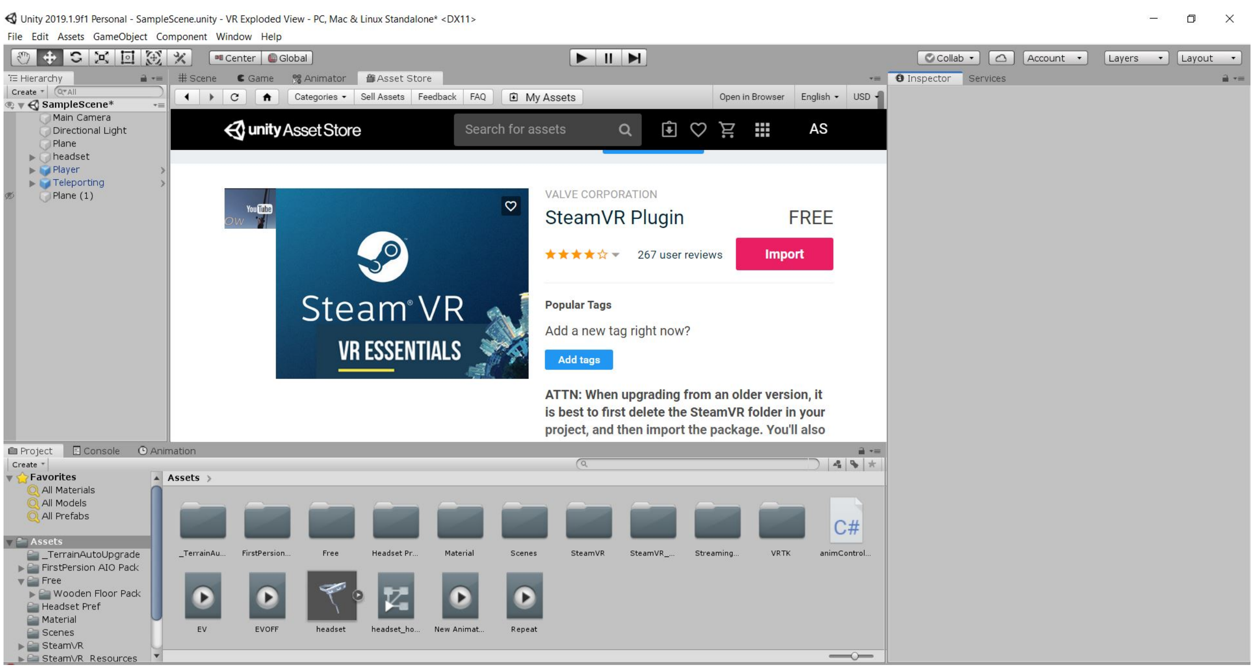


Figure 50. Importing Steam VR

The next step is to add the components we need into the hierarchy list. The first component we need is a player. Search Player on the search box and drag the asset to the hierarchy list (Figure 51).

