Product Design Prototyping in Consumer Grade Virtual Reality

An assessment of the feasibility of consumer grade VR, AR and MR for product design prototyping

Sigve Astrup Lien
Department of Design
Norwegian University of Science and Technology

ABSTRACT

The last few years have seen a rise in the availability of capable low-cost consumer grade VR and AR systems, this paper considers the applicability of this emerging technology in the area of product design prototyping. It gives a brief insight into some general aspects of VR, and looks at the different available technologies, sets up four success criteria for functional product prototyping in consumer grade VR, and evaluates in the light of traditional prototypes. From this some recommendations for whether to invest in the technology or not will be given.

KEYWORDS: Product design prototyping, VR, Industrial design,

1. INTRODUCTION

With the rise of low cost consumer grade virtual reality (VR) products within the last few years, the development of the technology is accelerating. The accessibility, and the fact that video games are a major driver of this (SuperData, 2018), seems to nurture this acceleration. With today's possibilities for technology sharing and crowdsourcing, the potential for the technology seems big. From being a high cost, high investment technology mostly used by professionals in car design, aviation training, military simulation, and medical training, it is now available to the majority of consumers.

As Coburn et al. (2017) indicated in their review paper of the capabilities of current low-cost VR technology: the importance of the availability of consumer grade VR could be compared to the impact the switch from mainframe computers to personal computers had on engineering.

With the supplements of augmented reality (AR) and mixed reality (MR), this branch of technology seems to have a high potential for use in product design prototyping in a medium to low cost environment, like schools and start-ups.

1.1 Scope and Structure

This paper will consider some of the most readily available and relevant VR products, and asses the feasibility of them in light of product design prototyping. It will also to some degree consider AR and MR as supplements and comparisons.

Section 1.2 will define more specific what the goal of this paper is, and what criteria will be used for evaluation in the assessment. To give a better foundation for looking at VR and its potential related to prototyping, section 1.3 will explain some key terms related to this topic, and how they are chosen to be defined in this paper. Next, sections 2.1 to 2.5 will look at different, relevant

VR, AR and MR related hardware and software on the consumer grade level, at its possibilities and challenges. Then section 3 will briefly look at product prototyping and what its demands are. In light of these sections an assessment in section 5 will be done based on the success criteria set in section 1.2. This will in turn make the foundation for some recommendations.

It should be noted that VR technology is a big technical field, so what will be presented in this paper is just a general understanding of it so as to give the reader a foundation for choosing or not choosing to explore the field related to product design prototyping. It should also be noted that this is a technology that is rapidly evolving, and that there does not seem to be much relevant scientific research on this field yet. This rapid evolvement leads to the possibility that several points made in this text might already be outdated when reading. The content in this article is based on research done in the autumn of 2017 and the spring of 2018.

1.2 Goal of the paper

The goal of this paper is to look at current consumer grade VR technology and asses if it is mature enough be used in product design prototyping. To do this, the assessment will be based four success criteria, which are as follows:

- VR modelling can be used from early stage idea generating and mock-up modelling, to late stage CAD modelling.
- Manipulating and testing of the model is not inhibited by the media, and testing in VR gives real and usable data.
- VR modelling allows for faster iterations than regular physical modelling.
- VR models are convincing to designers, users and clients.

These basic criteria are created out of the idea of replacing regular product prototyping with a virtual kind (as far as possible), and they are set from how the line between them is perceived today.

1.3 Definitions

In this section there will be presented some general, relevant terms regarding VR technology.

Virtual Reality: As Virtual Reality (VR) has some varying definitions, it is in this paper be defined as the replacement of one or more senses with a virtual (computer generated) one. Most often sound, sight and touch. (Coburn et al. 2017)

Head mounted display: The most common way to display VR is with a head mounted display (HMD). These most often consists of one or two displays that depict two slightly different images to each eye, generating a stereoscopic 3D view of the virtual depiction. Correction for focusing on a screen so close to the eye is often done with lenses and software.

