






Exploration and evaluation of CAD modeling in virtual reality

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ABSTRACT

Virtual reality (VR) technology has experienced a recent surge in popularity over the past few years and is finding more applications beyond entertainment. Three dimensional modeling is an application in which integration with VR technology is still in the development stage. The focus of this research is to evaluate the feasibility for computer-aided design in VR and to identify the best set of features for virtual reality modeling and practices in this new domain. A platform for testing CAD in VR is developed through the integration of CAD software with a game engine and compared against traditional CAD methods through testing. Modeling capabilities included previews, creating solid rectangular prisms and spheres, lock to grid, and cuts of similar shapes. User testing with four different models (i.e. chair, maze, truck, sculpture) and survey responses suggest respectively that design in virtual reality promoted greater creativity in modeling, allowed for a greater feature creation rate, and that a slight majority of test participants preferred modeling in VR compared to traditional CAD applications.

KEYWORDS

Virtual reality; modeling; user testing; proof of concept; 3D printing. rapid prototyping

1. Introduction

Current commercially available computer-aided design (CAD) software is limited to interfacing with the user at a computer terminal using common peripherals, such as a mouse and a keyboard, to interact with the software through windows, icons, and menus. While this method is effective and allows for the rapid transfer of ideas from the user to the computer, there exists methods of altering the traditional workflow that can enhance the user experience such as through gestures [8]. For example, it has been shown that when CAD users are enabled to use vocal commands, instead of solely interacting with the software through the mouse and keyboard, productivity is increased [17]. There has also been work done examining the implications of multi-modal inputs into CAD systems combining both gestures and voice commands [2]. Extensive work has also been done to allow multiple users to interact with the same virtual model at the same time [13]. Similarly, virtual reality (VR) has been explored to aid in the review process of CAD models [4]. The task of creating and editing CAD models from within a VR environment has also been researched to some extent [3, 23]. Research into VR software development has also received significant attention [7].

Commercially available software for VR allows the user to create and edit geometry through a sculpting interface where material is added and removed where

desired [15]. The idea of creating a virtual reality sculpting environment has also been the subject of academic research [19]. While this software is effective and allows for the creation of accurate and detailed models it is not capable of producing the boundary representation (BREP) models that form the basis of CAD software. As a result, they are not capable of parametric modeling and their usefulness in engineering is limited. Software has also been developed using the Open CASCADE kernel that does allow for the creation of BREP models from within the VR environment, but the software was designed only for the application of VR and did not interface with traditional CAD software [3]. More recently Mindesk, Inc. has developed a plugin for Rhino 5 that allows for CAD model creation from within a virtual environment, however the product is still in the alpha version and has not been fully developed [18]. Additionally Dassault Systemes has incorporated virtual reality tools into their 3DEXperience platform [1].

The intent of this research was to develop and test a proof of concept for VR software that would programmatically create BREP models in a traditional CAD system through the use of the developer's application programming interface (API) building on the work of [20]. Through the application of this API, it is possible to rapidly create geometry in the VR environment that can then be parametrically edited and refined in the CAD

software through the traditional terminal interface with all the support windows, icons, and menus. This application and proof of concept allows the user, from within a VR environment, to create models consisting of simple rectangular prisms and spheres utilizing the Fusion 360 software developed by Autodesk. The intent of this application is to progress towards mechanical modeling in virtual reality, as opposed to a tool an animator would use. In some instances it would be acceptable to keep all tasks and data within the game engine, however for engineering applications the capability to save models in actual engineering applications is required. To test this VR CAD implementation, testers were asked to create four simple models, two of them in the traditional Fusion 360 interface, and two within the VR application. The results of these tests enabled the evaluation of the effectiveness and efficiency of creating CAD models in VR when compared to modeling from the traditional interface. Here we examine the number of features created for the models, the overall model quality and accuracy, the level of creativity exhibited, and the user preference in modeling system.

2. Methodology

The objective of this research was to evaluate the effectiveness and efficiency of CAD Modeling in VR environments. In order to achieve this objective, a system of a standalone CAD engine, connected to a virtual reality platform, was developed through a new implementation. To assess the value of creating geometry in a virtual reality environment without having to create a new CAD engine from the ground up, the development process considered one of the ways this can be accomplished [22] by integrating the functionalities of two previously existing, professionally accepted applications. The main benefit from combining these two applications is that the CAD models made in VR could be viewed, edited, and evaluated in the traditional CAD engine once the user completed the modeling within the VR environment. In the current implementation the geometries available for modeling include rectangular prisms and spheres.

2.1. Implementation

At the highest level this implementation of VR modeling is accomplished by a network connection between the CAD software and game engine software that has built-in VR integration. Benefits of leveraging a game engine include prefabricated rooms or levels which have significant innate animation capability, built-in support for VR headsets and controllers, functionality for first

person perspective, and built-in mesh rendering capabilities. Benefits of using CAD software include: geometry creation is handled by a preexisting CAD kernel, cutting, intersections and other features, which are more complicated than extrusion, and triangle meshes accessible through the API similar to other implementations [6, 14]. The game engine used was Autodesk's Stingray game engine and the CAD software package was Autodesk's Fusion 360. An HTC vive was integrated for its immersive VR capabilities and a TCP network connection was established between Stingray and Fusion 360 that allowed for the transfer of text data. Scripts were developed using the Fusion 360 C++ API and the Winsock2 network library while a module for the Stingray game engine was written in the Lua programming language leveraging the Stingray API and the Lua socket network library.

In this network relationship, Fusion 360 functions as the server and waits for requests from Stingray to create geometry. The rectangular prisms are requested using the two controller locations as the opposite corners of the prism, creating the prism parallel to the walls and floor of the virtual room. Spheres are requested using one controller for the center of the sphere and the distance between the two controllers defining the radius. Fusion 360 creates the solid models and then displays them as boundary representations, which contain triangle mesh objects, for the purposes of their own visualization. This triangle mesh data is made available to the users through the Fusion 360 API. The API also allows users to choose their mesh quality, which defines how many triangles are used to represent surfaces. In order to reduce the network traffic and eliminate users experiencing lag the mesh quality was set to low, which reduced the numbers of triangles required to display a sphere from over a thousand to just over two hundred. The application experiences approximately 0.5 seconds of lag for every 2500 triangles, which is acceptable for small models and testing purposes but will need to be much lower for future applications. The triangle mesh data is sent across the network to Stingray in the form of char arrays. This data is unpackaged in Stingray and is used to create clean looking 3D models using Stingray's procedural mesh capabilities (see Fig. 1).

