

BUBBLEWORLD BUILDER

3D Modeling using Two-touch and Sketch Interaction

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Abstract: Commercial 3D modeling applications tend to be difficult and time consuming to use due to complex interfaces and functionality. In this paper we present a simple and intuitive interface for modeling “blobby” 3D objects using touch input. Objects are defined by sketching and modifying contours of cross-sectional slices. Two-touch interactions are used to zoom, rotate and slice the object. The resulting application allows rapid creation of 3D models and looks promising for medical imaging applications. A drawback is that intuitiveness depends on a user’s mental abilities such as 3D vision and the ability to develop a mental model and compare it with visual data.

1 INTRODUCTION

Three dimensional (3D) modeling is becoming increasingly valuable in fields such as entertainment, medicine and engineering. Despite this, modern 3D modeling applications remain difficult to use without extensive training. In order to make 3D modeling more accessible to inexperienced users we decided to investigate recent developments in multi-touch and sketch technologies and apply them to provide a more intuitive interface for 3D design.

One source of the complexity of current 3D modeling tools is the mouse and keyboard paradigm. The standard mouse provides bidirectional motion whereas input information in three directions is required to design 3D models. To compensate for this, existing applications provide a range of operations to specify this third dimension. This tends to result in complex interfaces with many buttons, menus and views of the object model, making them unintuitive as they lack analogy to real world interactions. Consequently it takes a significant effort to attain proficiency with them, and pen and paper is still preferable for early design stages.

New multi-touch screens surpass traditional touch screens by registering more than one point of contact at a time. We used a NextWindow (<http://www.nextwindow.com>) touch screen which provided two simultaneous touch points. The relative motion of

fingers and touch area recognition provides increased degrees of freedom to enable a variety of touch actions. Additionally it gives a greater sense of directness because the user puts their fingers directly on the item of interest. These properties can be used to provide input that is more analogous to real world actions than the traditional mouse and keyboard.

Sketching, or digital ink, is another recent area of development and is the digital analogy to pen and paper drawings. The motion of a user’s finger or stylus is captured and converted to a series of on screen strokes. This is useful for rapidly developing ideas because the user is less constrained by application semantics and tends to alter ideas more often (Black, 1990). Considering that free hand sketches are a common part of the 3D design process it may be useful to integrate sketching directly into the interactive modeling process. And because sketching can be performed with a touch interaction it can be combined with multi-touch systems.

Using touch-based techniques we designed and implemented an interface, where 3D objects can be modified by editing cross-sectional slices. A new 3D surface is then rendered from these slices using radial basis interpolation. By placing more functionality into the touch actions rather than buttons and menus we reduce the user’s mental load and simplify the interface. And by providing design flexibility with the slice-based approach our solution is suitable for simple rapid prototyping and design applications.

2 RELATED WORK

In the Origami Simulator (Chang et al, 2009) a virtual piece of paper can be moved and folded using two-touch interactions analogous to the art of paper folding known as Origami. Results from user evaluations on this application suggest that multi-touch interaction can be intuitive, enjoyable and useful for interacting with 3D environments. It was from this concept we decided to explore a more general 3D modeling interaction.

Previous sketch based tools for 3D modeling have used rapid and rough sketches with simple interfaces for fast modeling. For example, in Teddy (Igarashi et al, 1999) sketched 2D shapes are inflated to produce 3D shapes – it is suggested that about ten minutes of practice is required to be able to make fairly interesting shapes. However editing of the resulting object is limited.

Alternative input devices have used bimanual interaction to increase the available degrees of freedom for 3D environment interaction. In 3-Draw (Sachs et al, 1991) a remote control-like device is held in each hand. The 3D motion of the devices provides 3D input to generate models. This transcends the limitations of 2D motion of mice, however, is still limited by 2D display. Virtual surface models are also bimanually controlled in the Polygon Surface Design (Shaw & Green, 1994) tool. These tools require special devices which are less readily available than multi-touch screens.

In the Profile Driven Sketch tool (Bartolo et al, 2008) the profile sketch of an object is annotated with cross-section views at various points which are used to generate a wireframe model. However direct interaction with the wireframe is not provided. Commercial modeling tools such as AutoCAD (Autodesk Inc., 2010) provide lofting algorithms that interpolate surfaces through cross sections. These rely on fixed position mouse slices.

3 DESIGN

This section covers the early design phase of our project. It describes the requirements of the project and key factors considered for the solution design.

The focus of this research was to explore the use of multi-touch and sketch to develop a simpler and more intuitive interface for 3D modeling. In the first stage of our research we created a set of requirements for the application based on observations, evaluation of previous work, and

informal interviews. The key usability requirements derived were a minimal interface and intuitiveness. The interface should have fewer items on screen, which is achieved by transferring functionality from buttons and menus into touch gestures. This allows more room for model display. For the application to be intuitive the touch actions must be analogous to real life actions.