CAVE system: A CAVE (cave automatic virtual environment) system is an alternative to a HMD-system and is not that available to the public because of its cost and spatial demands. It is more common at universities or in industry. A CAVE system is a room with screens covering the walls, floor and roof. The user is located in the room wearing 3d-glasses with sensors, and the images depicted on the screens are generated to accommodate the user's perspective. (Onime et al. 2017)

Audio: Audio in VR often has its own function in creating spatial understanding. ("Spatial Audio | Google VR," 2017) The computer-generated sounds try to mimic the human ability to localize objects trough sound. This is often done with headsets or surround sound speakers.
Binaural recording is a way to record spatial sound and is done by placing microphones close to each ear on a person, or on a mannequin head. The playback is intended for headphones.

Haptic feedback: Haptic feedback is used to convey information in a way that one can feel.

Most often this is done with the use of a rumble motor that for instance can make a controller vibrate if the user bumps into something in the virtual world. Examples of other technologies in the haptic feedback arena are force feedback where motors push back on the user in some way. This can be done through i.e. exoskeleton gloves or a haptic suit. Another way is through methods of directing air streams to simulate physical feedback (Hoshi and Shinoda, 2016).

Augmented reality: Augmented reality (AR) is in this text defined as adding virtual information to the real world. As with VR this should be added to one or more of the senses. Most commonly this is done through mobile devices or glasses. An example of this could be a motorcycle helmet displaying how fast one is driving on the inside of the visor.

Virtual environments: A virtual environment (VE) is the virtual space you navigate in you VR experience.

Mixed reality: The term mixed reality (MR) is used when one combines the virtual world and the real world. This is often done with AR, augmented virtuality (AV), and other immersive technology (Milgram and Kishino, 1994). AV is defined as merging real world objects in to the virtual world. MR describes the spectre between the real world and the virtual world. In this paper, the term MR will mainly be used when the goal of the technology is to achieve something more than what is commonly known as VR or AR. For instance, a regular controller for a VR system will not be considered as MR, although it might exist in both simultaneously, but if the VR system scans the room and maps the physical features and/or objects to VR counterparts, it will here be considered as MR.

2. CONSUMER GRADE HARDWARE AND SOFTWARE

Different VR and AR related hardware and software have different strengths and application areas. Section 2.1 to 2.5 will shed light on some key features within the VR related technology.

2.1 VR technology

As stated by Leif P. Berg and Judy M. Vance (2017) in their survey about the state of VR: the technology now works, and is stable, mature, and usable. Still there are a lot of features that affect the quality and performance of the VR equipment. Here some of them will be listed.

Tracking: Tracking translates the user’s movement in the real world to the digital one. Discrepancy between the user’s movement and the perceived movement can feel unpleasant (Mazloumi et al, 2017), and can cause nausea, often known as cybersickness (Carvalho et al.2017). But a controlled discrepancy can also be used to manipulate the user to i.e. think and perceive that he or she is walking in a straight line when they are actually walking in a circle (Matsumoto et al. 2016) . This solution could demand very little space in contrast to the big VR experience it could provide.

There are several systems for tracking a HMD or a controller. Of these there are two main classifications: Outside-in tracking and inside-out tracking. These are used by Oculus Rift and HTC Vive respectably. The outside-in method is when active sensors, like the oculus-sensors, are stationary placed in a room and track passive emitters like LED-lights on e.g. a HMD or a controller. The inside-out method is when the active sensors are placed on what is being tracked. In the case of the SteamVR tracking system that the HTC Vive utilizes, there are two Vive Base Stations that sweep the room with lasers and pulses which the sensors on the headset and controllers use to calculate their position from (“SteamVR® Tracking”, 2017). The Windows Mixed Reality system also utilizes the inside-out system, but here it is only the HMD that has active sensors, not the controllers.

Figure 1 ("Inside-out vs. outside-in tracking",2010) shows the difference between the two tracking methods.

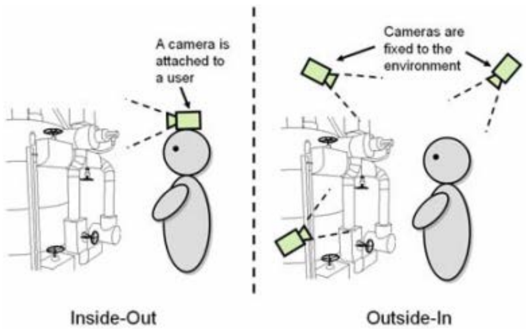

Figure 1: The difference between inside-out and outside-in tracking.

Latency: This denotes the time between the input or the user's movement, and the reaction of it in virtual space. An example of high latency is when a user wearing a HMD rotates his or her head and the displayed image rotates observably slower.