One of the most difficult challenges for this project was to find a way for users to preview what they would create instantly without relying on the CAD software for the preview, which would cause a constant lag due to network traffic. Responses from testers in preliminary testing made it clear that previews would be an essential aspect for this application for it to be a useful tool. Previews for rectangular prisms were achieved by using a 3D GUI available in stingray and creating custom surface

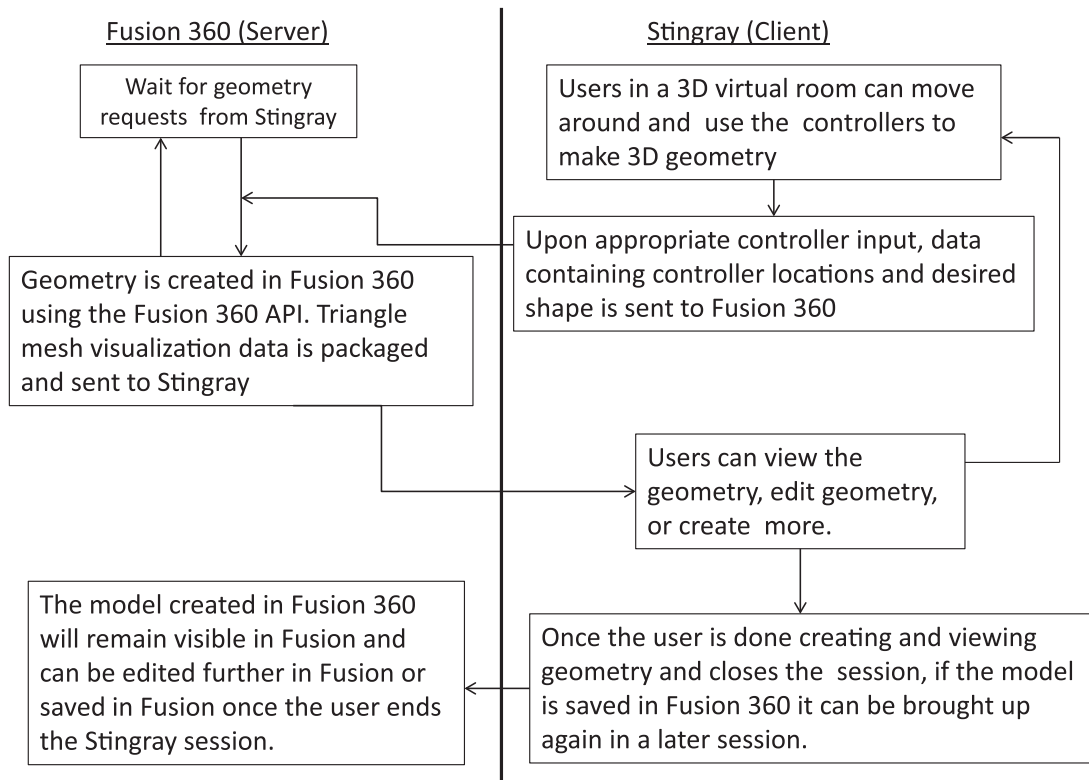


Figure 1. Flow chart detailing the network connection between Fusion 360 and Stingray.

calculation, shading and mesh occlusion methods. Previews for spheres were achieved by using Stingray's line object functionality. The previews, and the actual models, for the rectangular prisms snap to a grid that has a resolution of about 5 cm in real space. The previews and models for spheres do not snap to a grid to allow greater ease of use. Preliminary testing was also vital for determining these snapping to grid settings. Without snapping to grid for prisms the testers felt that they did not have the amount of accuracy they desired. For spheres however, the unsteadiness of human hands causes the center of the spheres to jump between snap points unintentionally. This creates radically different orientations and sizes of spheres which can be disorienting for the user. Ultimately, this can result in a feeling of less control and precision, negating the original purpose of snapping to a grid.

If the user holds down either trigger button, the application creates a preview of a rectangular prism between the two controllers (see Fig. 2). If the user taps the other trigger button the command is sent to Fusion 360 and the model of the rectangular prism is made and sent back to Stingray for visualization. If the user holds down either grip button that controller becomes the center of a sphere preview, using the other controller for the radius distance (see Fig. 2). If the user taps the other grip button the command is sent to Fusion 360 and the model of the

sphere is created and sent back to Stingray. The user is free to walk around in virtual reality as long as they do not collide with anything in the real world space, and virtual boundaries are set up to make that less likely. The users can teleport great distances in the virtual world using the trackpad if they want to get somewhere they cannot get to by walking (see Fig. 2). Pressing the menu button will toggle the mode of use to either "creation" or "cut" modes (see Fig. 2). In cut mode every space contained within the preview is cut away rather than being created as a solid.

Part of the effectiveness of this application comes from using Fusion 360 to create geometry, which allows for more complicated geometric features such as Boolean subtractions or "cuts". The ability to cut away geometry is one that is not seen frequently in other virtual reality creation applications because it requires the CAD kernel to perform such operations. While simple previews can be created and maintained using Stingray Lua API calls, using the CAD kernel also allows meshes to be created for more complicated geometries, like those seen in Fig. 3d and 3e below. The effectiveness of using the game engine is found in the users experience in virtual reality. While modeling, the user has an immediate and natural sense of depth, scale, and proportion. They can look at the model in real 3D, rather than a 2D projection onto a computer screen. Because of the tracking capabilities of the HTC Vive, the users can also accurately

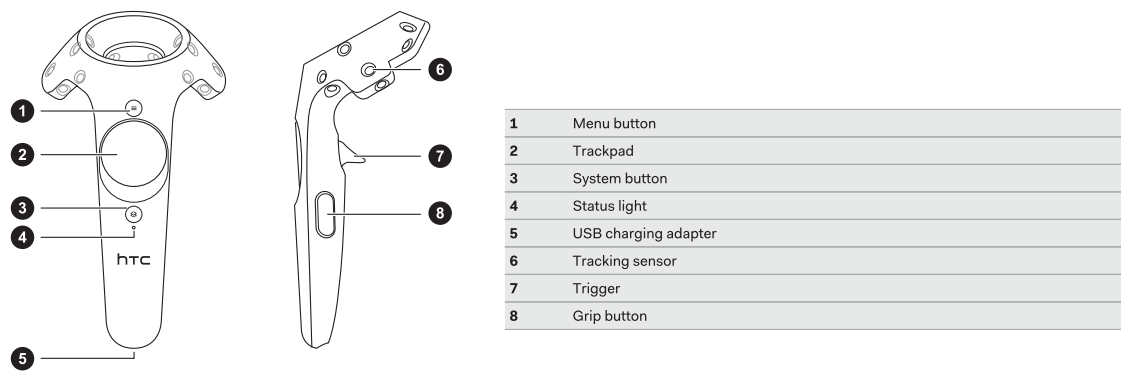


Figure 2. Schematic of HTC Vive hand controllers [12].

