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Towards Precise, Fast and Comfortable Immersive Polygon Mesh Modelling: Capitalising the Results of Past Research and Analysing the Needs of Professionals

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Abstract

More than three decades of ongoing research in immersive modelling has revealed many advantages of creating objects in virtual environments. Even though there are many benefits, the potential of immersive modelling has only been partly exploited due to unresolved problems such as ergonomic problems, numerous challenges with user interaction and the inability to perform exact, fast and progressive refinements. This paper explores past research, shows alternative approaches and proposes novel interaction tools for pending problems. An immersive modelling application for polygon meshes is created from scratch and tested by professional users of desktop modelling tools, such as Autodesk Maya, in order to assess the efficiency, comfort and speed of the proposed application with direct comparison to professional desktop modelling tools.

CCS Concepts

•***Human-centered computing*** → ***Virtual reality;*** *Interaction techniques; Interaction design process and methods;* •***Information systems*** → *Multimedia content creation;*

1. Introduction

Computer-aided three-dimensional modelling is indispensable for the design process of the majority of today's products. 3D modelling has many uses: from making machines and designing architecture to the creation of fabulous creatures for films or games. *Desktop-modelling-applications* (DMAs) such as *Trimble SketchUp*, *Blender* and others are extensively used in such design processes. However, these tools reduce the interaction and perception of 3D objects to a 2D world due to monoscopic monitors and a 2D-mouse interaction. But past research has ascertained that modelling in Virtual Environments (VE) provides new perspectives and possibilities for user interaction [SJT*12, DBW*00].

In this paper we summarise major results of past research and compile novel approaches for solving pending problems. The proposed system and user interface, shown in Figure 1, is developed with the goal of examining new ways and ideas for fast, precise and comfortable modelling of polygon meshes in the spotlight of a long-term use, since modelling usually requires extensive hours of work. Our main research interest focuses solely on the interaction of immersive polygon mesh creation and we do not focus on applying materials or textures. We conduct a case study with 10 experts of 3D modelling, the potential end-users, for evaluating the proposed system and extract subjective potentials and limitations of Immersive Modelling (IM) compared to today's DMAs.

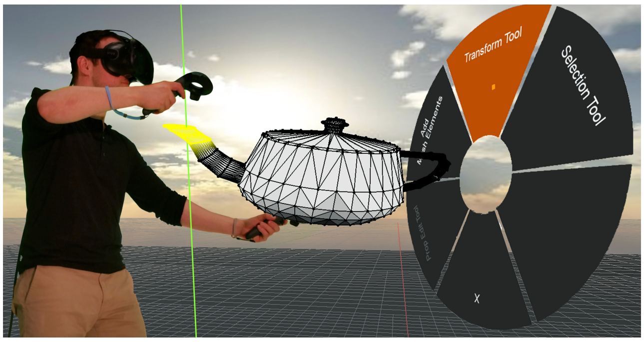

Figure 1: *Interaction with a menu while modelling a teapot. The green line indicates a constrained movement task to one axis.*

2. Related Work

The first work about IM was published by Clark [Cla76]. 16 years later, Butterworth et al. [BDHO92] introduced *3DM* which employs a 2D plane as a menu for system control. *HoloSketch* [Dee95], *FreeDrawer* [WS01] and Deisinger et al. [DBW*00] discovered some key results. Jackson and Keefe [JK16] developed an immersive modeller which supports advanced free-hand modelling and is similar to FreeDrawer. Bourdot et al. [BCP*10] investigated multimodal interaction for CAD applications. Hughes et

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al. [HZS*13] presented a one-handed interaction in a CAVE. Jerald at al. [JMY*13] introduced *MakeVR* which is based on the technique of Constructive Solid Geometry with Boolean operations. Mine et al. [MYC14] modified the commercial DMA SketchUp for using it in VEs. This work is the most related to ours. Mine et al. and Takala et al. [TMH13] were one of the first researchers who specifically compared and joined the possibilities of IM and DMAs. Takala et al. equipped Blender with head tracking and 6-DoF controllers and encountered problems with precise modifications.

Since VR technology became available for private users, various different modelling systems have been released recently: *Medium* by *Oculus, Kodon* by *Tenk Labs, SculptrVR* by *Nathan Rowe* or *Blocks* by *Google* offer different methods for the creation of models such as sculpting, modelling with Boolean operations or polygon mesh editing. The modelling process of Google Blocks is most related to our approach but has limited possibilities in regards to precise modifications and advanced changes of the mesh topology.