DOF: Different VR systems have different degrees of freedom (DOFs) for tracking. There are six basic degrees of freedom: Three for translation: movement in the x-, y-, and z-axis, which is also known as surge, sway, and heave. Three for rotation: rotating around the x-, y-, and z-axis, also known as roll, pitch, and yaw. Oculus Rift and the HTC Vive uses all six of them, while e.g. Google Cardboard only uses the three rotational degrees.

Occlusion: A problem that occurs with several methods of tracking is the one of occlusion. This is when something gets in between the sensor and the signal emitter. This can e.g. happen if the users body is between the controller and the Oculus-sensors on an Oculus Rift system.

Screen Door Effect: A challenge with a lot of HMDs compared to CAVE systems are the monitors they use. Because the screens are so close to the eyes, lenses are needed in front of them so that the user can be able to focus. This leads to several challenges for an immersive VR experience. One of these challenges is called the screen door effect (SDE). This is when the user can see lines between each pixel on the screen, like looking at the image through a screen door mesh. It mostly occurs if the screen does not have high enough resolution compared to their size, and is not considered a major problem in the available HMDs.

Focus: When viewing something on a VR HMD screen mostly everything on the image will be in focus. This does not reflect how it is in real life where only a tiny part of the object you are looking at is in focus and the rest is blurry. The lack of this feature could be tiresome for the eyes, and lead to a less immersive experience. FOVE is a currently available HMD VR developer kit that tries to mitigate and remove this problem by using eye tracking technology to calculate what the user is looking at. (Another factor with this is that the entire image on the screen does not have to be fully rendered at all times, which leads to potentially less processing power needed. ("GetFOVE", 2017)

FOV: In HMD a challenge for full immersion can be the field of view (FOV). The FOV in the leading VR HMDs is around 100-110 degrees which can be noticed on the sides, but companies like StarVR tries to solve this problem in their design.

2.2 HMD systems

The most accessible VR HMDs are the ones that utilize a smartphone as a display. Here are three examples of these.

Google Cardboard: The first and simplest HMD is the Google Cardboard. This is a system one can either buy, make or get for free. It consists of two lenses that adjust for the proximity of the smartphone screen, a cardboard housing, and often a magnet based button that lets one do simple interactions.
Utilizing the smartphone's internal sensors, it only has three degrees of freedom.

Daydream View: Similar to Google Cardboard, Google has another VR system that utilizes a smartphone as a monitor. But this is a more high-end product that includes a wand controller and is limited to only certain smartphones.

Samsung Gear VR: In the same category as Daydream View the Samsung Gear VR comes with a wand controller and utilize certain Samsung smartphones as monitors.

At the time of writing there are three major actors in consumer grade 6DOF VR, with a fourth one rapidly emerging. These are respectably: Oculus Rift, HTC Vive, Playstation VR, and Windows MR.
Since the Playstation VR system is not designed for computers, and therefore is not that relevant for product design prototyping, it will be omitted in this paper.
Specifications for some of the different HMDs can be seen in figure 2

HTC/Valve Vive:
The Vive is arguably the most versatile and popular VR headset. ("Epic's Tim Sweeney on Virtual Reality and the Future of Civilization", 2017) Because of the open platform system it is based on and integration with businesses a lot of games and applications are developed for this HMD.

Oculus Rift:
The Oculus Rift has been leading the VR market alongside HTC/Vive, and during the competition they have become more similar in terms of application support and equipment like controllers.

Microsoft MR:
Microsoft MR is the newest player to enter the consumer grade VR scene. With several different models produced by different companies, and with their computers starting to have VR support, they are pushing to make the technology accessible for most people.
A known problem with the Microsoft MR is that the controllers cannot be registered behind the headset of the user. This has been reported to be an issue in some games (Tested, 2017), but the occlusion problem is probably not a big of an issue in 3D modelling.
The use of the name Mixed Reality for window's system seem to be indicating something more than just a VR system, but rather a larger collection containing AR as well.
This in relation to Window's own MR-ready computers could indicate that it can be a system that in the future can cover a lot of relevant aspects of virtual product prototyping.