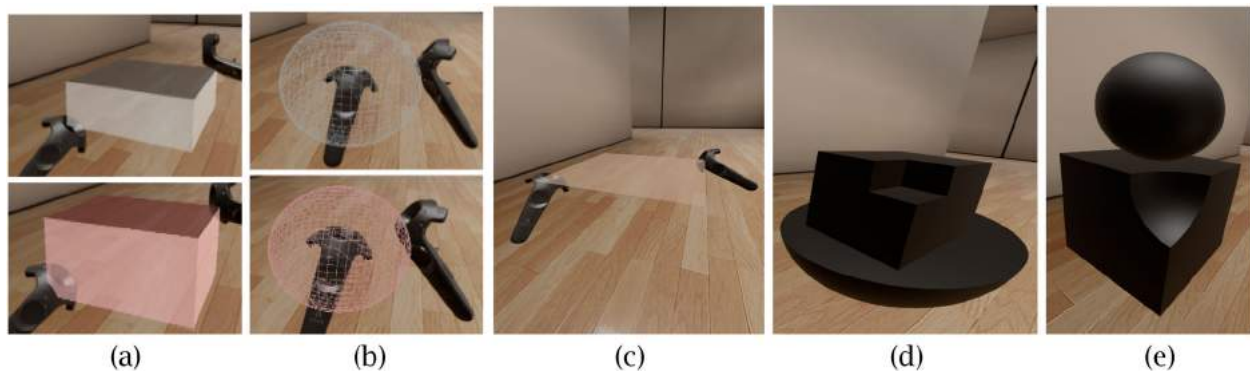


Figure 3. (a) Previews of prisms in both creation and cut modes, (b) Previews of spheres in both creation and cut modes, (c) Coloring for no depth prisms, (d) and (e) Preliminary test models showing the capabilities of VR modeling proof of concept and the appropriate sense of depth and proportion from the user's perspective.

walk around, bend, crouch under, or inspect the model from above which enhances the experience of working on an actual three dimensional model rather than two dimensional projections on a computer screen. Coloring is also enabled on previews to warn users of mode settings. In preliminary testing users would forget which mode they were in because there was no indication for each mode. Now, in creation mode the previews show up in gray, and in cut mode the previews show up in red. If the controllers are oriented such that the points snap to grid in a plane and there would be no depth to the prism to be created, an orange hued plane appears to warn the user that there is no depth to their geometry.

2.2. User testing

Using the software developed, testing was performed to determine the value of modeling in a VR environment as opposed to a traditional computer set-up. Participants varied from having no prior CAD experience or light CAD experience to extensive CAD experience, capturing the varying experience levels of the general population. Participants in the testing phase were given instructions on how to use both systems to create rectangular

spheres and prisms and perform cuts of each feature. For modeling in virtual reality the controls were as described in Section 2.1. For modeling in Fusion 360 the only input devices were a mouse and keyboard. Each participant was given up to five minutes in each system to feel comfortable with the controls (see Fig. 4). They were then tasked to create four models, having a five minute time limit for each model. These models include a simple chair, a truck, a maze, and a sculpture of a person from a starting block. The participants were randomly assigned the order in which they would create the models and in which environment they would create each model. For example, Participant 1 was assigned to create the chair and maze models in the virtual reality system and then the sculpture and truck models in Fusion 360. A screen capture of the VR and Fusion 360 sessions were recorded and the feature count was measured for each model.

Immediately after the conclusion of each modeling session the testers completed a short survey to better understand their experience which is discussed more fully in the following section. The survey was designed to compare and evaluate which method of modeling, if either, is faster, which method is preferred, which method allows for greater creativity, and which method results



Figure 4. Participant during VR Training.

in models of higher quality and accuracy. In order to remove confounding variables from the testing, participants modeling in either system were only allowed to create rectangular prisms and spheres and cuts of both. The final stage in the testing was the evaluation and ranking of the four different models for all the participants through blind judging. The judges were given as much time as they needed to sort the participants' models of one category from most to least creative. This process was repeated four times for each of the 11 judges, allowing them to judge all four types of models (i.e. chair, maze, sculpture and truck).

3. Results and discussion

Almost all of the participants (sample size of $N = 21$) used the full five minutes allotted for the creation of each model. In addition, most participants would use less than 5 minutes to familiarize themselves with each system before creating their models for a total testing period of around 50 minutes, which includes time for completing the survey. The resultant 84 models (21 from each category) developed as part of this study were then assessed, analyzed, and evaluated as described previously.

The rate at which participants could model in terms of features per minute can be compared across the two systems (i.e. VR and Fusion 360). Fig. 5 presents the average number of features added during the five minutes by the participants (on the left axis), and the equivalent rate in features added per minute (on the right axis). The error bars represent one standard error from the mean. For most of the four models, the number of features added was significantly higher in the VR environment (p-values below < 0.01) with the exception of the Maze models (p-value of 0.14) using a two sided t-test. The speed at which the participants were able to realign their hands and controllers in the 3D environment was much faster than in the traditional CAD system where multiple mouse clicks for choosing a plane, rotating the models, dragging the mouse, and other motions were more time consuming.

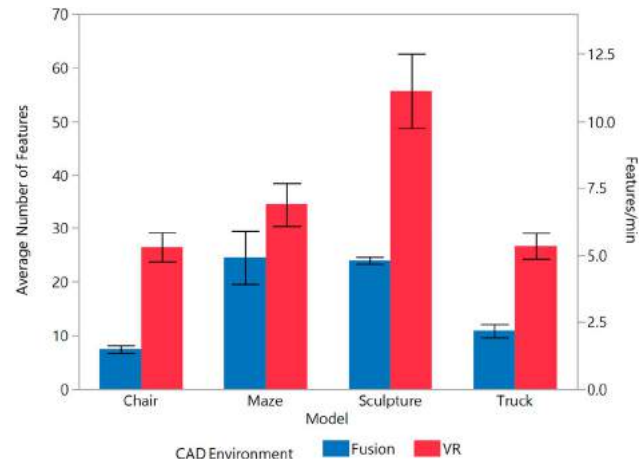


Figure 5. Comparison of the two CAD environments with respect to the average number of features and rate of adding features in the four categories of models.

This suggests that VR could be leveraged to generate concepts and ideas more quickly than traditional CAD when used for simple models or communicating information quickly about 3D geometry.

Since the rate at which participants could model in VR exceeded that in Fusion 360, it was expected that the creativity or innovation of the models would be correspondingly higher as well. The ranking by 11 different judges shows that indeed the creativity was evaluated as higher in general for VR. Fig. 6 shows the rank ordering for the chair (left) and sculpture (right) models for each of the 11 judges (J1 through J11). Each of the points (labeled by letters) in Fig. 6 represent how the 11 judges ranked each of the 21 models within a category from 1 (top) through 21 (the bottom). The models created in the VR environment (V) are in red while the models developed in Fusion 360 (F) are in blue. In each column, the judges would rank the particular models without any knowledge of whether these models were created in Fusion 360 or the VR system. Overall, more chair models were ranked better in VR, evidenced by a larger percentage of judges ranking VR models on the top half. A similar trend was observed in the sculpture models on the right hand side of Fig. 6.

