Thesis Title

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Abstract

This thesis addresses the development of a novel sample thesis. We analyze the requirements of a general template, as it can be used with the LaTeX text processing system. (And so on...) The abstract should not exceed half a page in size!

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Introduction

Digital 3D shape modelling is a field that has received a lot of attention over the past years as a result of increasing rendering possibilities and a growing demand for 3-dimensional digital content. The recent surge in interest for VR (Virtual Reality) has driven the development of better GPUs (Graphics Processing Unit) even more, while also further increasing the demand for digital 3D content. The process of 3D shape modelling has so far been almost exclusively suitable for trained professionals or users with a lot of experience. While 3D modelling software generally comes with an abundance of options and possibilities it also usually has a steep learning curve. This causes 3D modelling to become inaccessible to novice users who would like to create (simple) 3D models, but who do not have the time to learn how to use these programs.

Sketch-based 3D modelling seeks to simplify the process of 3D modelling in order to make it more accessible for this user group. Its goal is to provide the user with intuitive ways to interact with and edit the mesh that is being modelled. Previous work regarding sketch-based modelling tools has produced multiple software products which present the user with this intuitive method of 3D modelling. However, these have only been made available for use with a PC and mouse and not for usage in VR.

Recently a variety of art creation tools for usage in VR have been created. These applications range from painting in 3D to voxel modelling and 3D sculpting. VR gives artists the possibility to look at what they're creating from a literally new perspective. Directly modelling in 3D can give an improved perception of the proportions of different parts of a model and the orientations between them.

The goal of this thesis is to develop a sketch-based 3D modelling program explicitly created for usage in a VR setting. This combines the simplicity and intuitiveness of sketch-based designing with the immersiveness of modelling in actual 3D space and the possibility of viewing the

results immediately in 3D. The software is targeted to users that are new to 3D modelling and should therefore be straightforward to use and easy and quick to learn.

Chapter 2 will discuss previous work that is done in the fields of sketch-based 3D modelling and give several examples of software for 3D modelling in virtual reality.

In Chapter 3, we will give a detailed description of the VR sketch-based 3D modelling program that was developed as part of this thesis. It describes the algorithms that were used and gives a description of the user interface including the rationale behind the design decisions that were made.

Next, in Chapter 4 we let target users test our software and summarize the feedback that they have given. We also compare the VR sketch-based 3D modelling tool with a version of the software that is developed for non-VR use with a computer and mouse.

Finally, Chapter 5 provides ideas for future improvements on the software and summarizes the findings of this thesis.

2

Related Work

A lot of software for the purpose of 3D modelling exists, with some of the best known ones being Maya [**?**], Blender [**?**], Autodesk 3ds Max [**?**] and Zbrush [**?**]. Typically these software let their users manipulate meshes on vertex, edge or face level, resulting in very fine-grained control over the appearance of created models. Although this makes these programs very powerful and versatile for the creation and editing 3D models, they come with a very steep learning curve and are overcomplete for recreational users. This chapter will instead focus on describing some of the more intuitive and easy-to-use sketch-based 3D modelling software, as well as a couple of relatively new software for creating 3D content in VR.

2.1 Sketch-based Modelling

Sketch-based modelling is a modelling technique that aims to transfer the way that people draw shapes with pen and paper to a method of modelling 3D shapes on the PC with a mouse. With the mouse the user draws strokes on the screen, whose interior is subsequently meshed and then inflated to smooth rotund 3D meshes. Typically the user can then edit this initial mesh by specifying additional strokes that for example create extrusions or cut the mesh. The software that was written as part of this thesis also adopts the sketch-based modelling paradigm.

2.1.1 FiberMesh

FiberMesh is a system that allows modelling freeform surfaces by drawing 3D curves [**?**]. The user-defined curves are used to create a 3D model and stay present on the model and can be used to edit the geometry. This allows for a very intuitive method of deforming and editing meshes

after their initial creation. FiberMesh lets users define curves as smooth or sharp, add and remove control curves on the mesh and pull curves to deform the mesh. Additionally it allows the user to change the mesh topology by cutting parts of the mesh and creating extrusions or tunnels.

Algorithmically FiberMesh depends on two main steps, namely curve deformation and surface optimization. In addition to these two steps, there are also a mesh construction and remeshing step, which only occur after new mesh topology has been created (e.g. after creation, cut or extrusion).

For curve deformation they used a detail-preserving deformation method that combines differential coordinates [**?**] with co-rotational methods [**?**]. A sequence of linear least-squares problems is solved, while satisfying the user-defined positional constraints on the drawn curves. The rotation matrices are explicitly represented as free variables, as they cannot be derived from the curves which are nearly collinear. In order to accommodate for large linear rotations, the gross rotation is computed by iteratively concatenating small delta rotations that are each obtained by solving a linear system. The linear system that is solved in each step can be seen in equation 2.1.

$$\arg\min_{\mathbf{v},\mathbf{r}} \left\{ \sum_i \left\| \mathbf{L}\left(\mathbf{v}_i\right) - \mathbf{r}_i \mathbf{R}_i \delta_i \right\|^2 + \sum_{i \in C_1} \left\| \mathbf{v}_i - \mathbf{v}_i^{'} \right\|^2 + \sum_{i,j \in E} \left\| \mathbf{r}_i \mathbf{R}_i - \mathbf{r}_j \mathbf{R}_j \right\|_F^2 + \sum_{i \in C_2} \left\| \mathbf{r}_i \mathbf{R}_i - \mathbf{R}_i^{'} \right\|_F^2 \right\} \tag{2.1}$$