An overview of four of the different HMDs can be seen in table 1 (Oculus VR,2018. Acer, 2018. HTC corporation, 2018. Microsoft, 2018)

Specs/HMD	Oculus Rift	HTC Vive	Samsung Windows VR	Acer Windows MR
Display	OLED	AMOLED	AMOLED	LCD
Resolution	2160x1200	2160x1200 (1080x1200 per eye)	1440x1600 (Dual Panel)	2880x1440 (Dual Panel)
Refresh Rate	90Hz	90Hz	90HZ	90Hz
Platform	Oculus Home	SteamVR, VivePort	Microsoft Windows Mixed Reality	Microsoft Windows Mixed Reality
FOV	110 degrees	110 degrees	110 degrees	105 degrees
Tracking area	1,5x1,5 metres(two sensors), 2,5x2,5 metres (three)	5x5 metres	No limit*	No limit*
Built-in audio	Yes	Yes/extra, 3.5 mm headphone jack	Yes	No
Built-in mic	Yes	Yes	Yes	No
Controller	Oculus Touch, Xbox One controller	Vive controller, PC compatible gamepad	6 DOF Controller / Xbox One Controller Support	6 DOF Controller
Sensors	Accelerometer, gyroscope, magnetometer, Constellation tracking camera	Accelerometer, gyroscope, Lighthouse laser tracking system, front-facing camera	6-Axis ACC & Gyro ; 3-Axis Compass ; Proximity sensor ; IPD Sensor	Accelerometer, Gyro Sensor, Magnetometer, Proximity Sensor
Connections	HDMI, USB 2.0, USB 3.0	HDMI, USB 2.0, USB 3.0, bluetooth	HDMI, USB 3.0	HDMI, USB 3.0
Requirements	NVIDIA GeForce GTX 960 / AMD Radeon RX 470 or greater, Intel Core i3-6100 / AMD FX4350 or greater, 8GB+ RAM, Compatible HDMI 1.3 video output, 1x USB 3.0 port plus 2x USB 2.0 ports, Windows 7 SP1 or newer	NVIDIA GeForce GTX 970 /AMD Radeon RX 480 equivalent or greater, Intel Core i5-4590 or AMD FX 8350 equivalent or greater, 4GB+ of RAM, Compatible HDMI 1.4 video output, 1x USB 2.0 port, Windows 7 SP1 or greater	Nvidia GTX 1050/AMD RX 460 equivalent or greater, Intet Core i5 (6^{th} generation) equivalent or greater, 8GB+ of RAM, Compatible HDMI 2.0 video output, 1x USB 3.0 port, Windows 10 Fall Creators Update	Nvidia GTX 965M/AMD RX 460 equivalent or greater, Intet Core i5 (6th generation) equivalent or greater, 8GB+ of RAM, Compatible HDMI 1.4 or 2.0 video output, 1x USB 3.0 port, Windows 10 Fall Creators Update
Price (By April 23rd, 2018)	$399	$499	$499	$399.99
IPD adjustment	yes	yes	not specified	not specified

Table 1: Overview of the specifications of four different HMDs

2.3 AR

Pure AR headsets are not yet as available and popular as their VR cousin. This could be because they have to interact more with the real world, and therefore have a higher demand for mobility, comfort, computing power, design and usability. It could also be that they miss a defined driving force in the way that VR has games driving it forward. But products like Microsoft HoloLens are getting more and more ready for the market ("Mixed Reality momentum continues in the Modern Workplace and Microsoft HoloLens expands to 29 new markets", 2017).
The probably biggest arena for AR at this moment is smartphones. Apple have already integrated AR in their operating system iOS11, and the android version is right around the corner ("ARCore Overview | ARCore", 2017).

2.4 Input and feedback devices

A lot of controllers and input devices have and can have potential for use in VR and VR based product design prototyping. Covering several aspects of interaction and input levels, as well as giving feedback.

Keyboard/Pad: A standard input device is the regular keyboard which is used extensively in regular CAD modelling. Close to this is a numeric pad, or a self-programmable pad. These are often used to access shortcuts to modelling tools, navigating and entering specific values for precise modelling.
The second main tool for regular CAD drawing is the Spacemouse or 3d-mouse that lets one navigate the 3d space in an easy and precise way.

Game Controllers: Game controllers, like the Xbox One controller, was used by Oculus Rift before they developed their own VR controller. The game controller is a standard and well-integrated interaction device for gaming, and is also sometimes used by CAD modellers and the like as a self-programmed controller for shortcut commands.