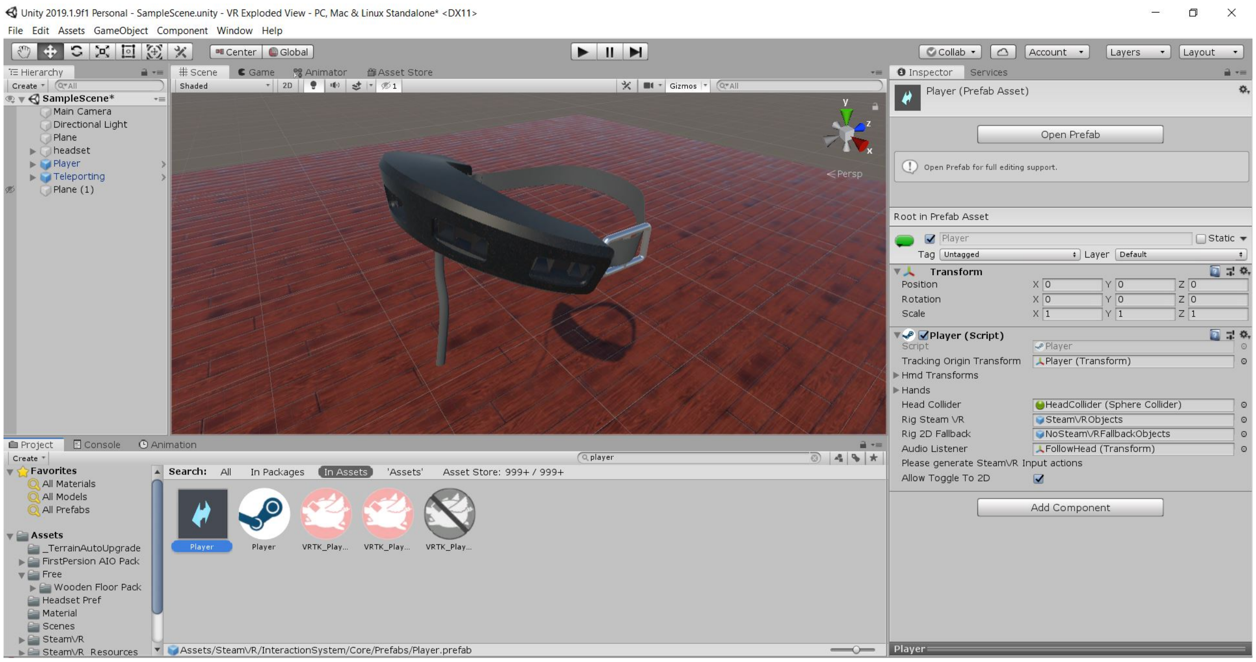


Figure 51. Adding player to the project

After that, we need to add the teleportation component in order to be able to walk through the scene. To do so, first we need to add "Teleporting" asset to the hierarchy list. Then we need to duplicate the plane that we already created as the ground and turn it to a teleporting area in order to track the teleporting component we just added. That can be done by selecting the duplicated plane, clicking on "Add Component" and search for "Teleport Area". Now we have a teleporting area overlaying the ground which let us to walk through the scene (Figure 52).