3. System

3.1. Hardware

Our system has been primarily developed for the HTC Vive but can also be used with other HMDs such as Oculus Rift. The out-of-the-box setup of the HTC Vive is used which consist of two 6-DoF controllers, two *Lighthouse* trackers and the HMD. Development and user tests ran on Windows 10 with an Intel i7 4790K, 16GB RAM and a Nvidia GeForce GTX 970.

3.2. Software

The application is written in C++ and utilises the library OpenSceneGraph as an extensible frame work. OpenSceneGraph was chosen over one of the major game engines because it allows developers extending internal mesh data with topology information which allows efficient and complex mesh operations. The engine for mesh operations is specifically written for the proposed modelling application and is based on the *half-edge mesh data structure OpenMesh* by Botsch et al. [BSBK02]. Basic mesh operations such as selection of mesh elements (vertices, edges and faces) as well as translation, rotation and scaling are available. Furthermore, mesh areas can be duplicated, deleted and extruded to new forms as well as be cut into separated parts. OpenVR is implemented and serves as the SDK and API to the HTC Vive and similar hardware.

4. The Modelling Application

Related work has shown many advantages for 3D modelling in VEs. The spatial perception of a model is better since the view can be freely adapted and the user perceives the depth in the scene through head tracking and stereoscopic rendering as well as 6-DoF controllers allow an intuitive and natural way of interaction. However, this long line of research has uncovered many unresolved problems. Creating a fast, comfortable as well as intuitive UI is not an easy feat.

Mine et al. [MYC14] and Takala et al. [TMH13] reported limitations while converting DMAs into immersive modelling applications. The access to the source code of DMAs is limited and even if the source code is available, many efforts have to be made in order to implement new features, since the UIs are specifically made for the mouse and keyboard. Our application is developed from scratch to ensure an unrestricted development of a spatial user interface. However, the creation of an entirely new modelling application has a disadvantage: our application can not compete with the wealth of tools that DMAs provide but our system is sufficient for investigating the most commonly used mesh modifications of professionals which were determined during foregoing expert interviews.

4.1. Interaction Design Principles

Many design principles have already been revealed by past research. In particular, Deisinger et al. [DBW*00], Mine et al. [MYC14] and Jackson and Keefe [JK16] revealed important design guidelines. The following guidelines extend these ideas or demonstrate design alternatives.

4.1.1. Minimise energy and maximise comfort

Modelling requires often long sessions of progressive refinements of a model. Ergonomic problems and fatigue over a certain time have been severe problems in past research as Jackson and Keefe [JK16] and Hughes et al. [HZS*13] have reported. Therefore, conserving energy and keeping a high level of comfort are major priorities. Mine et al. [MYC14] designed their system to be used in a seating posture and they use action-at-a-distance for object manipulation which offers a comfortable interaction. In addition to this, we recommend the following three advancements:

First, our application interface is designed to choose between a seated and a standing posture. The user should feel free to walk around, and to examine and edit objects in a room-scaled environment in order to exploit the full possibilities of VEs. Moreover, it was observed that the user was more comfortable changing the position after hours of modelling.

Second, our system supports the possibility of resting the arms on the armrests of a chair. It is a simple advancement, but has significant impact for long-term use.

Third, similar to Mine et al. [MYC14], the proposed application avoids holding the user's arms in a stretched position in front of their bodies for an extended period of time. We enhance this approach by utilising the interaction of the hand which is mainly carried out by the wrist. Lubos et al. [LBAS16] investigated the efficiency and comfort of using spatial user interfaces which are controlled by different arm joints. Lubos et al. revealed using the wrist joint for interaction (compared to elbow and shoulder joint) may lead towards spatial user interfaces which are efficient and suitable for productive long-term use.

4.1.2. Use constraints

The possibilities of a bi-manual 6-DoF controller interaction support intuitive movements and object translation but a high degree of freedom is not always necessary. In many cases of simple modifications, it is even counter-productive. Therefore, our system supports a reduction to coordinate axes for the main modifications methods such as translation, rotation and scale. Additionally, a snap functionality within incremental steps is available. Constraints are also used by DMAs as well as other immersive modelling applications such as Hughes et al. [HZS*13] and we assess it as a mandatory feature for fast and precise mesh modelling.

4.1.3. Consistent high precision modelling

Utilising constraints is a good way to achieve symmetry and specific shapes of models but precise modifications between constraints and snapping steps are also necessary to give users the freedom of performing very accurate modifications. Unfortunately, the usage of 6-DoF controllers come with a disadvantage: they are not as precise as a computer mouse and for specific cases it is difficult to reach an exact position in a VE. Accuracy is improved by the use of arm rests, but this solution is generally unsatisfying. Therefore, our system offers the possibility of zooming into a model so that modifications can be performed with 10 or even 100 times higher precision, depending on the level of zoom.