Although judging in terms of ranking creativity can be subjective, sufficient scores were obtained to identify a distinctive trend that modeling in VR was considered comparatively more creative overall. The rank ordering of the judges was combined into a total score for each model by assigning 20 points if a model was ranked as the best (in a category), 19 points as second best, 18 points as third best, etc.. Summing these 11 values provides the total score (T) for a model such that $T = (21-r_1) + (21-r_2) + \dots + (21-r_{11})$ where r_i is the rank order from the

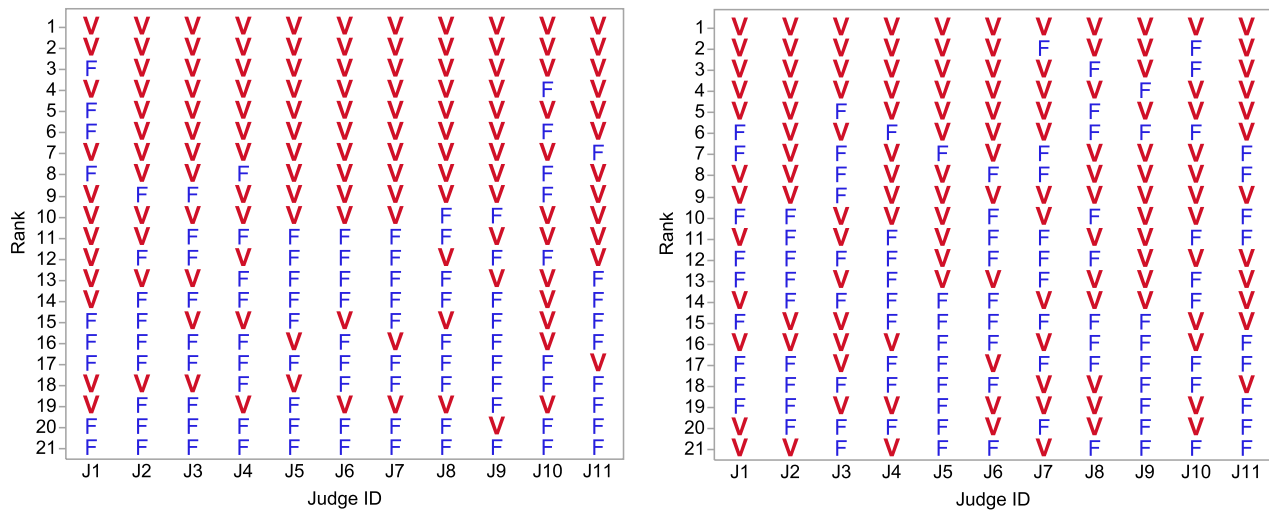


Figure 6. Rank Ordering by the 11 judges for the 21 chair models (left) and sculpture models (right). Top ranked models are at the top (VR environment (V) - red, Fusion 360 (F) - blue).

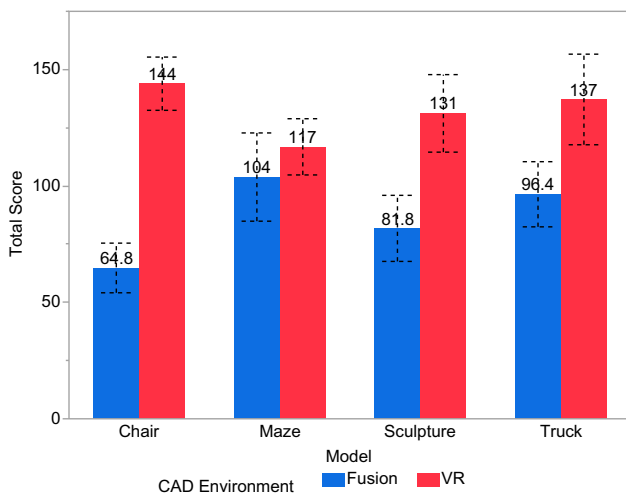


Figure 7. Comparison of the two CAD environments with respect to the total ranking score across the four categories of models.

ith judge. For example, if a specific model is ranked 3rd by all 11 judges, the aggregate score will be $(21-3)+(21-3)+ \dots +(21-3) = 198$. This analysis revealed that the highest ranked chair had a total score of 186 while the worst ranked chair had a total score of only 11.

Finally, these 84 scores are averaged within the modeling category and are presented in Fig. 7 demonstrating that the judges ranked VR models 12% to 122% more creative than the models developed in traditional CAD environments (based on the rankings process previously described). Hence, the results concur with previous studies in communicating ideas rapidly [5] and conveying information to superiors [9].

However, since the quality of the various designs varied across model categories, the variance across

individuals was also assessed. The four different total scores of the 21 different participants were also combined and analyzes. The participant with the highest aggregated ranked models had a total score of 701, while the participant with the lowest aggregated ranking had a total score of 154. The four models of these two individuals with total scores at the extremes are respectively presented in Fig. 8 and Fig. 9 below. In Fig. 8, the participant with the highest total score modeled the chair and sculpture in VR and the other two models in Fusion 360. The individual with the worst score modeled the truck and sculpture in VR and the other two models in Fusion 360. It was clear from these and other examples that the experience of the participants was a large factor in the quality and creativity assessed by the judges. In general, an individual who was better in one of the CAD environments tended to do well in the other. However, separated by participant, the models in VR scored better than the models in Fusion 360 from the same individual. The mean of all VR models had an average score of 132.4, compared to an average score of 88.6 for models in Fusion 360. Additional analyses and observations are made within each model category in the following sections.

3.1. Chair modeling

The eight chair models shown in Fig. 10 were created in Fusion 360 and the eight chair models shown in Fig. 11 were created in the virtual reality modeling application. By inspection, and supported by the judges rankings in the previous session, the variability and variety that exist in the chairs created in VR is much higher for those created in Fusion 360. Those created in Fusion 360 are mostly dinner table type chairs that have a very similar

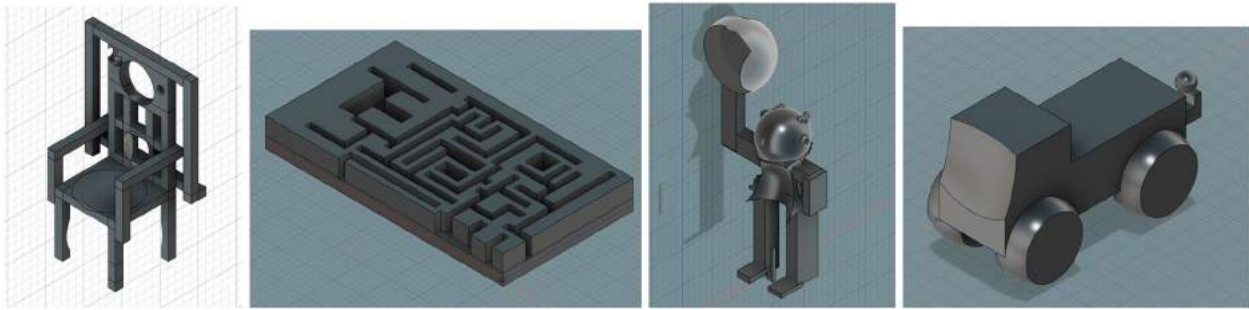


Figure 8. The four models developed from the participant with the highest total ranking score.