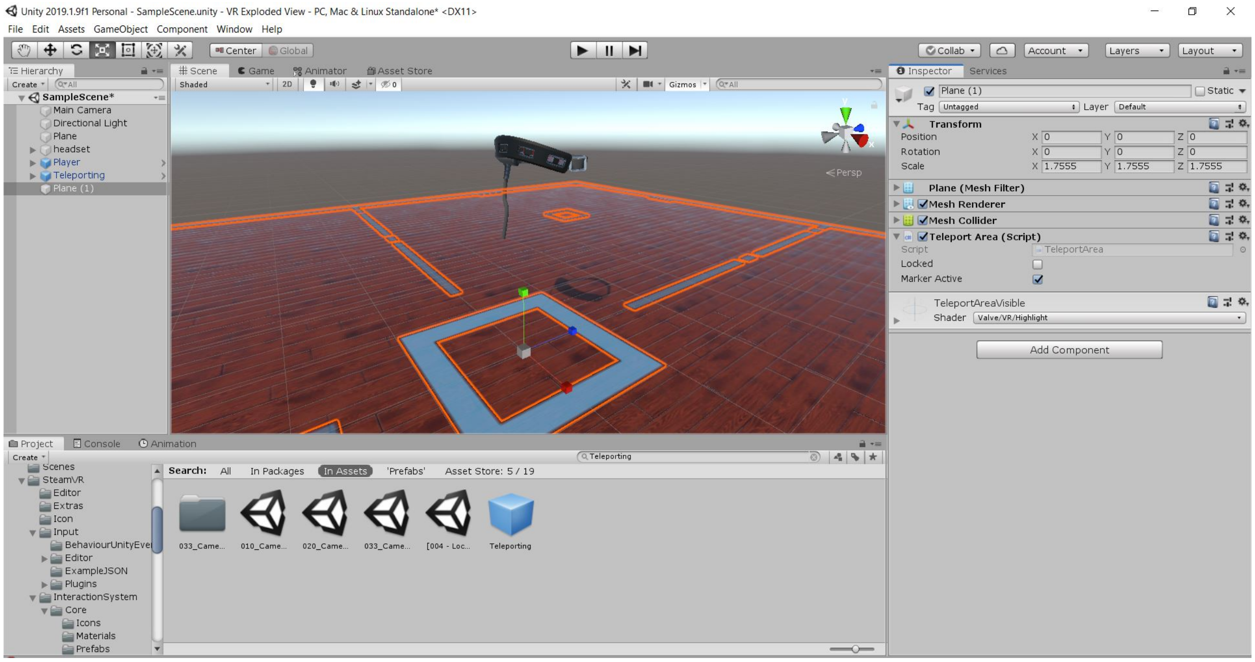


Figure 52. Adding teleportation to the project

Adding an Interactable model

In order to improve the communication between designers and engineers, it's better to let them interact with the real scale model just like they would in the real world. To do so, we need to have a real scale model and attach some physics to it so that it will be acting like an actual object in the real world.

To have a real scale model, since we already added some material to the model that we used for exploded view, it's easier to just duplicate that model and scale it to fit the actual scale. The only thing we need to do is to remove the animation component from the duplicated model so that this model will be still.

Next step is to add a collider to the model so that Unity recognizes it as a physical object. To do so, select the model > click on "Add Component" > Physics > Box Collider. And then scale the collider down to fit the model. (Figure 53).