4.1.4. Support modifications with feedback

If precise modifications are required, accurate feedback in numbers is useful for the users to gauge their movements. Deisinger et al. [DBW*00] determined this issue during the evaluation of their modelling tools. Thus, the interaction with our system is supported by indicators next to the controllers which inform the users about the current progress in millimetres, degrees or percentage. We observed that users incorporate this information into their design process, even if they only create sketches.

4.1.5. Speed up interaction by proprioception

Modelling requires many changes between tools and the selection of different menu items. Using the users' knowledge about their body posture and body relative information is a powerful way to speed up the system control. Mine et al. [MYC14] recommend using proprioception for interaction. The system control of their application was specifically focused on touch interaction by controllers as smartphones which were controlled by the thumbs. We attempted the same interaction with the HTC Vive controllers but run into problems while creating a similar pie menu: the touch pad is smaller than the touch area of a common smartphone, and therefore we are restricted to a small number of menu items on the touch pad. We extended this approach by using a similar pie menu with a different modality. As mentioned above, Lubos et al. [LBAS16] suggested using the wrist joint for long-term and efficient use of spatial user interfaces. Based on Lubos' research, we have developed a pie menu with a pick-ray metaphor which appears in front of the user and requires only minor movements of the hand.

4.1.6. Speed up menu selection

We noted in past research as well as in recently released IM applications that item selection of menus is relative tedious. The process of selection usually consists of: a.) opening a menu by pressing and releasing a button; b.) selection of an item; c.) confirmation of selection by pressing and releasing a button again. We suggest the control method of Kurtenbach's Marking Menus [Kur93]: a.) opening a menu by pressing and holding a button; b.) selection of an item; c.) confirmation of selection by releasing the same button. This interaction in combination with proprioception was found as fast and more comfortable.

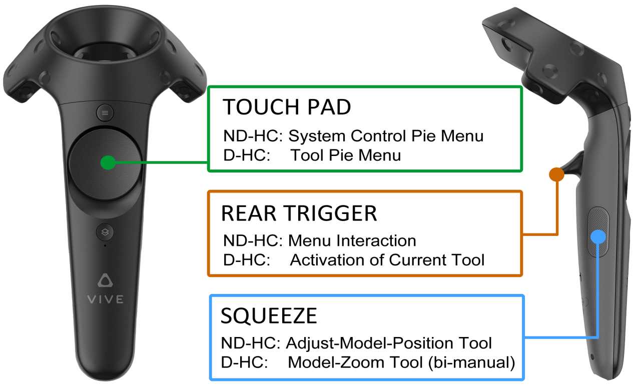

Figure 2: *The system is controlled by touch pads, rear trigger and squeeze buttons which have different functions for each controller.*

4.1.7. Use tactile feedback

Tactile feedback is a good way of informing the users about system states and system changes, since it is possible for the users to receive notifications without the need of visual cues. By nature, haptic or tactile feedback can be experienced in many operations in the real-physical world. Bringing this subconscious sense to VEs strengthens not only the quality of immersion but also speeds up many operations in the virtual world. We employ tactile feedback for menu interaction as well as for selection of vertices, edges and faces; it is also a good way to emphasize the latch for snapping to constraints.

4.2. Menu Interaction and System Control

The control of our application is based on a bi-handed interface with touch-enabled controllers. Both controllers have a rear trigger, a touch pad which also serves as a physical-pressable button, and squeeze buttons on the sides as shown in Figure 2. We created three menus with different interactions which exploit specific capabilities of the menus in specific tasks. The capabilities are either fast selection, comfort or large number of items.

Furthermore, we follow the Seven Fundamental Design Principles by Norman [Nor02, p.71]. Although Norman's research is focused on WIMP-Interfaces and was conducted three decades ago, Poor et al. [PJL*16] has confirmed that Norman's model is also applicable to immersive spatial menus for VEs nowadays.

THUMB-DRIVEN PIE MENU. As Figure 3A shows, our system uses thumb-driven pie menus which hover over the virtual controller model. A powerful feature of pie menus is that 'beginners became experts' regarding the menu interaction. After a short time, the users control the menus without visual attention. To retain this valuable feature, it contains only four items at a time since changing the number of items during run time would confuse the users and more buttons would decrease the accuracy of selection.