Here $\mathbf{L}(\cdot)$ is the differential operator, $\mathbf{v}_i$ is the coordinates of vertex i, $\| \cdot \|_F$ is the Frobenius norm, E is the set of curve edges and C_1 and C_2 are the sets of constrained vertices, primed values are constraints, $\mathbf{R}_i$ represents the gross rotation (in the deformed curve) corresponding to vertex i obtained from the previous iteration, and finally $\mathbf{r}_i$ is a linearized incremental rotation for vertex i given by a skew symmetric matrix with 3 unknowns

$$\mathbf{r}_i = \begin{bmatrix} 1 & -r_{iz} & r_{iy} \\ r_{iz} & 1 & -r_{ix} \\ -r_{iy} & r_{ix} & 1 \end{bmatrix}.$$

Rotations are updated by setting them to $\mathbf{R}_i = \mathbf{r}_i \mathbf{R}_i$ and orthonormalizing the result using polar decomposition [**?**]. In the iterative process of estimating rotations, they use first order differentials (L_0), and for computing the final vertex positions using this estimated rotations they use the second order differential (L_1).

$$L_0 = \mathbf{v}_i - \mathbf{v}_{i-1}, \quad L_1 = \mathbf{v}_i - \frac{1}{|N_i|} \sum_{j \in N_i} \mathbf{v}_j.$$

For surface optimization, FiberMesh solves 3 sparse linear systems in order to compute a smooth mesh surface that adheres to the user-defined constraint curves. The first system solves for a set of smoothly varying Laplacian magnitudes $\{c_i\}$ which approximate the scalar mean curvature values. The least-squares minimization that it solves is as follows:

$$\arg\min_{c}\left\{\sum_{i}\left\|\mathbf{L}\left(c_i\right)\right\|^2+\sum_{i}\left\|c_i-c_i^{'}\right\|^2\right\} \tag{2.2}$$

Where $\mathbf{L}(\cdot)$ denotes the discrete graph Laplacian, which is independent of the exact mesh geometry, allowing us to reuse it in multiple iterations. In the first iteration, the target Laplacian magnitudes are only set for the constrained curves by using the scalar mean curvature along the curve.

To obtain a geometry that satisfies these target Laplacian magnitudes, Nealen et al. use the uniform Laplacian as an estimator of the integrated mean curvature normal, which is computed by $\delta_i = A_i \cdot c_i \cdot \mathbf{n}_i$, where A_i is an area estimate for vertex i, c_i is the target Laplacian magnitude and $\mathbf{n}_i$ is the estimated normal from the current face normals. However the uniform Laplacian is not a accurate estimator of the integrated mean curvature normal when the incident edges to a vertex are not of equal length. To solve for this problem without using a geometry dependent discretization and thus avoiding recomputing the matrix for every iteration, they prescribe target edge vectors in an attempt to achieve equal edge length. This is done by solving the following linear system (which uses the same matrix as the system that solves for target Laplacian magnitudes) to obtain a smooth set of target average edge lengths e_i:

$$\arg\min_{e}\left\{\sum_{i}\left\|\mathbf{L}\left(e_i\right)\right\|^2+\sum_{i}\left\|e_i-e_i^{'}\right\|^2\right\} \tag{2.3}$$

Again the first iteration is performed with only the edge lengths along the constrained curve. The target average edge lengths are then used to compute target edge vectors for a subset B of mesh edges (in the first iteration this subset only contains edges along the constrained curves, and afterwards it contains all edges incident to the constrained curves) as follows:

$$\eta_{ij} = \left(e_i + e_j\right)/2 \cdot \left(\mathbf{v}_i - \mathbf{v}_j\right) / \left\|\mathbf{v}_i - \mathbf{v}_j\right\|. \tag{2.4}$$

These target edge vectors are then used to solve a linear system that gives the updated vertex positions as follows:

$$\arg\min_{\mathbf{v}}\left\{\sum_{i}\left\|\mathbf{L}\left(\mathbf{v}_i\right)-\delta_i\right\|^2+\sum_{i\in C}\left\|\mathbf{v}_i-\mathbf{v}_i^{'}\right\|^2+\sum_{(i,j)\in B}\left\|\mathbf{v}_i-\mathbf{v}_j-\eta_{ij}\right\|^2\right\} \tag{2.5}$$

The systems for solving for target Laplacian magnitudes, average edge lengths and optimal vertex positions are solved iteratively until convergence (approximately 5-10 iterations). Since only a geometry independent discretization of the Laplacian is used, the system matrix can be reused between iterations, until the mesh topology is changed (for example by a cutting action). Because of this, the slow matrix factorization only needs to happen once for a given mesh topology, resulting in a fast algorithm that allows for interactive rates.

2.2 3D Modelling in Virtual Reality

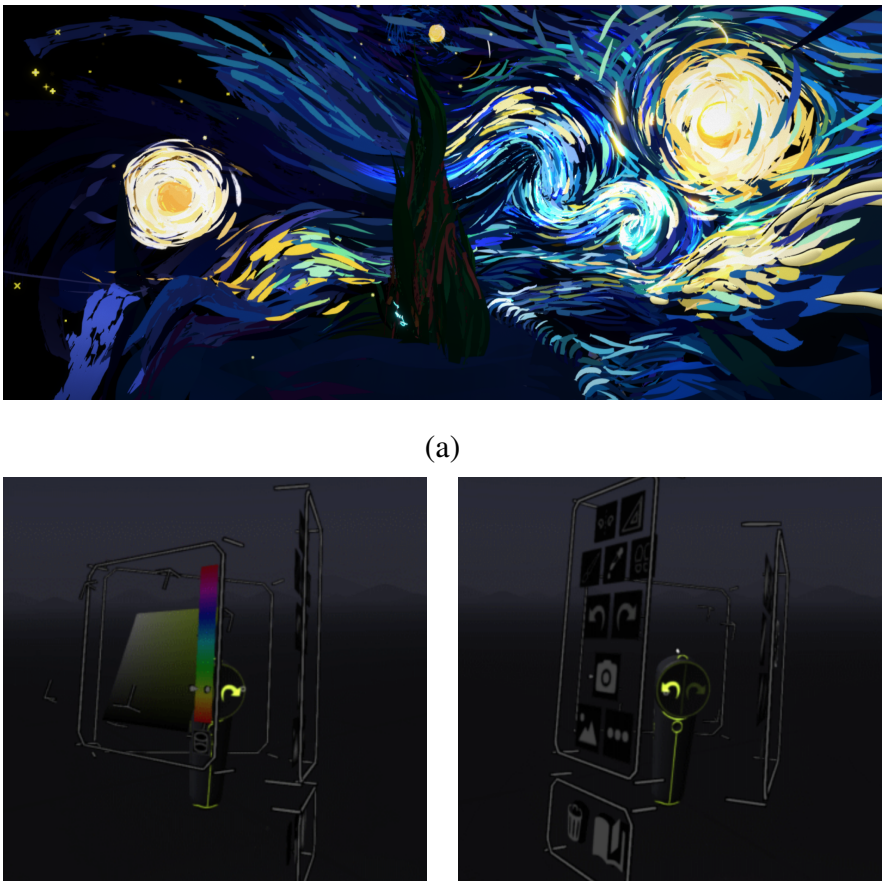
Over the last couple of years, plenty of VR applications have been published that involve creating some type of digital 3D content. The software can roughly be split into 2 categories, namely for creating 3D paintings and for creating 3D models (assembled from a structure of vertices, edges and faces). Whereas the former category focusses on the artistic side of 3D content and usually does not result in work that can be exported to some standard format, the latter category more aims to provide a tool for producing 3D models that can be exported and then used in some other VR or 3D application. This section will described a variety of these 3D virtual reality applications, their interfaces and what kind of content users can make with them.