VR controllers/Wands: The major VR systems have developed their own wireless controllers to work with both their tracking and their operating system.

In addition to a wand controller, HTC also offers a self-contained tracker unit, often called the puck, that allows the user to connect it to real world items and track them in the VE.

A problem with the VR controllers is that feedback is often not corresponding to the expectations of the brain, like on the input side. E.g. one can move one's hand through a virtual, "solid" object and the only feedback is a vibration in the controller. This of course limits the haptic feedback and the spatial understanding regarding touch, but it also ensures that one does not break one's hands if hitting an object in the VE.

There are some companies that try to bridge the haptic feedback gap using different technologies. The company Dexta Roboticsdevelops an exoskeleton glove with servos pulling the fingers back when the user is "touching" a virtual object, this is supposed to allow for recognizing a shape with minimum visual feedback. But there are still some problems in making it convincing (Tested, 2017), and making it simple enough to be a feasible product for the marked (weight and price). But it is available, and they are currently selling a development kit.
Another company working with the haptic challenge is HaptX. They are also developing an exoskeleton glove, but they are also including a system of micro pneumatic actuators that are to simulate touch over a large portion of the hands. Being able to simulate texture, movement and more. In addition to this they are working on ways to give temperature feedback in the glove. They are also planning to make a full body suit. But there is still some way to go before these products are functioning as desired, and available to the wider market (Haptx, 2018).

In addition to these controllers there are another kind of technology available on the market that utilizes cameras to track the user so that the user is free from controllers. Here there is no form of haptic feedback, but there are also no limitations by a controller and its buttons. In this area, Leap Motion is a small hand gesture system compatible with VR, and the Microsoft Kinect (which is now out of production) also has a lot of possibilities regarding tracking of the body. But a problem with this kind of camera tech is occlusion, as with the Oculus Rift system one should have at least three cameras to get full coverage.

2.5 Software

When it comes to software there are a lot of different possibilities. Here regular 3D-modeling software will be presented, as well as more VR specific software.

Related to regular 3d computer modelling there are a several different kinds of software in different price classes and for different applications.

Starting with the software used more for engineering, one has examples like: SolidWorks, NX, Fusion 360, Rhino3d, and SketchUp.
These are powerful 3d modelling tools where the shape and dimensions of the object are the most relevant. This is so that a digital 3D-model can be used to accurately produce real world objects. These modelers are often parametric based, which means that the base geometry information is retained, and this is something that lets one go back and be able to alter or undo features later. These applications vary a lot in functionality, and the most complex ones often have a wide variety of functions for analysing different designs.

On the other end of 3d modelling one has the more sculpting based tools like Blender, ZBrush, 3DS Max, and Maya, which are used more for animation and visualization, and not for producing precise geometries.

These applications are mostly not supported in VR, but there are some applications that can bridge these gaps to some degree. For the most part this type of applications only lets one navigate the 3d model in question, as well as adjusting light, make measurements, and making notes, but they do not allow to make any changes to the geometry.

There are several of these applications that are specific viewing software, often for evaluating architectural models (where the haptic interaction is not that important as in product design). Examples of this are IrisVR, YulioVR and Kubity.

On a bit more complex level there are the game engines like Unity, Unreal and Stingray, that gives a lot more options regarding features like physics, lighting and interaction, but still altering geometry is not that easy, and they also have a large threshold for mastering, as they are quite complex applications in of themselves. Nevertheless, the online communities for these applications are big, and there are a lot of accessible information and guidelines for use and development of VR related software on the websites of Google, Vive, and Oculus.

When it comes to software for modelling in VR that is available for the general public, there are some, but none of them seem to have taken of at an engineering level. A reason for this could be that the computing need is still a bit too big for running both a massive engineering 3d modelling software as well as at the same time making it viewable in VR (Hammond, 2017).

Of the applications that are available there are several freeform, sculpting tools like MasterpieceVR, Oculus Medium, Kodon, Gravity Sketch, Google Blocks and Tilt Brush.
These are not very presice, and are mostly used for making visual objects.

On a bit more precise level, but still intended for a playful use, is MakeVR. Here one can work with dimensions and get the designs easily exported for 3d-printing. But it has not got a professional engineering touch and looks more like a game than a CAD software. It also seems that the creators of it are focusing mostly on makers and hobbyists (Hammond, 2017).