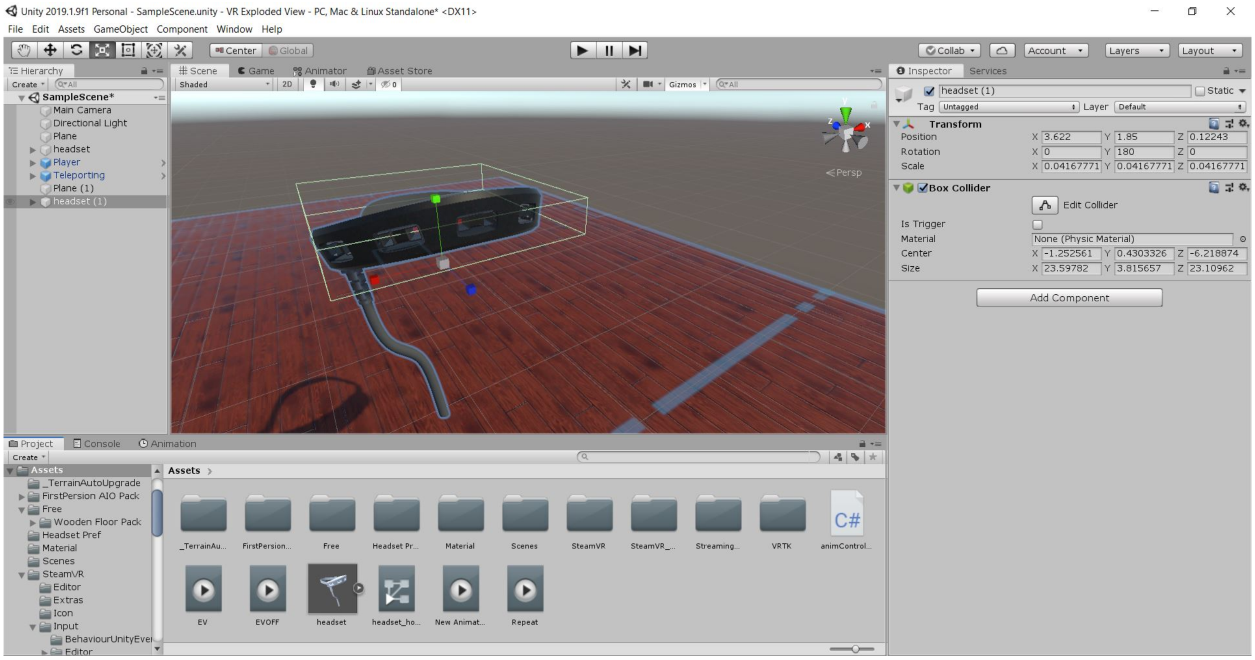


Figure 53. Adding a collider to the model.

The next step is to add some script to be grabbable and throwable by the user in order to feel like an actual object. To do so, click on "Add Component" and search for "Interactable" and add the script to the model. Do the same thing once more and search for "Throwable" script and add that to the model as well. The throwable component has the Rigid Body feature, so that the model will be acting like an actual object and follow the physics of the real world (Figure 54).

We can still improve the overall experience and look of the scene by adding small features like a stage to hold the real scale model, as well as adding some labels to indicate the exploded view and the interactable model so that it would be easier for the user to interact with the application for the first time. And a humanoid for representing the interactivity between multiple people (Figure 55).