2.2.1 Google Tilt Brush

Google's Tilt Brush is available for the Oculus Rift and HTC Vive and allows the user to create room-scale art in the style of 3D paintings. The software provides different types of tools and brushes, including special effects tools like a fire or stars brush. Users cannot export their creations to typical model formats such as .obj or .off, but they can turn them into a GIF or upload them to Google Poly where other users can explore and enjoy their work. Figure 2.1 (a) shows a screenshot of example 3D artwork that has been made with Google Tilt Brush (the original work has stars that change their light intensity and seem to twinkle). In order to give the user easy access to the large set of different painting tools, Tilt Brush has created an embedded menu in the form of a painters palette that is attached to the controller in the user's non-dominant hand. Several of the menus allow for browsing through further submenus. The dominant hand is used to select a tool from the menu and paint with it. Figures 2.1 (b) and 2.1 (c) show two examples of what the hand-held palette menus looks like and you can see that the user can twist his hand in order to view more menu options on the backside of the palette.

2.2.2 Oculus Medium

Oculus Medium is a 3D sculpting tool that is only available for the Oculus Rift. Conceptually the user can paint with volumetric brushes, much like sculpting with clay. For instance the user will draw a simple circle and this will result in a donut shape. With several tools the user can sculpt away or add extra clay, as well as assigning multiple colors to the surface. Unlike Google Tilt Brush, Oculus Medium does allow the user to store created models in .obj format, so they can be exported for use in other programs. The interface is quite intuitive since it shows a very strong connection to the method of creating 3D shapes with the use of clay in real life which most users have experience with. Users can quickly create rough shapes and refine them by adapting the brush size and adding small-scale details. The dominant hand of the user serves as the so-called "Tool hand" which can be used to sculpt with, while the non-dominant hand serves as the "Support hand" which can be used to open up several hand-held menus. Figures 2.2 (a) and 2.2 (b) show examples of complicated 3D models that have been made in Oculus Medium. One of the unique features of Oculus Medium is the functionality to create and use stamps, which helps easily create interesting textures on the models like the fur and grass in Figure 2.2 (a).



(a)

(b) (c)

Figure 2.1: *Google Tilt Brush.* (a) *Recreation of Van Gogh's Starry Night (moving version available at https://poly.google.com/view/e-Zqenw7Dui).* (b) *Left-side view of the "hand-held" user interface of Google Tilt Brush.* (c) *Right-side view of the "hand-held" user interface of Google Tilt Brush.*

2.2.3 MasterpieceVR

MasterpieceVR brings a combination of the design paradigms used by Oculus Medium and Google Tilt Brush, letting the user mix volume sculpting with 3D painting. It is available for Oculus Rift, HTC Vive and Windows Mixed Reality, and for each of them it requires the accompanying controllers for input. One of MasterpieceVR's biggest selling points is that it allows multiple users to work on one model simultaneously, allowing interactive collaboration with direct feedback between artists. Like Oculus Medium, MasterpieceVR lets the user export models (including vertex colors) to .obj, as well as .fbx format. Additionally, users can load reference images or models into the program, which can greatly simplify modelling. MasterpieceVR implements menus in a similar fashion to Google Tilt Brush and Oculus Medium, with a menu of icons held in the user's non-dominant hand. Compared to these two, MasterpieceVR however has a larger and less intuitive menu layout. Figure 2.3 (a) shows a complex model created in MasterpieceVR and Figure 2.3 (b) shows the menu interface.