WRIST-DRIVEN PIE MENU. A good way to increase the number of available menu items for the thumb-driven pie menu are submenus with different modalities. Pressing the 'hammer symbol', shown in Figure 3A, invokes a pie menu in front of the users which

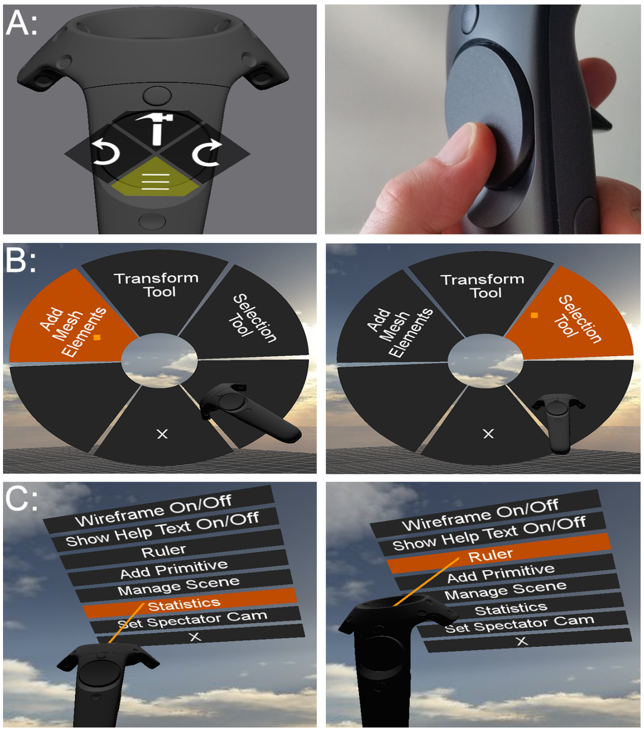

Figure 3: *A: The thumb-driven pie menu; B: The wrist-driven pie menu; C: The wrist-driven 2D widget menu*

can be controlled by a ray-casting selection, as shown in Figure 3B. The invisible ray is attached to the controller and a signifier is rendered on the intersection point as an orange quad onto the menu which helps the user to navigate. This menu has similar advantages to the aforementioned thumb-driven pie menu, but is slower because of the larger number of menu items. Anyway, it is a comfortable menu for long-term use as Lubos et al. [LBAS16] confirms for wrist-driven spatial interaction.

WRIST-DRIVEN 2D WIDGET MENU. Even though pie menus have many advantages, they limit the maximum number of items. The development of an additional menu was mandatory, as different tools require different context menus with a varying number of adjustable parameters. A 2D widget menu is capable of retaining many different parameters and is future-proof in terms of growing menu complexity due to further development of the system. Our 2D widget menu appears next to the controller and is also controlled by a ray-casting technique, shown in Figure 3C. The rotation of the menu is based on the *inverse view matrix* of the HMD, which ensures that the menu always faces to the user. The menu offers an interaction with a ray which is perpendicular to the menu's plane surface and follows the controller movements relative to the menu's surface along the X- and Y-axis.

4.3. Mesh Modelling and spatial UI Tools

Modelling is performed with different tools and interaction techniques. The selection of tools and techniques is managed by the wrist-driven pie menu while frequent parameter adjustments and sub-tool selection is performed by the thumb-driven pie menu. The wrist-driven 2D widget menu contains less frequently used parameters and miscellaneous tools.

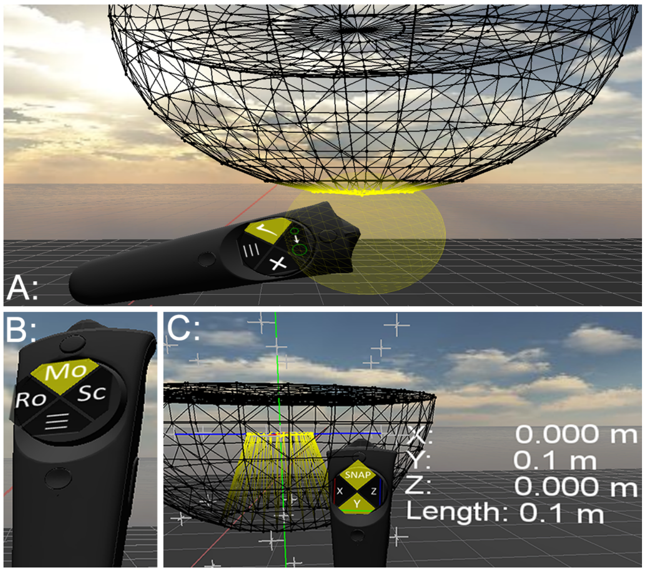

Figure 4: *A: Selection Tool with yellow selection sphere allows spatial selection. Vertices inside the sphere are selected. B: The thumb-driven pie menu allows the selection of a Ro(tate), Mo(ve), Sc(ale) tool. C: As soon as one of these tools are activated (rear trigger), the menu changes and gives access to constraints*