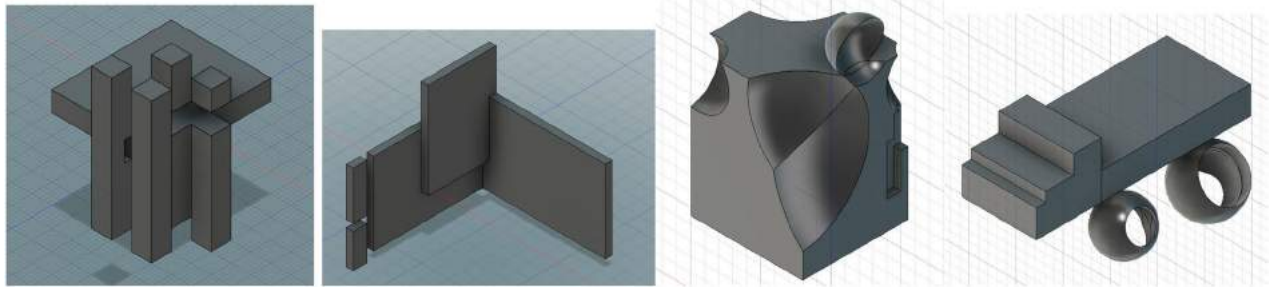


Figure 9. The four models developed from the participant with the lowest total ranking score.

form, with one exception on the bottom right. On the other hand, the models created in VR exhibit a wide variety of styles and show much more freedom in the interpretation of a “chair.” Furthermore, we see the use of spheres in the chairs that were created in VR compared to a complete lack of spheres in any chairs developed in Fusion 360. Although, the both environments were able to create both spheres and rectangular prisms, the participants that implemented spheres in their chair designs were those using VR. In the survey that participants completed after the testing they frequently commented that

it was much easier to create and position spheres in VR and we suspect that contributed significantly to their use in VR and increased creativity.

In modeling the chairs, we frequently observed that the participant would first create the seat of the chair and then model the legs before moving to the back of the chair. In Fusion 360, this rarely created issues. However, in VR this frequently caused the user to bend over, kneel, or lie down in order to create the legs at the desired height. Often the participant felt uncomfortable and was somewhat hesitant to complete the required motions.

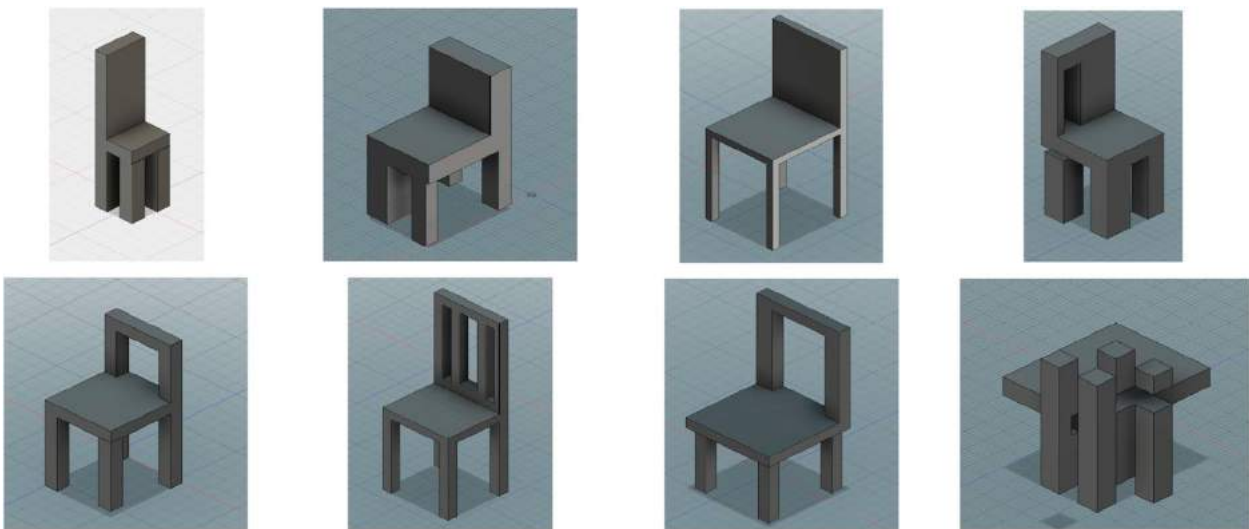


Figure 10. Eight chair models created in Fusion 360.

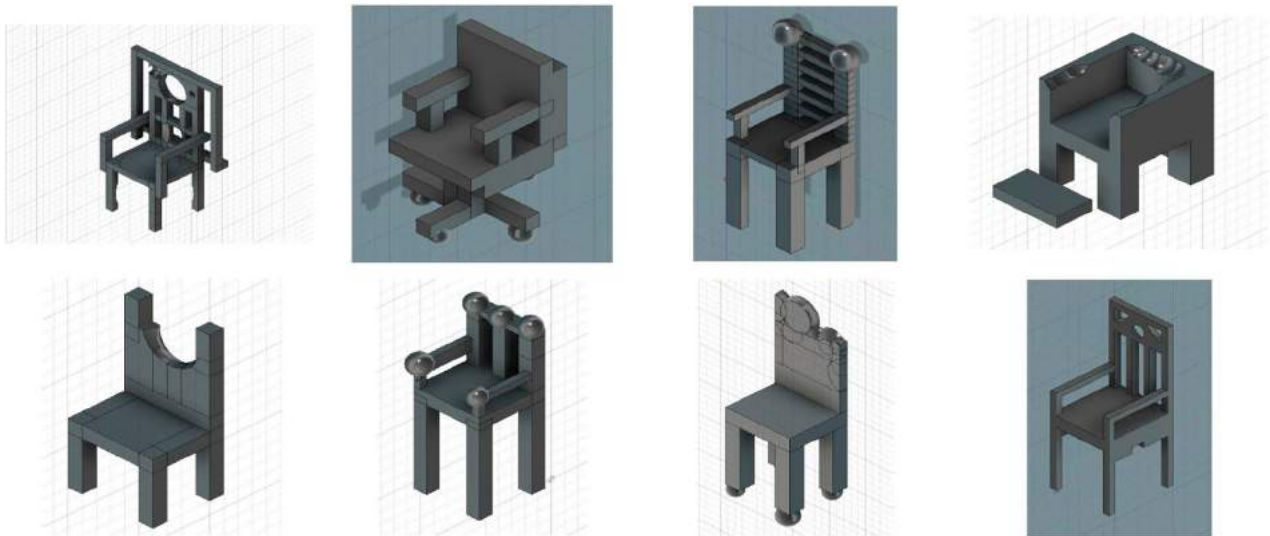


Figure 11. Eight chair models created in the VR environment.



Figure 12. Validation of VR chair models through 3D printed designs.

We hypothesize the cause of this hesitancy is due to the unfamiliar motions required or a self-awareness that other people (i.e. test proctors) were watching in the physical world, but we leave this exploration for future work. Regardless of the cause, they were often less accurate in the positioning of the legs which resulted in lopsided chairs. In Fig. 12 a selection of the chairs that were created in VR were 3D printed in order to more fully validate and evaluate their appearance. As seen in Fig. 12 two of the four chairs are leaning significantly and do not sit flat on the surface. In the second chair from the left, the lopsided model could have been corrected had the spheres snapped to a grid in the same way done for the creation of the rectangular portions, however this would have caused other problems as discussed in section 2.1. Since post processing reveals that the legs are all equal, the lean is caused solely by the varying sphere size at the base of the legs. Finally, while some users noticed and mentioned the increased effort required for

modeling in VR, we note that this could lead to increased workplace enjoyment and potentially improve the health of employees as explored by other researchers [11,16]. This was also reflected in the comments of multiple users that mentioned that modeling in VR was much more enjoyable compared to the traditional CAD modeling process.