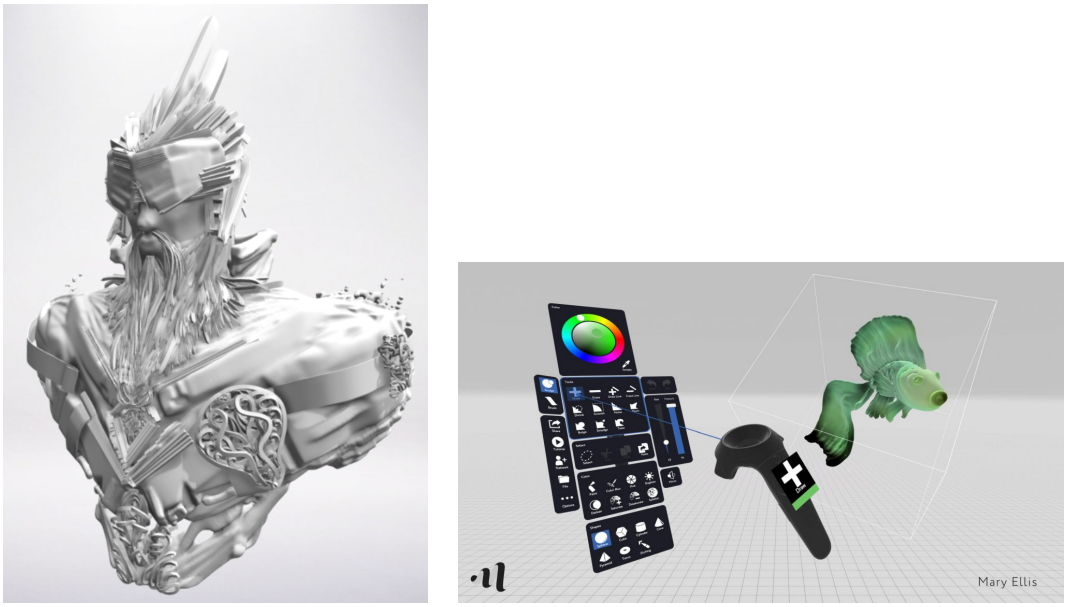
(a) (b)

(c) (d)

Figure 2.2: *Oculus Medium.* (a) *Model of a furry monster created in Oculus Medium by artist Goro Fujita.* (b) *Model of an African figure created in Oculus Medium by artist Goro Fujita.* (c) *Sculpting view in Oculus Medium.* (d) *Menu view in Oculus Medium.*

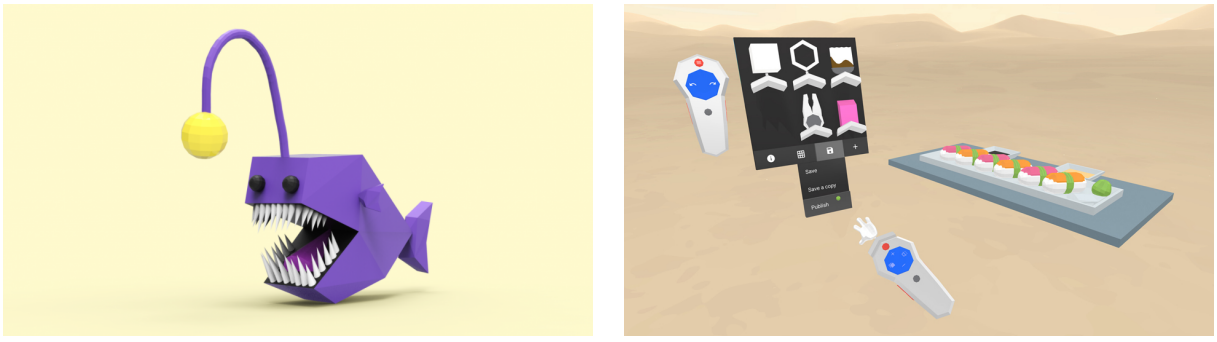
2.2.4 Google Blocks

Google Blocks is available for Oculus and HTC Vive and is Google's software for creating 3D objects in VR. From the programs mentioned in this section, Google Blocks seems the most similar to professional non-VR based modelling software like Blender [**?**] or Maya [**?**]. Users can start with several predefined shapes like spheres, cubes or cones and can edit the models on face, edge or vertex level. While this gives the user a lot of artistic freedom and extra modelling possibilities, it also makes its usage a lot less intuitive than the other VR 3D modelling software that is available. Although the user has low-level control, the created meshes are very low-poly compared to the models created with for example Oculus Medium. The user does not have control over the number of polygons, which results in less realistic and smooth models. Again the created models can be exported as .obj file. Figures 2.4 (a) and 2.4 (b) show a simple model of an anglerfish created in Google Blocks, and the simple Google Blocks interface.



(a) (b)

Figure 2.3: *MasterpieceVR.* (a) *Model of a warrior created in MasterpieceVR by artist Vladimir Ilic.* (b) *Interface of MasterpieceVR (model by Mary Ellis).*



(a) (b)

Figure 2.4: *Google Blocks.* (a) *Model of an anglerfish created in Google Blocks.* (b) *Interface of Google Blocks.*

3

System Description

This chapter will give a description of the VR sketch-based modelling software that was developed as part of this thesis and we have aptly named SketchMeshVR. The software aims to provide users with a simple and intuitive sketch-based 3D modelling tool within a VR environment. Specifically the software is developed for use with the Oculus Rift including one Touch controller and targets users that are new to 3D modelling. Compared to the VR modelling software that was discussed in Section 2.2 our system provides a novel method for creating 3D models. Whereas the existing modelling tools utilize volumetric brushes or predefined 3D shapes, our tool lets the user define the outline of a 3D shape and then fills in the inside of this silhouette.

3.1 Algorithms

Algorithmically, SketchMeshVR largely follows the FiberMesh software that was described in 2.1.1. Similar to FiberMesh, users can draw strokes that define the 3D mesh surface, and these drawn strokes stay on the model surface to later function as deformation handles. Users can create an initial mesh, cut parts of the mesh away, create extrusions, add and remove additional control curves and deform control curves on the mesh. Unlike in FiberMesh, SketchMeshVR does not give users the option to choose between smooth and sharp constraint curves and instead all curves are treated as smooth. The functionality to create tunnels through meshes is also not supported in SketchMeshVR.

SketchMeshVR is built inside the framework of libigl [**?**] and uses Oculus C++ SDK in order to render everything to the Oculus Rift. The standard overlay menu that is included in libigl is disabled since the concept of overlays does not port well to the VR setting. Overlays are displayed too close to the eye making it very difficult for the eye to focus on them, which

results in a highly unpleasant user experience.

The system is multithreaded such that the VR display keeps on being updated while the mesh computations are being executed. When multithreading is not enabled the screen will freeze during the mesh computations, and therefore will stop updating when the user moves his head, breaking immersion and likely inducing motion sickness.