In terms of functional requirements, the key factors are 2D to 3D mapping, flexibility, simplicity and shape predictability. Considering the touch screen provides two spatial dimensions it is necessary to have a mechanism to provide input for a third spatial dimension yet have the flexibility to model a range of objects. Lastly the application should accurately infer the shape the user wants to create.

3.1 Solution Design

From the above requirements we designed a cross-section based solution where the user manipulates the shape by editing slices of the shape. Cross sections are a common 3D design approach. They can be used to provide 2D to 3D mapping because the orientation of the slice plane (the plane on which the cross-section rests) and the slice profile (the profile seen on the cross-section) provides three spatial dimensions of information.

With a cross-section approach the lofting method must be chosen: how will a 3D shape be generated from the cross-sections? The three methods considered were Morphing, Edge-Minimisation and Radial Basis Function Interpolation; the later was chosen as the best balance between flexibility, simplicity and shape predictability. It would enable a greater range of objects to be modeled because unlike the other two, it naturally deals with cross-sections in arbitrary orientations. And because it produces curved surfaces based on the idea of bending energy minimization it better reflects the curvature of natural objects. As a drawback the method does not allow straight edges or corners. However, we felt that users would be more interested in modeling objects with curves rather than flat faces. And although we hypothesized that the other methods may be more understandable, the flexibility provided by it was more important.

Other investigated design methods were discarded because they did not meet the requirements. For example, direct manipulation of vertices, edges and faces is a common operation, however, would pose greater challenges in terms of 2D to 3D mapping despite providing more

flexibility. Silhouettes are similar to cross-sections and have been successfully employed for modeling (Igarashi et al, 1999), but impose restrictions on the types of shapes. Domain specific solutions can be very elegant (McCord et al, 2008), but are unsuitable for general modeling tasks.

Our application is implemented in C# and uses the OpenTk framework for OpenGL and the Microsoft Ink API. The system architecture is shown in Figure 1. The Multi-Touch component manages an interface to the NextWindow dynamic link library.

Table 1: Comparison of proposed modeling methods.

	2D to 3D Mapping	Flexibility	Simplicity
Cross-Section Based	Easy	High	Expected High
Vertex Control	Difficult	High	Low
Domain Specific	Easy	Low	High

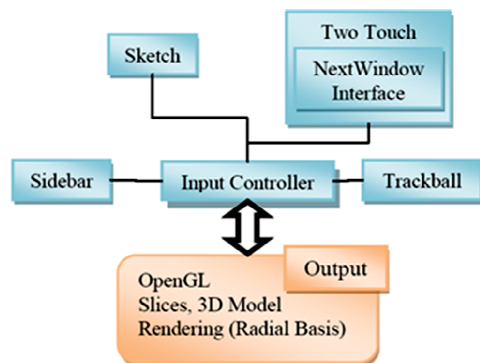


Figure 1: System architecture of our application.

4 INTERACTION

To create a model the user specifies cross-sectional profiles that lie in arbitrary orientations in a 3D space. There are two interaction modes. In object mode two-touch actions are used to position the model. In sketch mode the user draws the profile shape from which a 3D surface is interpolated with a radial basis function interpolation.

The object is shown in an off-white colour and the slice planes are shown in pale grey (Figure 2). A selected slice is green to visually indicate that it is editable (Figure 3).

The design process occurs in three steps. First the object is positioned as required by rotation and zooming. Next a slice plane is specified to define the

area to be edited. Lastly the slice profile is drawn and the new shape of the object generated. This process is repeated to extend and edit the shape as the user sees fit.

4.1 Interaction Gestures

In object mode two-touch actions are used to zoom and rotate the object and create slices. These are analogous to real life object interactions. A single touch gesture across the screen rotates the object like a spinning globe. Two contact points moved closer together or further apart zoom the object out and in respectively, like stretching a rubber band. One touch, moving around a stationary touch, rotates and zooms at the same time.

An area touch, formed by a knuckle or three finger contact, dragged across the screen creates a slice. The cross-section plane lies along this line perpendicular to the screen. Once cut, the object rotates to put the slice flat on to the screen for sketching. Figure 2b shows a slicing action between two points in the direction of the arrow.



Figure 2: Object actions: a) Zooming and rotation b) Slicing.

Once in slice mode the user can sketch and erase the intended profile (Figure 3). Dragging a finger across the screen sketches a black line along the finger path. Scribbling quickly over existing lines erases them (analogous to using an eraser on pencil). Once erasing begins, any sketched line that the finger passes over is removed. When the new cross-section is finished the 'Done' button commits the sketch to the slice and renders the altered object in object mode.