The only software that really stands out at the time of writing is the MindeskVR plugin for Rhino 5.0. This lets one navigate, edit and build 3d CAD models in VR in a more professional way. (Food4rhino, 2018). And with Rhino already being such a versatile tool related to 3d modelling, and with it being widely used by architects and designers, the community for it is already in place. (Rhino3d, 2018) Showing promise, there is still little to be found about people who have used this software, and examples of it being used.

Modelling in VR is a bit different than in regular on screen 3d modelling. The interface is quite different, and the precision one has in regular CAD work seems to be difficult to apply in VR space. A factor for this could be that the VR controllers demands much more energy from the users arm to be able to hold it still at the desired point in space.

3. PROTOTYPING

A product prototype is an object that approximates one or more features of a product. Techniques for prototyping vary, as do the reasons for making a prototype. Loughborough Design School's ID-cards present a taxonomy of design representations in relation to new product development ("IDSA iD cards", 2017). Here they propose eight types of prototyping, eight types of models, and several types of sketches and drawings. This paper will regard all of the prototypes, models, and some of the drawings mentioned here to be under the prototyping umbrella.
In addition to that, prototyping will also here include the 3d sketching with real materials, and exploration and concept generation trough form and material.

3.1 Spatial understanding

A large reason for making physical models is to understand it's size and shape in the real world. An on-screen model is difficult to interpret in this way because the 3d model has to be viewed through a 2d screen, this is especially a challenge if the object is to interact with other real-world items like in the case of a chair.
With good additive manufacturing technology now being relatively low cost, and widely available, it is bridging the gap between the digital and the physical models to some degree, but there are still limitations in size here.

3.2 Cost of making prototypes

The making of models and prototypes can often be expensive, and demand a large number of tools, materials and equipment. It can be expensive and time consuming to make even small changes to a prototype, and this can go on the expense of the company or the design.

5. DISCUSSION

On the basis of this overview one can ask some questions regarding prototyping in VR.
3d modelling seem to be different form gaming in how the user perceives what is on the screen. In gaming the focus if often on a general view, while in 3d modelling the focus is often quite intense on what is being modelled. So in regard to this more testing is probably needed to see how 3d modellers would react to working on the relative low resolution screens of the VR HMDs over longer periods of time, and how issues like the SDE will effect this work. And if HMDs like the FOVE is necessary for conducting a VR prototyping workday.

The big elephant in the VR room is of course the lack of good haptic feedback.
In view of what could be most beneficial with VR prototyping compared to regular CAD work and workshop prototyping, is the possibility to interact with the object that is being designed in

a to scale and somewhat realistic way. This is beneficial in observation of the object, but also here one seems to need reference geometry to really understand size and form in relation to other things than one self. In this field AR seems to be more relevant as a tool in the future, since it can (in theory) put virtual geometry into real world situations, and let the user view it through 3d glasses instead of a 2d screen.
Another important part of modelling in VR is the spatial understanding of the geometry one is working with.
When it comes to interaction with a 3d object, the sense of touch is limited to what feedback the controller can give. With no product on the market that can convey shape, texture or softness, the need for physical objects is still there. There also seems to be a long way to go before there exists a flexible feedback system that can let the designer e.g. test sit a chair in VR. Problems like this can of course be mitigated through MR, through simple real-world objects being brought in to the VE through the use of a Kinect camera or a HTC tracker. Still, to convey and test angles, texture, and so on, the real-world object has to have such a high level of construction that the VR system would seem no longer to be that relevant.

So, from the information conveyed so far, the success criteria will here be revisited to evaluate the feasibility of using VR modelling as a prototyping tool.

- VR modelling can be used from early stage idea generating and mock-up modelling, to late stage CAD modelling.