Due to the direct availability of the actual 3D coordinates, some changes were made in comparison to SketchMeshVR's non-VR counterpart FiberMesh. These implementation differences will be discussed below.

3.1.1 Drawing

The process of drawing the initial mesh curve stays mostly unchanged when converting to virtual reality. However, whereas the non-VR version in drawing mode starts by converting mouse positions to screen coordinates and then unprojects these to 3D coordinates with a z-value of 0, SketchMeshVR takes the actual 3D coordinates and only projects them to 2D to allow triangulation. The z-coordinates of the originally drawn stroke points is however still lost after the triangulation and for each of the vertices that belong to the constraint curve is set to their mean z-value, resulting in the initial curve to lie in the XY-plane.

3.1.2 Adding and removing control curves

In the non-VR case, adding control curves on the mesh and later removing them is done by unprojecting the screen coordinates onto the mesh in order to get 3D positions and decide where the user wanted to add/remove a curve. In VR, instead of unprojecting the screen coordinates of the hand or taking the direct hand coordinates, we cast a ray from the hand position in the direction that the controller is being held. This intersection between this ray and the mesh is then used as the final 3D position for adding/removal.

3.1.3 Cutting

When cutting in the non-VR program, the drawn stroke is interpreted purely in 2D screen coordinates. In order to create a loop on the front and back of the mesh surface, the algorithm checks which edges are crossed (in 2D) by a line segment between two consecutive stroke points. Since the same 2D points are used for creating a surface path on the backside of the mesh, this results in perpendicular cuts (meaning that the "cutting knife" always goes perpendicular through the screen, and never at an angle). On the other hand, when cutting in VR we take the coordinates of both the first (front side) and second (back side) intersection between the cutting ray and the mesh. By doing this, we enable the possibility for the user to cut the mesh diagonally. In order to check which edges are crossed by the stroke segments, we check for intersections between edges and the plane that is formed by the two points that make up the stroke segment and the position of the hand at the time of drawing that stroke segment. If an edge is intersected within its range, we know that the stroke segment crosses that edge.

One problem that arises due to the fact that we are using 3D intersection points between the cutting ray and the mesh, is that we cannot easily derive the start and end points of the cutting stroke. These points are the final point outside of the mesh before we start drawing on top of the mesh and the first point outside of the mesh after drawing on top of the mesh respectively. We need these points in order to be able to find the mesh boundary edges that we need to cross to wrap the surface path around to the backside of the mesh. As mentioned before, in the non-VR case we simply use 2D coordinates based off the screen coordinates of the mouse pointer. In VR we cannot take the position of the controller as the user is likely cutting from a distance.

What we have done in order to determine the start and end point is storing the controller position and direction for a start and end point. The start point is updated with every sampled point that does not intersect the mesh that is sampled before we have started going over the mesh. The end point is updated with every sampled point that does not intersect the mesh and is drawn after we have been on the mesh before. Then when the user releases the controller buttons after drawing the cut stroke, we take these positions and directions and along their resulting rays find the two points that are closest to the first and last point drawn onto the mesh. Under normal circumstances this will then give the two points outside of the mesh that are closest to the first and final cutting stroke points on the mesh. This method does however somewhat restrict the user in their freedom on how to draw the cut stroke. If the user holds his hand too close to the mesh when starting the cut stroke, it is possible that the closest point to the initial on-mesh point actually is projected onto the mesh. This will make it impossible to create a looped surface path over the mesh. If this happens, a beep will sound and the cut stroke will be drawn in black, as is shown in Figure 3.1. Figure **??** gives a schematic overview of the problem that might arise with a cut stroke.