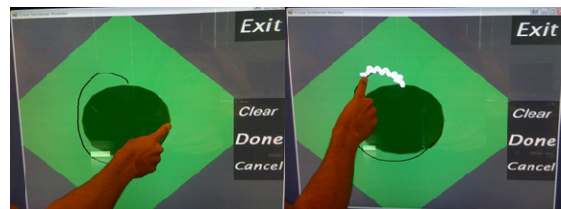


Figure 3: Sketch actions. a) drawing b) erasing.

5 RADIAL BASIS FUNCTION INTERPOLATION

The 3D model corresponding to the sketched slices is obtained by creating a 3D density field $f(\mathbf{x})$ which has the property that $f(\mathbf{p})=0$ for every point \mathbf{p} on a sketched contour, $f(\mathbf{p})>0$ for every point \mathbf{p} inside a sketched contour, and $f(\mathbf{p})<0$ for every point \mathbf{p} outside a sketched contour. The 3D surface of the object defined by these contours is then given as all points \mathbf{x} in the 3D domain where $f(\mathbf{x})=0$. We extract this iso-surface using a Marching Cube Algorithm (Lorenson et al, 1987).

The function $f(\mathbf{x})$ is constructed by generating sample points which are on a contour, outside a contour, and inside a contour. We then perform a radial basis function interpolation such that $f(\mathbf{x})=0$, -1 and +1 for points on, outside and inside a contour, respectively. Using a function $f(\mathbf{x})$ of the form below results in a visually pleasing surface with minimal bending energy (Carr et al, 2001):

$$f(x) = \sum_{i=0}^n \alpha_i R_i(d_i(x)) + \sum_{j=1}^m \beta_j p_j(x) \quad (1)$$

Here $R(r_i)$ is the basis function

$$R(r_i) = r_i * r_i * \log r_i \quad (2)$$

By inserting the n sample points with the conditions that $f(\mathbf{x})=0$, -1 and +1 (for sample points on, outside and inside a contour) we get the linear system of equations

$$M \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} f \\ 0 \end{pmatrix} \quad (3)$$

where a and b are vectors with the α and β coefficients of each equation and f is a vector with the field values at the sample points (0, -1 or 1). The unknown coefficients are found by solving the linear system of equations using an LU decomposition or a more efficient solver as described in (Carr et al, 2001).

Sample points on the contour are easily obtained by sampling the underlying parametric curve with an arclength parameterization. Alternatively a curvature based measure can be used (not implemented) to create more sample points in regions of high curvature.

Points inside and outside of a contour are created by taking normals to the cross-section shape

vertices. We define that the inside (outside) areas of the cross-section contours on each slice form the inside (outside) of the resulting 3D object. In order to get a well behaved surface we need to find a sufficient number of sample points on the inside and outside. We calculate these points using the vertices defining a contour.

Let us take a vertex P on an arbitrary slice. P has two adjacent vertices P_1 and P_2 . From these three vertices we form two vectors V_1 and V_2 .

$$V_1 = P_1 - P \quad (4)$$

$$V_2 = P_2 - P \quad (5)$$

Next we calculate two sample points, one inside the shape and one outside the shape, as follows.

$$V_{in} = P_1 + P_2 \quad (6)$$

$$V_{out} = P - V_{in} \quad (7)$$

We give V_{in} the field value 1 and V_{out} the field value -1. Positive field values occur inside the shape and negative field values occur outside the shape.

This approach assumes convex contours, however we perform an extra operation to account for concave curves. A point inclusion algorithm is used to ensure the correct selection of V_{in} and V_{out} . The algorithm is run over V_{in} to check that a point is actually inside the shape. This is done by firing a ray from outside the shape to V_{in} . The number edges passed to reach the point is counted. If the number is odd the point is considered to be inside. Otherwise, V_{in} and V_{out} are swapped.

The algorithm is applied to each sample point on a contour so that we get an equal number of sample points inside, outside, and on the surface of the object to be modelled. Note that this algorithm fails if the distance between two parallel lines is less than the length of the normalized normal – in that case the outside point or one contour might lie inside another contour.

Figure 4 shows a cross-section with generated sample points. The black dots have field values of 0, the green dots field values of 1 and red dots of field values -1.

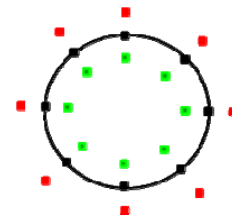


Figure 4: Density field of sample points of a slice.