3.2. Truck modeling

The four truck models presented in Fig. 13 were all modeled in Fusion 360. The first two on the left received high creativity scores from the judges and are considered some of the better truck models while the two on the right received low creativity scores and are considered two of the worse truck models. As mentioned previously, both good and poor models were observed in both environments but in general the models in the VR environment were ranked better.

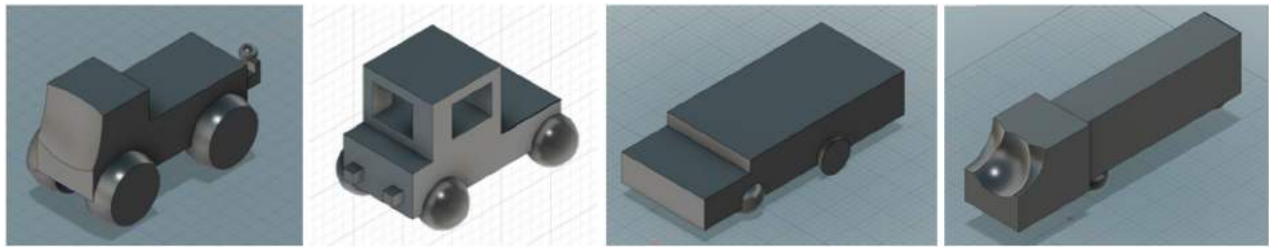


Figure 13. Truck models developed in Fusion 360, highly ranked (left), poorly ranked (right).

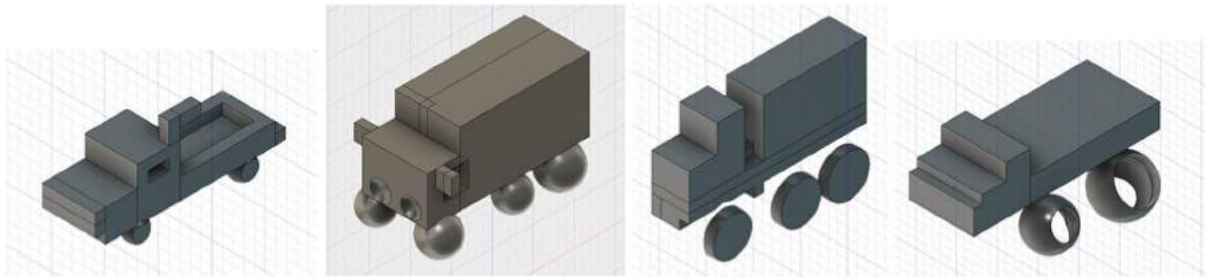


Figure 14. Truck models developed in VR, highly ranked (left), poorly ranked (right).

For comparison, four truck models developed in VR are presented in Fig. 14. Similarly, the two trucks on the far left were ranked high, while the two on the far right were ranked poorly. Precise placement of the wheels and matching the sizes of the wheels in the four or six different locations was considered one major factor in developing good truck models.

There is less of a discrepancy between truck models in Fusion 360 and VR as there was between chairs modeled in the different environments. While the chairs in VR tended to have more extra features, the trucks in Fusion 360 seemed just as likely to have extra features compared to the trucks modeled in VR. Head lights, side mirrors, windshields and flat wheels are all examples of common extra features seen in both environments. As expected, the trucks modeled in Fusion 360 tended to have more accurately placed wheels that avoided problems such as being off center or disconnected from the base of the truck. Fusion 360's capability to snap to grid in two steps was advantageous in these instances because participants could accurately place the center, and then dimension the radius. The VR environment could benefit from having a similar two-stage sphere snap to grid process which was not functional in the user testing. Furthermore, the VR environment could be further enhanced if enabled to turn snap to grid on and off, similar to capabilities in many CAD packages such as Fusion 360. With respect to the current implementation, the results suggest that virtual reality is well suited for idea expression, but not as much for precise accuracy in modeling.

3.3. Maze modeling

Fig. 15 shows two comparisons of mazes built in virtual reality and Fusion 360. The leftmost model was created in VR and it was created at life size according to the users perspective. The second model from the left was created in Fusion 360 with a height greater than most created in Fusion 360. In general, it was easier to control and set a uniform height in Fusion 360, again highlighting traditional modeling's effectiveness at accuracy over the VR environment. The third model from the left was modeled in VR with the final modeled in Fusion 360 at the far right. These two models demonstrate the advantage of sketching in traditional modeling. Participants who developed mazes using complex sketching composed of many rectangles were much faster and could create more exciting models within the five minute time span. Sketching allowed the participants to focus on the basic outline and then set the maze height in one step. In VR, users had to manage the height and relative position of both hands in each step, which took a significantly larger amount of time or the same time at the expense of accuracy. In these types of planar and almost 2D models, the increased 3D visualization inside a VR environment is less beneficial. Producing sketches will be an essential step for VR environments in the future, and it provides exciting possibilities, such as 3D sketches that are three dimensional and not bound to any plane.

Still, participants working in VR were able to plan mazes that were more unique or creative than the others.

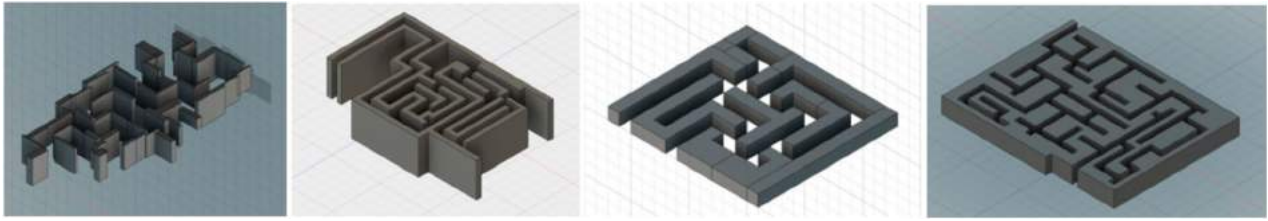


Figure 15. Comparison of Maze models for VR and Fusion 360.

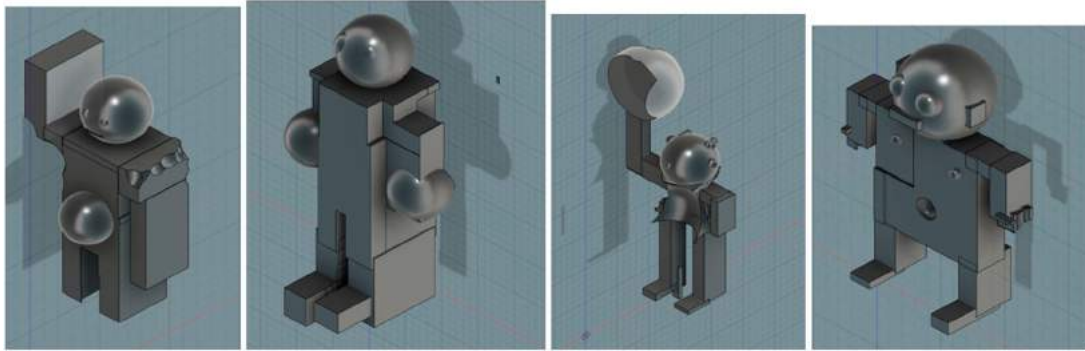


Figure 16. Four sculpture models with high ranking scores.