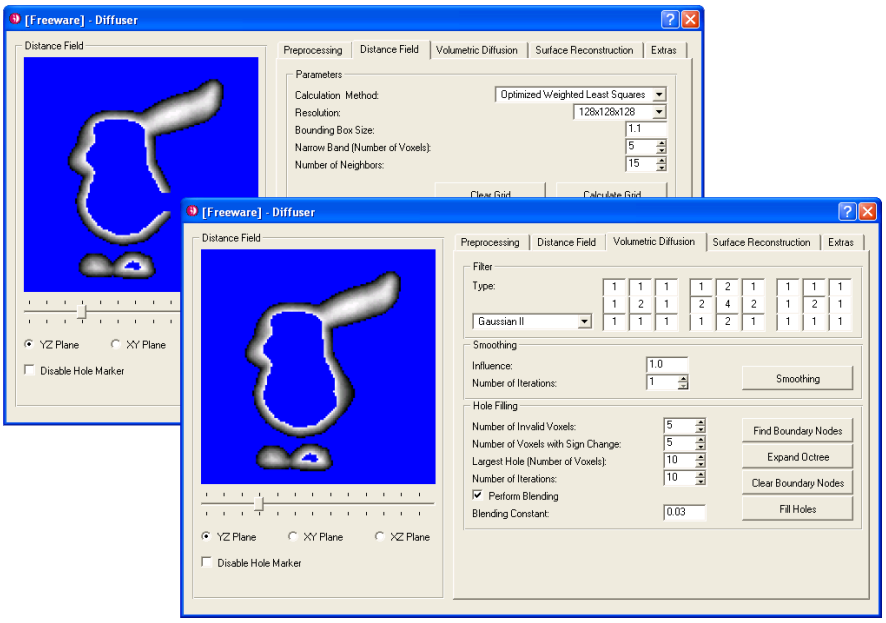


Figure 3.1: *Error screen as result of a problematic cut stroke.*

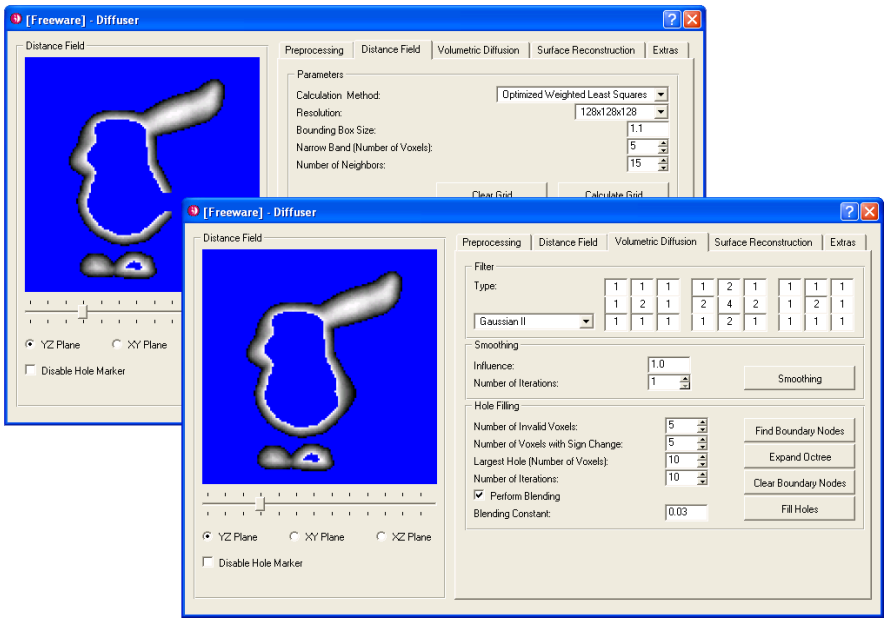


Figure 3.2: *Schematic drawing of problematic and correct cut stroke.*

3.1.4 Extrusion

The surface path for the extrusion base is created in a similar fashion to the cutting path, except that only the first hit between ray and mesh (front side intersection) is used. Drawing the extrusion silhouette in VR is significantly different from the way it is done in non-VR. When defining the silhouette stroke in non-VR, the user first has to rotate the mesh such that it is shown from a side view. Only then can the user sensefully specify the shape and depth of the extrusion silhouette, since we cannot specify any depth information from a frontal view of the extrusion base. In VR on the other hand, we know the actual 3D positions of the controller and can therefore directly specify the extrusion silhouette in a frontal view of the extrusion base. If the user prefers to do this from a side view instead (to get additional visual feedback about the silhouette depth on top of the tactile feedback), this is also possible.

3.1.5 Curve deformation

Finally there are some changes in the way that curve deformation is handled when moving from non-VR to a VR setting. Whereas in the non-VR version of SketchMeshVR we project all vertices on the constraint curves to 2D in order to find the closest vertex to the 2D screen position of our mouse pointer, in SketchMeshVR we simply compare the 3D position of the Touch controller with the 3D positions of all selectable vertices (vertices that are part of a constraint curve). If the closest vertex is within our threshold distance, we select it as the deformation dragging handle. In the case that the vertex is further away than the threshold, we instead go into navigation mode in the non-VR case and in VR we simply ignore the action. Directly using the vertex 3D coordinates instead of projecting vertex positions to 2D avoids ambiguity when multiple 3D coordinates with different depth values result in the same screen coordinates.

When determining where to move the selected handle vertex to, in non-VR we unproject the screen coordinates to a 3D coordinate using the z-value belonging to the projection of the deformation handle vertex, resulting in a displacement in the XY-plane. In VR on the other hand, we simply take the actual 3D position of the Touch controller.

3.2 User Interface

For the user interface in virtual reality it was important to keep the controls for all actions very intuitive. Unlike the VR 3D modelling programs that were discussed in Section 2.2, SketchMeshVR does not have any menus in its interface. Instead all functionality in the program can be used with just the right Touch controller (in future versions the user should be able to choose whether to use the left or right controller as the primary one). To increase spatial awareness and simplify orientating the user's hand in the scene, a sphere is displayed at the location of the right Touch controller, together with a ray from the hand following the orientation of the controller. When the user is in draw or pull mode or is drawing the extrusion silhouette, the ray disappears and only the hand sphere shows. This is done in order to emphasize that the actual position of the hand is used to draw a stroke, instead of the intersection points of the ray and mesh.

Compared to drawing strokes with a mouse on a PC screen (which happens purely in a 2D plane), drawing strokes in virtual reality with the Oculus Touch controller allows the user to draw strokes directly in 3D. In SketchMeshVR we made use of this advantage whenever possible. However, when the user draws the stroke that is used to create the initial mesh, the software does assume that the stroke is drawn mostly on the plane that the user is looking at. This is due to the fact that the drawn points will be projected to this 2D plane before they are triangulated and all stroke vertices will receive a z-coordinate equal to their mean z-coordinate. Subsequent cutting or extrusion operations do not have to be made in the plane that is being viewed, as for these actions the actual 3D positions of the drawn points are used. The rest of this section will describe how to employ each of the editing modes from within our application.

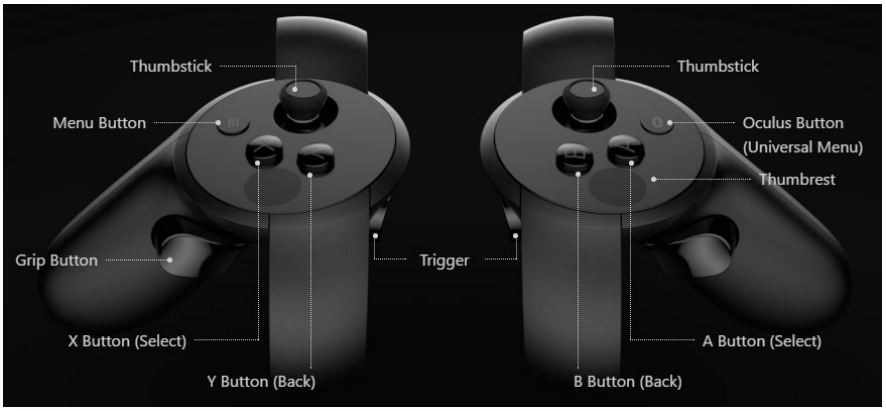


Figure 3.3: *Button layout of the Oculus Touch controllers.*

Action button	*Toggle button*	*Actions*
Grip	A button	Cut & extrude
Trigger	B button	Add & remove curves
Grip + Trigger	Thumbstick	Draw & pull

Table 3.1: *Button mappings for the different actions (the default action is mentioned first).*

3.2.1 Drawing and mesh deformation

To create an initial mesh, the user has to simultaneously press and hold the grip and trigger buttons while drawing a stroke in the 3D space and subsequently release both buttons when the stroke is finished. If the drawn stroke results in a non-edge manifold mesh (for example if the stroke intersects itself), a beep will sound and the stroke is displayed in black. Otherwise the created mesh will be shown, with the originally drawn stroke overlayed.