It has potential. The only promising VR CAD software on the general market is MindeskVR, but it is still unclear how well it functions, since most available examples is marketing material from the company itself. Avoiding the gimmicks, the only benefit of using the VR software compared to regular CAD is to better understand the size of the object one is working with. The software definitely seems to be able to handle the early stage mock-up generation of models, but exploration of form trough material properties is still something that seems to be difficult in a software like this. Although form exploration through kitbashing in VR is an option (Tested, 2017)

- Manipulating and testing of the model is not inhibited by the media, and testing in VR gives real and usable data

As mentioned before, this seems to be one of the major challenges of VR-modelling, that one still cannot touch the model in any convincing way, let alone test features like sitting on a chair. The available technology of haptic feedback gloves and the like gives some good feedback, but it does not yet seem to be enough to be fully convincing. Here a MR addition of a real-life mock-up could be a good solution for approximating tests of the design (Kimishima and Aoyama, 2006). With little information available on the MindeskVR software, it is unclear how much analysing features they have opened for, or are able to integrate into their software, but since Rhino already has a large number of plugins and features, a stress test should for now be easy enough to conduct outside of VR. So usable data from VR prototyping alone is seemingly not that available.

- VR modelling allows for faster iterations than regular physical modelling

The possibilities in VR-modelling for duplication and formability, and with the rapidness, ease of material changes, fidelity modifications, and import function of other cad models, it indicates that the iteration time can be much faster in VR than real-world modelling.
Depending on the material used for real-world models, the shape of a VR model is almost always easier to change and demands fewer tools, and the possibility of saving multiple versions and iterations of a model makes it easier and less resource demanding to change the design, which again opens for less fixation during the development process.

- VR models are convincing to designers, users and clients.

Here as well the problem of haptics occurs, and it would probably be difficult to beat a real life prototype, but VR is an immersive technology so it would probably be better to show a VR model than a 2d screen model. It is also easier for an untrained eye to interpret a 3d model in VR than on a 2d screen. The VR technology also offers the possibility for several people to work on or view the same object in the same VE from several different locations in the world. This type of cooperation could offer a major advantage in meeting overseas manufacturers or clients.

6. CONCLUSION

VR product design prototyping seems to have a big potential, especially in early stage prototyping. It is a cheap way to rapidly build and evaluate products with fairly high fidelity in acceptable environments with real users. Compared to 2d screen modelling, the spatial understanding of the 3d geometries is much higher.
But there is a major gap in relation to haptics. The lack of convincing touch and physical testing it makes physical models still demanding, but the gap can be bridged to some degree with 3d printing and some haptic technology.

As the specs for most of the HMDs are quite similar, it could be wise to invest in a system that is expandable and has a high support to software. The HTC with separate tracking pucks, open source and high software support could be a good choice. An indication of this as a good choice is the use of the HTC in the development of hardware and software. Both MakeVR, MindeskVR and some of the haptic hardware seem to use and collaborate with HTC in development.
The Vive still has a larger play/operating area than the Rift, but the Windows MR has the largest. Still all are within the volume of general industrial design objects

With the technology development seeming to move quite fast, and the support community being quite big, depending on the product in question, It would probably be a good idea for start-ups and schools to invest in this kind of system as a supplement to mock up model making.

REFERENCES

RCore Overview | ARCore. (n.d.). Retrieved December 2, 2017, from https://developers.google.com/ar/discover/

Berg, L. P., & Vance, J. M. (2017). Industry use of virtual reality in product design and manufacturing: a survey. *Virtual Reality*, *21*(1), 1–17. https://doi.org/10.1007/s10055-016-0293-9

Buy Samsung HMD Odyssey Windows Mixed Reality Headset with Motion Controllers. (n.d.). Retrieved April 23, 2018, from https://www.microsoft.com/en-us/store/d/samsung-hmd-odyssey-windows-mixed-reality-headset-with-motion-controllers/8w91r774pdkk

Carvalho, P., Miyagawa, T., Maciel, F., & Melo, P. (2017). VR Rio 360: The challenges of motion sickness in VR environments. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *10280*, 495–504. https://doi.org/10.1007/978-3-319-57987-0_40

Coburn, J. Q., Freeman, I., & Salmon, J. L. (2017). A Review of the Capabilities of Current Low-Cost Virtual Reality Technology and Its Potential to Enhance the Design Process. *Journal of Computing and Information Science in Engineering*, *17*(3). https://doi.org/10.1115/1.4036921

Epic’s Tim Sweeney on Virtual Reality and the Future of Civilization. (n.d.). Retrieved December 2, 2017, from http://www.rollingstone.com/glixel/interviews/epics-tim-sweeney-on-vr-and-the-future-of-civilization-w459561

Home. (n.d.). Retrieved December 2, 2017, from https://www.getfove.com/

Hoshi, T., & Shinoda, H. (2016). Airborne ultrasound tactile display. In *Pervasive Haptics: Science, Design, and Application* (pp. 121–138). https://doi.org/10.1007/978-4-431-55772-2_8

Inside-out tracking - Virtual Reality and Augmented Reality Wiki - VR & AR Wiki. (n.d.). Retrieved April 23, 2018, from https://xinreality.com/wiki/Inside-out_tracking

Kimishima, Y., & Aoyama, H. (n.d.). *Development of Evaluation System for Style Design Using Mixed Reality Technology*.