4.3.1. Selection Tool

As a first step for modelling, the user has to select a mesh area of interest which consists of a group of vertices, edges or faces. Therefore, a spatial interaction with a sphere or a cube as a selector can be performed with our system. The selector is attached to the top of the controller and can be activated by pressing the rear trigger of the D-HC, as shown in Figure 4A. The size of the selector is adjustable via a press-and-hold action of the upper button of the selection tool's pie menu and concurrently by changing the distance between both controllers. The cross button and tick button, shown in Figure 4A, switch between the deselection and selection mode.

4.3.2. Transform Tool and Constraints

Once a mesh area is selected, modifications can be applied by the transform tool. It consists of three sub tools: the move tool, the rotate tool and the scale tool. The tools can be selected by the thumb-driven pie menu on the D-HC, shown in Figure 4B. Once the rear trigger of the D-HC is pressed, the selected mesh area follows the movements of the controller as an action-at-a-distance interaction.

The move tool reduces the degrees of freedom to only positional changes of the controller and the rotate tool records only rotation. The move and rotate tool are driven by a single-handed interaction while the scale tool requires a bi-manual interaction. Changing the distance between the controllers changes the size of the selected mesh area. As mentioned before, constraints are mandatory for fast and precise modelling. To maintain speed during the modelling process, it is important to activate the constraints in a direct manner. Therefore, as soon as the rear trigger is pressed, the thumb-driven pie menu changes its content and gives access to the constraints menu, as shown in Figure 4C. The menu allows activation of a 3D grid for translation (rendered in Figure 4C as grey crosses) and incremental steps for rotation as well as for scale. Additionally, it allows further reduction of degrees of freedom to one coordinate axis which is also shown in Figure 4C depicted as vertical green line.

4.3.3. Adjust-Model-Position tool and Model-Zoom Tool

When using a DMA, frequent adjustments of the virtual camera position and the field of view is required. Adjusting the camera position changes the user's focus to different mesh areas of interest. Changing the field of view helps with examining modifications in detail (zoom in) or assessing modifications in context of the whole object (zoom out). Consequently, we have transferred these operations into our system. By pressing the squeeze buttons of the ND-HC, the Adjust-Model-Position tool is activated and the entire object is grabbed and can be moved for adjusting the focus to a specific point of interest on the model. Substituting the change of the field of view of a DMA's camera is accomplished by scaling (zooming) the entire model. We give scaling-of-the-model preference over scaling-the-entire-scene because we observed that it causes cybersickness for some users. The Model-Zoom tool can be activated by pressing the squeeze buttons on both controllers concurrently and is driven by the distance between the controllers.

An important issue regarding to the Model-Zoom tool must be considered: The origin of scale of the model is crucial. Using the barycentre of the model lead to scaling out the model of the users' field of view, as depicted as method A in Figure 5. A design alternative is to use the midpoint between both controllers for the origin of scale. But if the model is not located between the user's hands, the model will move away from the user, as depicted as method B in Figure 5. Our final solution uses the barycentre of the current selected mesh area. The selection usually represents the area of interest of the users and helps to preserve the point of interest within the users' field of view, as depicted as method C in Figure 5.

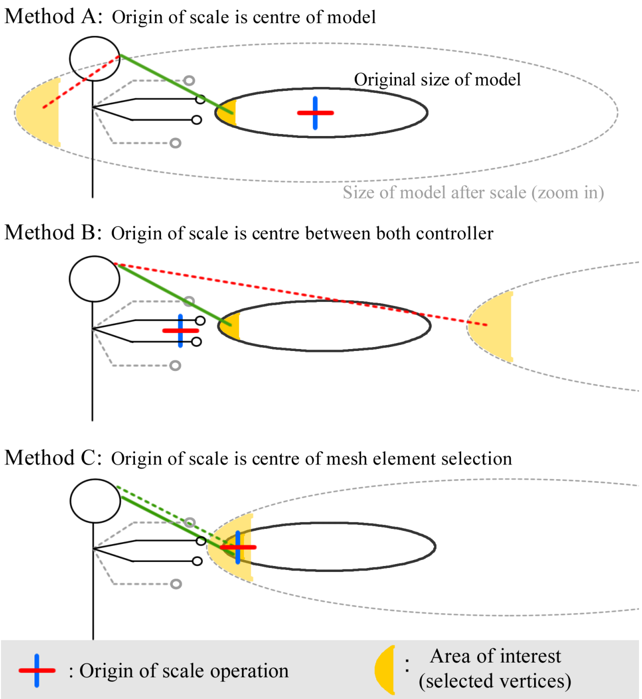

Figure 5: *Preserving the area of interest in user's field of view and interaction range: The area of interest moves outside of the user's focus, if the origin of the scale operation is wrongly positioned, as shown in Method A and B. Method C places the origin of scale into the centre of the selected mesh area and therefore preserves the area of interest in the user's interaction range*