In order to deform the mesh, a user can drag on all mesh constraint curves, which are indicated by a overlay that places coloured points on the vertices and coloured edges between them. The user can toggle between drawing and deformation mode by pressing the B button, with draw mode being selected upon startup. To perform the dragging, the user has to simultaneously press and hold down the grip and trigger buttons while his hand is close to the constraint vertex that he wants to pull to a new position. Then, while still pressing the grip and trigger buttons, the user needs to move his hand to the desired new position, and release both buttons when the desired result is achieved. The new vertex position is interpreted directly as the 3D position of the Touch controller, therefore also allowing deformation outside of the viewing plane (as compared to the non-VR version, which only allows in-plane deformation).

The combination of grip and trigger buttons was chosen for these actions as they most resemble the feeling of holding a pencil and grabbing something in order to pull on it.

3.2.2 Adding and removing control curves

To add extra control curves to an existing mesh, the user has to press and hold the trigger button while drawing the stroke onto the mesh. All points that are outside of the mesh will be ignored and will not be added to the control curve.

In order to remove control curves (which is available on all constraint curves except for the curve that created the initial mesh), the user can toggle from stroke adding mode to stroke removal mode by pressing down the right thumbstick. Upon startup the stroke adding mode is selected. Whereas the drawing and deformation modes use the actual 3D position of the Touch controller, for adding and removing control curves the intersection between the hand ray and mesh are being used.

We decided to map the trigger button to the functions of adding and removing control curves since this feels like a natural way to select objects (removal) and to highlight areas (addition).

3.2.3 Cutting and extruding

Finally with the A button the user can switch between cut and extrusion modes. Upon startup the toggle is set to cutting mode, which allows the user to cut parts of the existing mesh away. To make a cut the user has to first point the laser ray to somewhere outside of the mesh, and then while holding down the grip button draw the cutting stroke over the mesh and finally releasing somewhere outside of the mesh again. In order to minimize unwanted behaviour, the user's hand should be a distance of approximately the mesh diagonal away from the mesh when performing a cut action. If anything went wrong during the cutting procedure, the drawn stroke will show on the mesh in black and a beep will sound. When looking in the direction the stroke was drawn in, the part of the mesh that is on the left hand side of the stroke will be removed.

When in extrusion mode, the user has to start drawing the stroke on the mesh and then while pressing the grip button has to draw the entire extrusion base on the mesh and release the button when the stroke is complete. Just like in the control curve addition mode, any points that are drawn outside of the mesh will be ignored. To ensure a correct functioning of the algorithm, the drawn base stroke needs to have at least one vertex on its interior. Then to complete the extrusion, the user has to draw the extrusion silhouette stroke that will define the height of the extrusion. When drawing this stroke, the user has to press and hold the grip button again but this time the actual position of the Touch controller will be used instead of the ray-mesh intersection point. Releasing the grip button will start the extrusion computations.

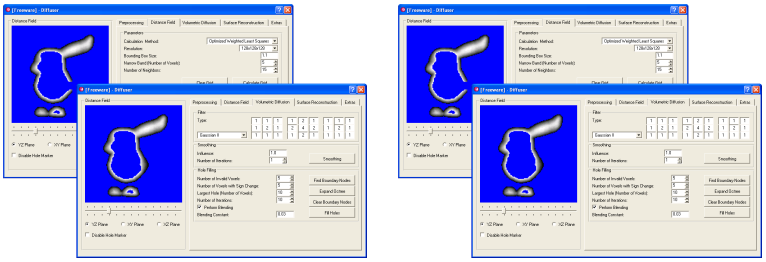
When pressing only the grip button, the hand often naturally assumes a position that resembles the way we symbolize pistols with our hands. Intuitively this maps to the concept of shooting a laser ray from your hand, which would be a sensible tool to cut a mesh with. For the case of extrusion we can argue something similar, as part of the mesh topology is also cut away. For this reason the grip button was mapped to the cut and extrude modes.

4

Results

4.1 Interface

As mentioned in the previous chapter, SketchMeshVR does not make use of any menus and instead solely relies on different combinations of button presses to differentiate between the multiple available modelling actions. This does require more effort from the user in order to keep track of the selected editing modes, but at the same time keeps the interface cleaner. In order to guide the user when drawing strokes, SketchMeshVR provides visual feedback on the positions that will be used to create a stroke. In case of the drawing and curve deformation modes this means that the user sees the position controller and in case of all other modes the user will see the position controller plus a ray shooting from it (the ray ends at any intersections it has with the scene). Figures 4.1(a) and (b) show what this looks like.