MakeVR Lets You Create 3D Models in Virtual Reality with Real CAD | Make: (2017a, March 27). Retrieved April 23, 2018, from https://makezine.com/2017/03/27/makevr-lets-create-3d-models-virtual-reality-real-cad/

MakeVR Lets You Create 3D Models in Virtual Reality with Real CAD | Make: (2017b, March 27). Retrieved April 23, 2018, from https://makezine.com/2017/03/27/makevr-lets-create-3d-models-virtual-reality-real-cad/

Matsumoto, K., Ban, Y., Narumi, T., Yanase, Y., Tanikawa, T., & Hirose, M. (2016). Unlimited corridor: Redirected walking techniques using visuo haptic interaction. Presented at the ACM SIGGRAPH 2016 Emerging Technologies, SIGGRAPH 2016. https://doi.org/10.1145/2929464.2929482

Mazloumi, Hodgson, D. M., & Nalivaiko, E. (2017). Effects of visual flow direction on signs and symptoms of cybersickness. *PLoS ONE*, *12*(8). https://doi.org/10.1371/journal.pone.0182790

Milgram, P., & Kishino, F. (1994). Taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, *E77-D*(12), 1321–1329.

Mindesk VR. (2016, February 29). [Text]. Retrieved April 23, 2018, from http://www.food4rhino.com/app/mindesk-vr

Mixed Reality momentum continues in the Modern Workplace and Microsoft HoloLens expands to 29 new markets. (2017, November 1). Retrieved December 2, 2017, from https://blogs.windows.com/devices/2017/11/01/mixed-reality-momentum-continues-modern-workplace-microsoft-hololens-expands-29-new-markets/

Oculus. (n.d.). Retrieved April 23, 2018, from https://www.oculus.com/

Onime, C., Uhomoibhi, J., & Wang, H. (2017). Mixed Reality Cubicles and Cave Automatic Virtual Environment (pp. 1–8). Presented at the Proceedings - 2016 15th International Conference on Ubiquitous Computing and Communications and 2016 8th International Symposium on Cyberspace and Security, IUCC-CSS 2016. https://doi.org/10.1109/IUCC-CSS.2016.009

Rhino Features. (n.d.). Retrieved April 23, 2018, from https://www.rhino3d.com/6/features

Spatial Audio | Google VR. (n.d.). Retrieved November 30, 2017, from https://developers.google.com/vr/concepts/spatial-audio

StarVR - Panoramic Virtual Reality Headset. (n.d.). Retrieved December 2, 2017, from https://www.starvr.com/

SuperData Research | Games data and market research » Virtual Reality Market and Consumers. (n.d.). Retrieved April 23, 2018, from https://www.superdataresearch.com/market-data/virtual-reality-industry-report/

Technology. (n.d.). Retrieved April 23, 2018, from https://haptx.com/technology/

Tested. (n.d.-a). *Modelmaking Toys with Virtual Reality Sculpting*. Retrieved from https://www.youtube.com/watch?v=HwJdYxRwxoo

Tested. (n.d.-b). *PROJECTIONS, Episode 31: Windows Mixed Reality + SteamVR*. Retrieved from https://www.youtube.com/watch?v=KVOkVkPzGo4

Tested. (n.d.-c). *PROJECTIONS, Episode 31: Windows Mixed Reality + SteamVR*. Retrieved from https://www.youtube.com/watch?v=KVOkVkPzGo4

VIVE™ | VIVE Virtual Reality System. (n.d.). Retrieved April 23, 2018, from https://www.vive.com/us/product/vive-virtual-reality-system/

Welcome to Steamworks. (n.d.). Retrieved December 2, 2017, from https://partner.steamgames.com/vrlicensing

Windows Mixed Reality Headset. (n.d.). Retrieved April 23, 2018, from https://www.acer.com/ac/en/US/content/series/wmr