4.3.4. Miscellaneous Tools

Some tools and mesh operation do not need positional input from the controllers and are called and executed once. These operations are: extrude, delete, duplicate and deselect-or-select-all. Extrude, delete and duplicate performs that which their names suggest on a selected mesh area. The deselect-or-select-all tool assists the selection tool which changes the selection of the mesh depending on the current state of selection. There are two states: First state: If at least one mesh element or more is selected, it will deselect all elements and remains the mesh in an entirely deselected state. This can be used for resetting the selection and starts a new selection with the selection tool. Second state: if no elements are selected, it will select all elements. This is useful in cases when some operations should be applied to the entire mesh, such as a creation of a copy or a deletion of all mesh elements.

Additionally, we created a 3D-free-form surface tool. It allows the users to add isolated vertices to the scene which can be connected to triangles in a subsequent step. The triangles can be created side by side which eventually represent a surface.

5. Case Study

We are interested in obtaining feedback on how the individual features would be used by professionals with a significant background in 3D modelling.

PARTICIPANTS. We invited ten experts who each have at least one year of professional full time experience with a DMA. All participants were male and have never made any experience with our, nor other IM applications before. Further information about the participants is listed in Table 1.

PRE-QUESTIONNAIRE. A preceding questionnaire enquires about age, years of experience with a DMA, favourite DMA, how many times the HTC Vive were used and if any restrictions in regards to Stereopsis are known.

TASK, TRAINING, PROCEDURE. The participants were asked to model a sailboat. The task was to create at least a hull, a railing, a mast with a boom and a sail. Each participant was shown 20 short instruction videos with a total play time of 13 minutes. The videos

ID	Age	Stereoblind?	Favorite DMA	Years of experience with DMA	Experience with Vive	Modelling duration	Comfort? [1-6]	Felt dizzy?	Would use it every day? [1-6]	Is learning modelling with IM easier? [1-6]
1.	21	Yes	Maya	>1	> 100 times used	32min	4	No	4	1
2.	26	No	SketchUp	>1	1 time used	39min	1	No	1	1
3.	24	No	Blender	>1	< 50 times used	19min	1	No	1	1
4.	23	No	Maya	>1	< 10 times used	26min	2	No	2	1
5.	26	No	3ds Max	>5	> 100 times used	32min	2	No	2	2
6.	27	No	Maya	>1	< 50 times used	25min	3	No	3	1
7.	22	No	Maya	>5	> 100 times used	28min	1	No	1	1
8.	26	Yes	Maya	>5	< 50 times used	21min	3	No	3	1
9.	26	No	Maya	>5	> 100 times used	15min	1	No	1	2
10.	27	No	Blender	>10	> 100 times used	11min	1	No	1	1

Table 1: *Information about participants and results of user study*

were shown to the users on a virtual video wall while being immersed in the application, allowing them to continue experimenting while watching. The users as well as the test conductor could pause and resume the video playback. The difficulty level of the videos rises over time and the participants were supposed to speak about their intents. There was no time limit for the task and it was important that the participants become familiar with the system in order to experience and assess as many features and issues as possible. The model task requires extensive use of constraints to axes and the users have to use the snapping functionality at least three times in order to reach specific points which were randomly given by the test conductor. This was done to cover and investigate different cases for precise modifications.

POST-INTERVIEW-QUESTIONNAIRE. After completing the modelling task, the participants were asked to rate the capabilities of the system and we asked to state advantages and disadvantages with direct comparison to DMAs in order to reveal satisfied requirements and unfulfilled needs. We used a 6-point Likert scale which omits a neutral point to force at least a tendency. The questions were verbally asked and the answers were written down by the test conductor. This ensures that the participants answer freely without any bias and discuss their thoughts with the test conductor.