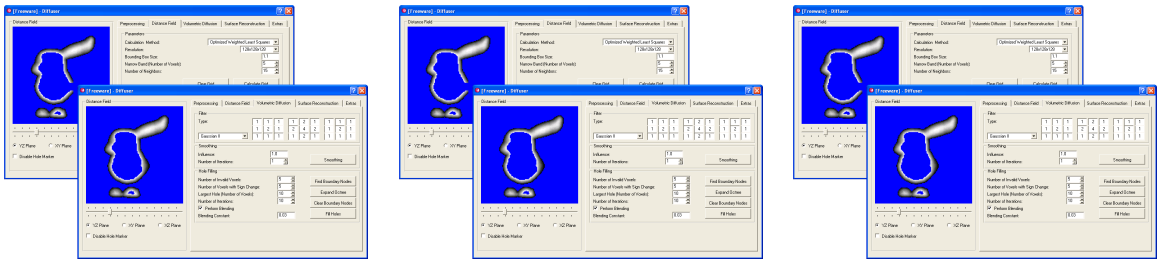
(a) (b)

Figure 4.1: *SketchMeshVR interface.* (a) *Controller reference point that is displayed in drawing and deformation mode.* (b) *Controller and ray reference that are displayed in all other editing modes.*

4.2 User review

TODO:

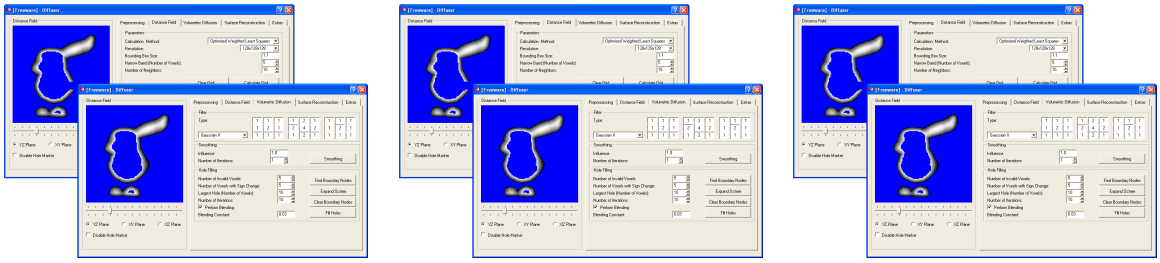
- mention test users' prior experience with 3D modelling and VR
- explain test setup: asking users to recreate an example model both in VR & non-VR version of program
- summarize any comments they have on the test/experience
- what did they think of ease of learning/modelling?
- Is there a difference in efficiency between modelling in VR or non-VR?
- show side-by-side comparisons of example model and user recreations



(a) (b) (c)

Figure 4.2: *SketchMeshVR recreating models.* (a) *Example simplified mesh of a teddy bear.* (b) *Resulting recreated model made in VR (took X seconds to complete).* (c) *Resulting recreated model made in non-VR (took Y seconds to complete).*

n seconds in



(a) (b) (c)

Figure 4.3: *SketchMeshVR recreating models.* (a) *Example simplified mesh of a dolphin.* (b) *Resulting recreated model made in VR (took X seconds to complete).* (c) *Resulting recreated model made in non-VR (took Y seconds to complete).*

n seconds in

5

Conclusion and Outlook

5.1 Future work

The developed software still offers potential for future expansion and improvements. For instance, the software misses some of the useful tools that are present in other modelling software such as simple predefined shapes (like cubes or cylinders), mirroring and merging meshes. Using a second VR controller (e.g. the Oculus Touch controller) gives enough buttons to map these functions to, allowing us to implement them without the addition of menu, thus staying with the principle of "intuitive" hand gestures. Adding an extra controller also allows for the user to switch between smooth and sharp curve deformation. The functionality for this is embedded in the software, but is not mapped to any button because all buttons of the first controller are already occupied by other functions.

Another functionality that would prove to be useful in many cases is the possibility to use blueprint images. When working with blueprint images, the user defines a series of different images of an object each taken from a different viewpoint. This allows them to trace these silhouettes from different angles and precisely recreate the object they want to model.

Additionally, the quality of the created meshes could greatly be improved by applying intermediate remeshing. As can be seen from the mesh examples, the triangle sizes differ greatly between triangles that are part of the initial created shape and triangles that are part of a subsequent cut surface or extruded part. This makes the appearance of the mesh rather chaotic and this could be avoided by remeshing every time a new surface is created. The purpose of the remeshing would be to make the edge lengths more uniform across the different parts of the mesh, resulting in a much more homogeneous mesh structure.

Final possibilities for improvements to the software lie in improving the interface. Implementing

hand avatars for hand orientation instead of a simple sphere greatly increase the feeling of immersion. Furthermore, displaying the currently selected tool modes (for example cutting versus extrusion mode) is an addition that will greatly help the user in keeping track of the type of mood that is selected, especially when there is a lot of switching going on. This could be done either by including a HUD (head-up display), a distanced billboard or customized meshes for each tool as is done in Google Blocks (Figure 5.1 gives an example). Additionally enabling the user to navigate the mesh either with one of the thumbsticks or with hand gestures using the two controllers is a valuable extension that will improve the usability, especially for users who do not have a lot of space available to physically walk around the mesh.

Figure 5.1: *Google Blocks' customized hand avatar for the eraser mode.*

5.2 Conclusion

In this thesis we have presented a novel way of creating 3D models in virtual reality. Modelling 3D objects in VR in itself is not a novel concept, but to the best of our knowledge our software newly introduces the sketch-based 3D modelling paradigm to VR. Whereas other programs mostly work with volumetric brushes and tools to edit the created "clay-like" models, ours transfers the concept of sketch-based modelling to VR by letting the user define model silhouettes. Although volumetric brushes allow for more fine-grained control over the resulting model, we believe that our method provides a more accessible and effortless way of creating simple models. In our opinion, if the goal is to provide the user with an intuitive and uncomplicated way of creating 3D models in VR, SketchMeshVR is better suitable to do the task than other 3D modelling tools for VR like Google Blocks or Oculus Medium.

We can conclude that virtual reality provides a very useful and powerful extension to 3D modelling and that bringing the sketch-based paradigm to a VR setup makes it even more versatile.

The source code for SketchMeshVR (and also its non-VR version), along with instructions for installation can be found online at `https://github.com/FloorVerhoeven/SketchMeshVR`.

Bibliography