Three of the participants in VR created life sized mazes that they walked and teleported through as they created them. Another participant attempted to create a 3D maze cut into a sphere. Both of these ideas would be much more challenging on traditional CAD software. The capability to model at scale could find valuable applications in modeling products and ensuring from the beginning that the products have the right size and proportion in 3D.

3.4. Sculpture model

The sculpture model was the most challenging and opened ended modeling assignment given to the participants and it had the largest variability as a result. It was also different in that the participants were given a starting block from which to make their sculpture by removing or cutting material away. The starting block for the VR and

Fusion 360 environments was identical. One important difference in the VR environment is that snap to grid for rectangular prisms were turned off. This allowed the users to have more freedom in where they wanted to cut or add than the other models. However, it was disconcerting for most of the participants. Many of them commented on how they wish they could still snap to grid, because they could not be accurate enough to get the rectangular prisms to line up the way they wanted in many situations. This illustrates the importance of implementing the ability to control snap to grid for all shapes, and potentially changing the refinement on the snapping to grid capability.

Fig. 16 shows four of the best sculptures that consistently ranked high in the creativity sorting exercises. All of these models were created in virtual reality.

Fig. 17 shows four of the worst sculptures that consistently ranked low. The first and third models from

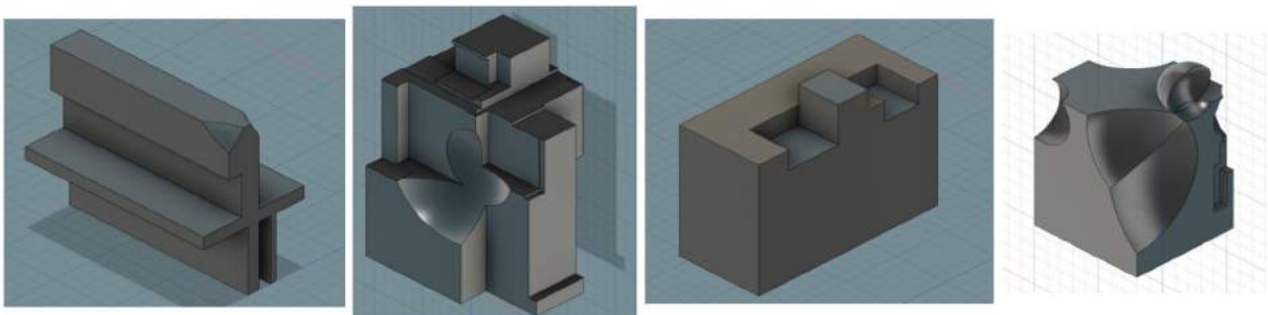


Figure 17. Four sculpture models with low ranking scores.

the left were both created in Fusion 360 and the other two models in the VR environment. Although virtual reality helped some participants express their creativity more effectively, it did not replace the basic skills and imagination of the designer.

Overall, modeling the sculpture was easier in virtual reality because it lends itself to an immediate sense of position, and allows easier access for placement of geometry. For example, users are free to place spheres wherever they want and are not bound to finding a construction plane on which to center the sphere. As could be expected, spheres were a more common modeling element in the VR model. Likewise, modeling in virtual reality allowed participants to work on the sculptures faster and thus end with a noticeably higher feature count in the same amount of time as shown previously. In much the same way that planar shapes resulted in a lower barrier to modeling for participants creating a maze in Fusion 360, the complicated 3D shapes involved with sculptures seemed to be a high barrier for those working in Fusion 360. These results suggest that working in virtual reality, which feels like a real 3D environment, more easily promotes creativity in three dimensions, while using the monitor and mouse limit the sense of freedom in three dimensions.

3.5. Survey response

After the testing each user was asked which system they would prefer to use overall as well as which system they would have preferred to use for each of the four models. The results of this polling are shown in Fig. 18. The overall preference for modeling system was almost equally split with 10 of the users preferring to use Fusion 360 and 11 users preferring to use the VR system. Interestingly, when asked about individual models the majority preferred to model in VR for many of the models. The maze is the exception to this case where there was 11 who preferred Fusion 360 with 10 who preferred VR. This phenomenon may be related to that described previous with respect to planar-like models.

The reasons that users provided for preferring one system over the other were sometimes contradictory in nature. Some participants mentioned that they would prefer to model the maze in VR because they wanted to make it human size and they felt that it would be easier in the VR system. Other users said that making a human sized maze in VR would be unmanageable and preferred Fusion 360 for that reason. Some users also mentioned the power of sketching in Fusion 360 to be able to quickly create a complex shape and then use an extrude to transfer it instantly in 3D. Finally, other users expressed how challenging it would be to create the required sketch in

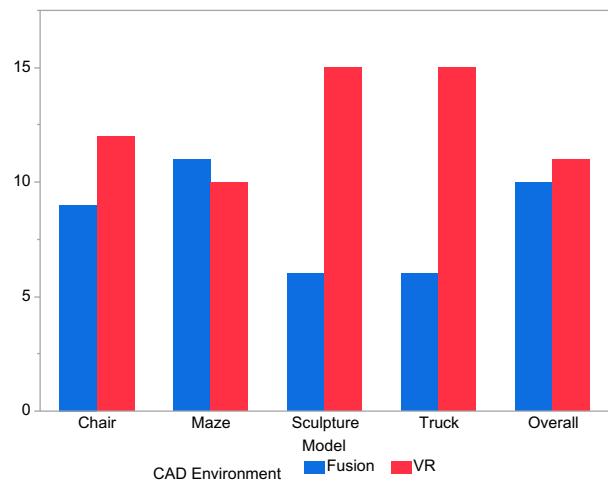


Figure 18. User Preference overall and for each of the four modeling categories.

Fusion 360 and for that reason indicated that they would have preferred to make the model in VR.

With respect to modeling the chair the preference was slightly in favor of modeling in VR, but not by a significant amount. The majority of responses indicated that they would prefer to have modeled the chair in VR because it was easier to move around the model and look at it from different angles. Some users also mentioned that virtual reality “helped in the creation process.” However, many participants discussed the difficulty associated with viewing the bottom of the model and the desire to have tools that would allow them to move, pan, or rotate the model. The user preference for modeling the truck and sculpture are both skewed heavily with a preference for modeling in VR. The responses provided three main reasons for this preference. The first is that the participants found the experience for these models to be more fun in VR. The second was the ability to easily, accurately, and quickly move around the model. Lastly, participants expressed that it was quicker to make a variety of sizes and shapes in VR.

Following the question regarding the system preferences the participants were asked to identify any features that they thought could be improved in either system. This was especially useful to determine the efficacy of the VR environment because it allowed for the identification of critical features that users felt were lacking. Some of the most common suggestions were an undo button and a way to move the model in the VR environment. A need for an undo button was also often verbally mentioned during the testing. Often times a user would unintentionally create an undesirable feature and in order to remove the feature the user would have to cut it away, potentially along with a part of their model. The second requested

feature, a way to move the model, is something that was observed as well when users were often timid or unwilling to kneel, or lie down, to access the bottom sections of a model. For Fusion 360, the most requested feature was a more intuitive rotation control process. We suspect that the ease with which users were able to move around in VR made the challenges of moving in Fusion 360 more apparent and for this reason most users requested something more intuitive.