5.1. Results

Every participant completed both the tutorial and the sailboat and some participants even enhanced their boats with additional parts which can be seen in Figure 6. The required modelling time varied between 11 minutes and 39 minutes. Modelling additional parts, which extended upon the original task, were not measured. The participants were asked in the post-questionnaire to rate the overall comfort of the application. A Likert scale with 1 to 6 was given, with 1 as *very comfortable* and 6 as *not comfortable at all*. The average rating is 1.88. Furthermore, no one stated that they felt dizzy at any time during the experiment.

The participants were asked to rate if they would use the application every day for several hours. A Likert scale with 1 to 6 was given, with 1 as *yes, no problem* and 6 as *I absolutely don't want to*. The average rating is 1.94.

Eight out of ten participants attest that the system would be easier for learning 3D modelling compared to learning modelling with a DMA. The remaining two participants said that the system could be easier to learn modelling if the hardware problems were fixed such as the resolution and weight of the HMD.

Overall, the participants were astonished by the new possibilities of IM and were excited about further developments and some of the participants were even interested in a version of our system for their private use.

The following list of subjective advantages and disadvantage is the summary of all of the individually compiled answers. Many answers were similar to each other and have been combined into short statements for the sake of a compact overview. The italic phrases are the condensed statements and the number in brackets indicates the frequency of how often it was mentioned:

ADVANTAGES.

- A major advantage was the *better spatial perception and better sense for proportions* (10) of the model and distances in the scene. Minor changes can be assessed much easier.
- It was mentioned that there was a *stronger focus on the model* (7) since no distraction from the real environment was experienced. The participants felt that they were part of the virtual world and that they were closer to the model.
- *More intuitive interaction* (6) was mentioned because of the direct mapping of 3D-to-3D instead of 2D-to-3D interaction.
- *Faster navigation of the view* (5) was mentioned. Additionally, it was assumed that the general modelling speed is increased because modelling with the hands and adaptation of the view can be performed at the same time. DMAs allow only one process at a time: changing the view or changing the model.
- After an initial adaptation period to the user interface, it was mentioned a *blossoming of creativity* (3) took place for different design ideas. It appears that the improved spatial perception stimulates the users' creativity.

DISADVANTAGES.

- A major disadvantage was that there was *less precision compared to DMAs* (7).
- It was stated that the selection tool has benefits, especially in cluttered scenes with many polygons, but head tracking, stereo rendering and 6-DoF input devices are better suited for managing cluttered scenes than image-based selection techniques. Though overall, in most cases our selection tool is inferior to advanced selection tools of DMAs such as the *Edge-Loop-Selection tool* or *Grow-Selection tool* which were often used by professionals. In conclusion, *DMA's selection tools are faster* (6).
- It was mentioned that the *lack of keyboard and keyboard shortcuts interfered with the experience* (5) and would slow down the creation process, since the participants could not access the desired tools as fast as they are used to.

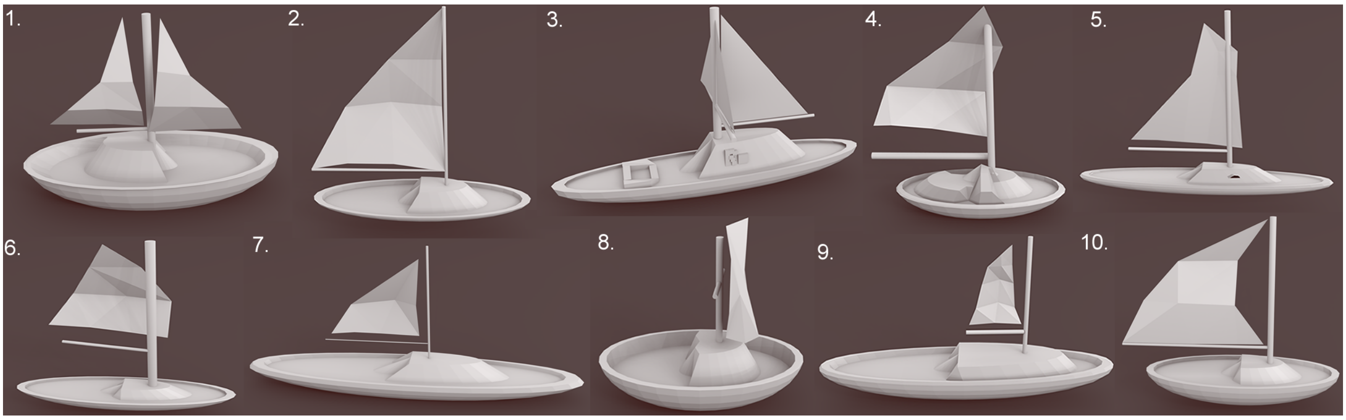

Figure 6: *Sailboats modelled during the user test. Models are rendered by Blender Render*

- Especially the *missing possibility of direct number input* (5) for metrics was criticized.
- One participant experienced *higher physical strain* (1) but it was not mentioned as exhausting.