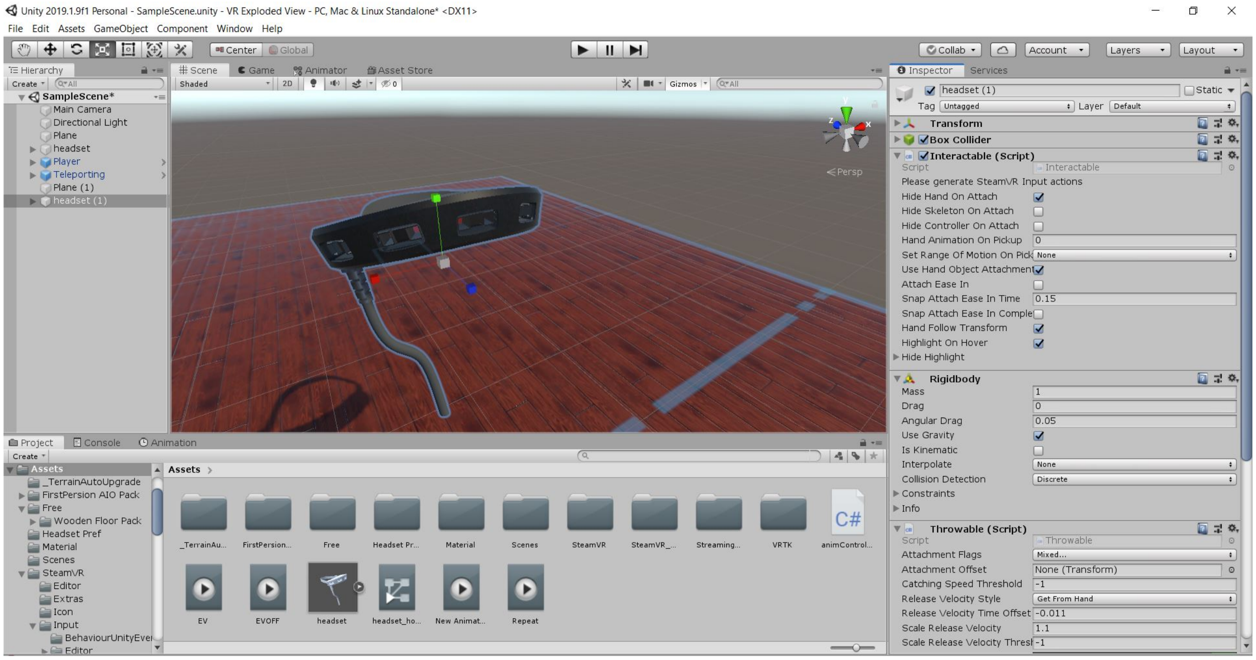


Figure 54. Adding Interactable and Throwable script to the model

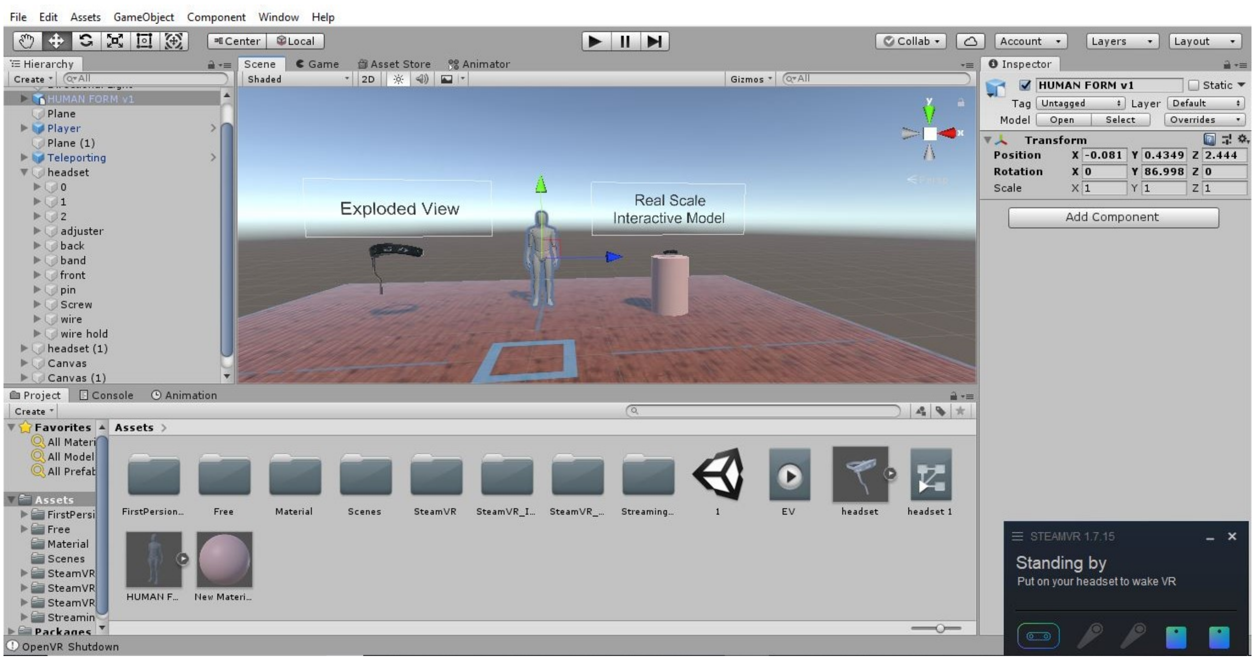


Figure 55. Final application.

After adding those details, our project is done, and the application is ready to run. You can also build an ".exe" file (or other formats depending on what platform you want to run your app on) in order to run the app on other computers.

As you saw, we just built a VR app from scratch that meets all the requirements that we needed and customized it based on our need in our design project. Obviously, this was just an example of how we can implement immersive technology into our design project; the possibilities could be limitless for achieving what we need out of this technology.

Chapter 5: Conclusion

Summary

The intention of this thesis was to explore immersive technology by defining different types and terminologies of this field and its place within the industrial design process. New technologies bring their own pros and cons. Although they can be beneficial in many cases, there might be certain cases that may decrease the efficiency of the process.

The guidelines that are developed in this thesis demonstrate when immersive technology can be efficiently used in the industrial design process as well as indicating those phases of the design process that immersive technology would not be beneficial to use. It was also shown how these guidelines can be used and practiced in how a VR application can be created from scratch in order to meet all the requirements of our design project.