4. Conclusion

Modeling in virtual reality is an exciting new possibility that will become more important as virtual reality technology becomes more affordable and common. This research has shown that modeling in VR is possible and that there are already some noticeable benefits such as increased enjoyment, potential for accelerated or elevated creativity and ideation, a reduction in some obstacles for adding features [21], increased workplace physical activity, and a more realistic sense of scale [10]. In order for modeling in VR to become viable in the professional world, however, it must be developed further to rival the current capabilities of traditional CAD systems. Initial CAD in VR capabilities that would be required include implementing translation, rotation, scaling and toggling snap to grid on and off. Offering more geometry features would also be essential. The ability to make sketches in 2D or 3D would offer additional actions such as sweeps and lofts. It is also clear that undo/redo capabilities are very important to users. Implementation of menus would be required for many of these additions. After these initial capabilities were added implementing an assembly module for part interaction would be a top priority. More advanced capabilities would also be beneficial such as parametric modeling, dimensioning, and even developing the possibility for multi-user CAD in VR.

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References

- [1] <https://www.3ds.com/products-services/3dexperience/>, Dassault Systemes.
- [2] Alibay, F.; Kavakli, M.; Chardonnet, J.; Baig, M.: The Usability of Speech and/or Gestures in Multi-Modal Interface Systems, Proceedings of the 9th International Conference on Computer and Automation Engineering, 2017, 73–77. <http://doi.acm.org/10.1145/3057039.3057089>
- [3] Bourdot, P.; Convard, T.; Picon, F.; Ammi, M.; Touraine, D.; Vezien, J.-M.: VR-CAD integration: Multimodal immersive interaction and advanced haptic paradigms for implicit edition of CAD models, *Computer-Aided Design*, 42, 2010, 445–461. <http://doi.org/10.1016/j.cad.2008.10.014>
- [4] Castronovo, F.; Dragana, N.; Liu, Y.; Messner, J.: An Evaluation of Immersive Virtual Reality Systems for Design Reviews, Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30–31 October 2013, London, UK.
- [5] Cecil, J.; Kanchanapiboon, A: Virtual engineering approaches in product and process design, *The International Journal of Advanced Manufacturing Technology*, 31(9), 2007, 846–856. <https://doi.org/10.1007/s00170-005-0267-7>.
- [6] Corseuil, E. T. L.; Raposo, A. B.; da Silva, R. J. M.; Pinto, M. H. G.; Wagner, G. N.; Gattas, M.: ENVIRON – Visualization of CAD Models In a Virtual Reality Environment, *Eurographics Symposium on Virtual Environments*, 2004, pp 79–82.
- [7] De Tryer, O.; Kleinermaun, F.; Pellins, B.; Bille, W.: Conceptual Modeling for Virtual Reality, Tutorials, Posters, Panels and Industrial Contributions at the 26th International Conference on Conceptual Modeling, 83, 2007, 3–18.
- [8] Dipen, D.; Ashirwad, C.; Thendurussi, K.: Gesture Interface for 3D CAD Modeling using Kinect, *Computer-Aided Design and Applications*, 10(4), 2013, 663–669. <http://doi.org/10.3722/cadaps.2013.663-669>.
- [9] Eckert, C.; Stacey, M.: Fortune Favours Only the Prepared Mind: Why Sources of inspiration are Essential for Continuing Creativity, *Creativity and Innovation management*, 7(1), 1998, 9–16. <https://doi.org/10.1111/1467-8691.00080>.
- [10] Jayaram S.; Vance J.; Gadh R.; Jayaram U.; Srinivasan H.: Assessment of VR Technology and its Applications to Engineering Problems, *Journal of Computing and Information Science in Engineering*, 1(1), 2001, 72–83. <https://doi.org/10.1115/1.1353846>
- [11] Hamilton, M.T.; Hamilton D.G.; Zderic, T.W.: Role of low energy expenditure and sitting in obesity, metabolic syndrome, type 2 diabetes, and cardiovascular disease, *Diabetes*, 56(11), 2007, 2655–2667. <https://doi.org/10.2337/db07-0882>
- [12] HTC, Vive PRE User Guide, http://www.htc.com/managed-assets/shared/desktop/vive/Vive_PRE_User_Guide.pdf, HTC Vive.
- [13] Jensen, G: Collaborative Multi-User Synchronous and Asynchronous modeling, analysis and design, *Defense Manufacturing Conference*, 26–29 NOV 2012, Orlando, Florida
- [14] Kim, S.; Weissmann, D: Middleware-based Integration of Multiple CAD and PDM Systems into Virtual Reality Environment, *Computer-Aided Design and Applications*, 3(5), 2006, 547–556. <http://doi.org/10.1080/16864360.2006.10738408>
- [15] Kodon, <http://store.steampowered.com/app/479010/>, Tenk Labs
- [16] Levine, J.A.; Vander Weg, M.W.; Hill, J. O.; Klesges, R.C.: Non-Exercise Activity Thermogenesis, Arteriosclerosis, Thrombosis, and Vascular Biology, 26(4), 2006, 729–736. <https://doi.org/10.1161/01.ATV.0000205848.83210.73>.

- [17] Martin G.: The utility of speech input in user-computer interface, *International Journal of Man-Machine Studies*, 30, 1989, 355–75. [http://doi.org/10.1016/S0020-7373\(89\)80023-9](http://doi.org/10.1016/S0020-7373(89)80023-9)
- [18] Mindesk, <http://www.mindeskvr.com/site/>, Mindesk Inc.
- [19] Peng, X.; Leu, M.: *Interactive Solid Modelling in a Virtual Environment with a Haptic Interface in Virtual and Augmented Reality Applications in Manufacturing*, Springer London, London, 2004, http://doi.org/10.1007/978-1-4471-3873-0_3
- [20] Rabatje, R.: Integration of basic CAD functions into a VR environment, *Proceedings of the International Computer Graphics Conference*, 1998, 238–241, <http://doi.org/10.1109/CGI.1998.694271>.
- [21] Simmons, J. E. L.; Robinson, G.; Russell, G. T.; Ng, F. M.: Immersive virtual reality in cable and pipe routing: design metaphors and cognitive ergonomics, *Journal of Computing and Information Science in Engineering*, 4(3), 2004, 161–170. <https://doi.org/10.1115/1.1759696>.
- [22] Weidlich, D.; Cser, L.; Polzin, T.; Cristiano, D.; Zickner, H.: *Virtual Reality Approaches for Immersive Design*, *CIRP Annals - Manufacturing Technology*, 56(1), 2007, 139–142, <http://doi.org/10.1016/j.cirp.2007.05.034>.
- [23] Zhong, Y.; Xiaobu, Y.; Ma, W.: Virtual Reality Based Solid Modeling, *Proceeding of the 5th World Congress on intelligent Control and Automation*, 2004, 3214–3218. <https://doi.org/10.1109/wcica.2004.1343116>