ADDITIONAL EVALUATION OF MODELLING SPEED. After completing the modelling task, we asked three participants to create the same sailboat in their favourite DMA as quickly as possible. In order to compare the results, one of the authors, an experienced user of our system, modelled the sailboat as quickly as possible in the proposed application. The modelling of the sailboat began with the identical sphere which was adapted step by step into the final model.

The outcome shows that neither the hull, cabin nor the mast vary in their visual appearance. Also, the topological connection of the meshes are identical. Only the sail differs since the techniques for creating the sail are fundamentally different. The participants, who used DMAs, applied tools such as *Proportional Editing* of Blender or *Soft Selection* of Maya which convert a mesh into a kind of deformable clay. Our system offers the 3D-free-form surface tool which creates a scaffold of vertices which is extended by triangles. Table 2 lists the required times for every individual modelling task:

Person	Time	Compared to proposed app.
Proposed app.	3:40	100%
Blender A	3:54	106%
Blender B	3:22	92%
Maya	4:20	118%

Table 2: *Comparison of required time for a quickly-as-possible modelling task of the sailboat for a DMA and the proposed system.*

5.2. Discussion

Some of the advantages and limitations above are already known from past research, however, the study reveals surprising facts and important insights regarding immersive modelling. Although our system was geared towards precision, seven out of ten participants mentioned a decrease in accuracy compared to DMAs. One reason could be the relatively rarely used Model-Zoom tool. If zooming is required while using a DMA, the goal of *getting closer for detail* is associated with using the mouse wheel. But the goal in a VE with *getting closer for detail* is to get closer with the head to the model rather than scaling the model larger which causes imprecise modifications. Another reason could be the unfamiliar interaction with a computer while using a 6-DoF controller and the impracticality of moving it with the precision of a mouse in a millimetre range. Another additional reason could be the lack of numerical input, since the snap-constraints were assessed as useful but it was also mentioned that it could not fully substitute a physical keypad since the steps must be adjustable to any number rather than to fixed step sizes.

Furthermore, the participants are used to their accustomed interfaces. The physical keyboard is a versatile and well-known device. The use of keyboard shortcuts is a powerful and time-efficient interaction scheme. The majority of people today are familiar with the layout of a keyboard which contains usually more than 100 keys (or commands) and can even be expanded in functionality by key combinations. Another problem is that users are accustomed to 2D GUIs. Regarding to Norman's model [Nor02, p.38], the *Gulf of Execution* is significant for new (VR) UIs, since WIMP UIs are commonly well known and VR UIs are not. In addition, at this point the proposed application supports only basic modelling functions. More functions are possible with more menu elements and therefore higher menu complexity. To avoid slowing down the modelling speed and overwhelming the user it is necessary to investigate new interaction methods for selecting many menu elements and tools for IM.

6. Conclusions and Future Work

This work has presented the realisation, development and evaluation of a novel polygonal 3D immersive modelling interface which focuses on precise and fast mesh modification and comfortable interaction. We have analysed problems of past research and have developed further advancements to existing design principles and user interfaces for immersive modelling. The proposed system is capable of creating models such those as shown in Figure 7.

We have shown that precision is still an ongoing topic for IM and that it still has to be investigated further. We compared the required modelling time for the same model in our system against DMAs and found similar results in regards to the required time as well as quality of the models. Our case study reveals no severe issues regarding to comfort and the application was assessed as ergonomic.

Though we have yet to satisfy all requirements of professional users, we observed that many of our approaches and features were well adopted. We believe that our system is a solid basis for further research. Our focus in the future will be on the integration of numerical input, tools for higher precision and more advanced modelling tools which will be supported by different modalities such as gestures and speech.

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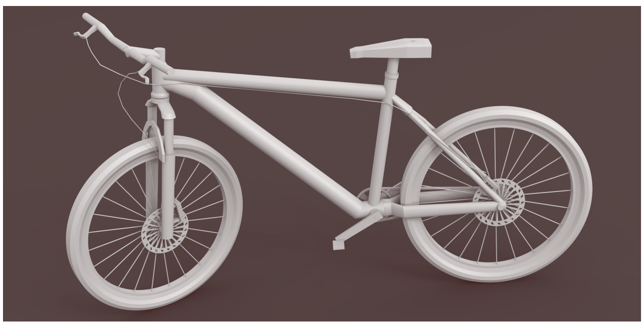

Figure 7: *Model created with the proposed system*

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