Further Development

Immersive technology has improved significantly in this decade and will be improving even faster in the near future since now there are more demands for this technology than before, and there are more companies investing in this field, which causes it to be improved rapidly. As this technology grows, there will be more capabilities that it will be providing; therefore, there is a potential to have complementary research to this study for the upcoming technology.

References

Borzak, R. A. (1974). A Methodical Approach to Problem-Solving for Industrial Designers, Auburn University, Auburn, AL.

Bruder, G., Steinicke, F., Rothaus, K., & Hinrichs, K. (2009). Enhancing Presence in Head-Mounted Display Environments by Visual Body Feedback Using Head-Mounted Cameras. 2009 *International Conference on CyberWorlds, Bradford, West Yorkshire, UK* 43-50. 10.1109/CW.2009.39.

Covarrubias, C. *What is Immersive Technology?.* Retrieved from https://advrtas.com/immersive-technology/

Davis, N. (2019). Showcasing the world's first photorealistic mixed reality demo by Varjo and Volvo. Retrieved from https://blogs.unity3d.com/2019/09/09/showcasing-the-worlds-first-photorealistic-mixed-reality-demo-by-varjo-and-volvo/

Design Council. (2005). The Design Process". *A study of the design process – The Double Diamond.* Retrieved from https://innovationenglish.sites.ku.dk/model/double-diamond-2/

Evans, M. (n.d.) *How They Do It. Loughborough Design School, UK, with support from IDSA.* Retrieved from https://www.idsa.org/education/how-they-do-it

Handa, M., Aul, G., & Bajaj, S., (2012). Immersive technology – Uses, Challenges and Opportunities, *International journal of computing and business research.* (2229-6166).

Ismael, K. E. (2019). From Star to Sun: The Qualcomm Institute's CAVE Expands. Retrieved from https://ucsdnews.ucsd.edu/pressrelease/from-star-to-sun-the-qualcomm-institutes-cave-expands

Mealy, P. (2018). Virtual and augmented reality for dummies. Hoboken, New Jersey: John Wiley & Sons Inc.

Mealy, P. (n.d.) *Virtual & Augmented Reality for Dummies Cheat Sheet.* Retrieved from https://www.dummies.com/software/virtual-augmented-reality-dummies-cheat-sheet/

Mortice, Z. (2017). Augmented Reality in Construction Lets You See Through Walls. Retrieved from https://www.autodesk.com/redshift/augmented-reality-in-construction/

Nessler, D. (2016, May 19). *How to apply a design thinking, HCD, UX or any creative process from scratch.* Retrieved from https://medium.com/digital-experience-design/how-to-apply-a-design-thinking-hcd-ux-or-any-creative-process-from-scratch-b8786efbf812

NexCave, (n.d.) Retrieved from http://chei.ucsd.edu/toolbox/vr/nexcave/

Ramsey, D. (2015). Qualcomm Institute Convenes Conference on Future of Virtual Reality. Retrieved from https://ucsdnews.ucsd.edu/pressrelease/qualcomm_institute_convenes_conference_on_future_of_virtual_reality

Reda, K., Febretti, A., Knoll, A., & Aurisano, J. (2013). Visualizing Large, Heterogeneous Data in Hybrid-Reality Environments. *IEEE Computer Graphics and Applications.* 10.1109/MCG.2013.37

Sherman, W. R., & Craig, A. B. (2019). Understanding virtual reality: interface, application, and design. Morgan Kaufmann. Cambridge, MA: Elsevier Inc.

Skarredghost, (2017). Sketchup Viewer for HoloLens review. Retrieved from https://skarredghost.com/2017/03/20/sketchup-viewer-for-hololens-review/

Szymanski, J. (2018, March 20). *6 Use Cases for Enterprise Mixed Reality.* Retrieved from https://www.kaleidoinsights.com/6-use-cases-for-enterprise-mixed-reality/