There are two significant limitations to the modeling system. First, certain slice combinations are contradictory and hence result in no surface being constructed. Second, slices that are too far apart do not result in a surface that flows between both slices and instead two separate surfaces are formed for the contour of each slice.

The contradictory slices include overlapping and intersecting slices as illustrated in figure 5. In this example the blue point is considered by slice A to be inside but by slice B to be outside the shape. Since the density field function $f(\mathbf{x})$ cannot have two different values for the same point, no solution exists and consequently no object surface is constructed and displayed. In this situation the last valid state of the object is restored. Getting around this problem requires a testing of consistency of sketched contours and appropriate warning messages. Alternatively conflicting contours could be automatically adjusted (contours must be disjoint or correspond where slices intersect).

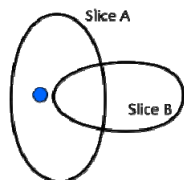


Figure 5: The blue point has an ambiguous density field value since it is inside the contour of slice A, and outside the contour of slice B.

The second problem is due to the bending energy minimization nature of the radial basis function. If two slices are a sufficient distance apart bending energy is minimized by producing two separate surfaces rather than one large one. The problem could be resolved by adding interpolated slices, but this contradicts the nature of the radial basis function interpolation. Furthermore, it is not clear under what circumstances a user would expect one combined or two separate surfaces. Both of these limitations reduce predictability of the surface and hence its intuitiveness and usability.

6 RESULTS

We used our application to create a variety of simple blobby objects (for example figure 6). While the sketch input is efficient, the control of the shape is limited. The range of possible shapes is limited because we don't allow nested contours on a slice in order to construct hollow objects

6.1 User Evaluation

A user evaluation was performed in order to determine the efficacy of Bubbleworld. The factors of interest were the naturalness of the touch actions, the ability of users to model objects using the cross-section approach and a comparison to mouse interaction for the same process. The evaluation was conducted by observing users performing modeling tasks and recording qualitative feedback (from post-task surveys) and quantitative measurements (time taken to perform tasks). The details of the study are presented below and an interpretation is provided in section 7.

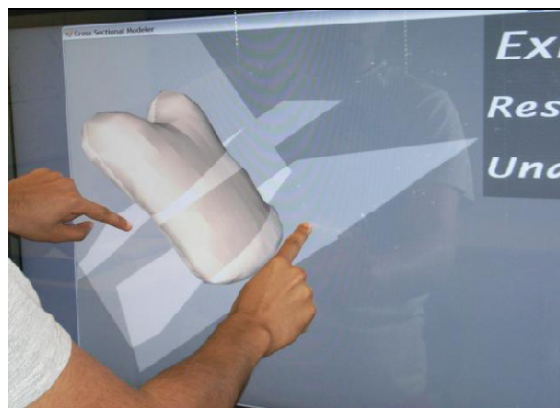


Figure 6: Result of using two horizontal and a vertical contour.

Ten software engineering students who had experience with 3D environments (mostly from computer games), and were familiar with 3D modeling tools participated in the study. A few students frequently used two-touch iPhones and most had previously used a multi-touch screen (at least a few times). Their experience with technical drawings varied from 'a couple of times' to 'frequently'. The participants could be considered very technologically capable with little 3D modeling and multi-touch experience.

The participants were individually shown Bubbleworld running on a NextWindow touch screen and given basic training. This included demonstrating and teaching them all the main operations (Zooming, Rotating, Slicing and Sketching). They were then given two minutes of free time with the application to familiarize themselves with the actions and screen.

The participants were then asked to perform four simple tasks while we video recorded them. The tasks were zooming the object, rotating the object, elongating the object and widening the bottom of the

object. This was to observe their ability to understand the actions. Next they were asked to create a banana shape. This was to observe their ability to design with the application. Finally they were asked to repeat the process using the mouse instead of the touch screen. At the end of the procedure they filled out a questionnaire.

After all the participants had completed the procedure we extracted the time to complete the banana task from the video recordings. The time is recorded as the time between the user understanding the task and when they were happy with their design (Table 3). On average, user's performed the task faster with the mouse than the with the touch screen. This is partially explained by the fact that once user's had performed the task with the touch screen, they knew what to do hence could more quickly complete it with the mouse. An additional factor would be the difficulties in using this particular screen. This is discussed further in the next section. Results for questions from the survey are presented in Table 3.

Table 2: Task completion times.

	Time Taken (min.sec)	
	Touch Screen	Mouse
Mean	1.54	1.48
Range	2.42	3.30

Table 3: Survey results on seven-level Likert scale (-3 = strongly disagree to 3=strongly agree).

Question	Mean Result
Interaction was enjoyable	2.3
Interaction felt natural	0.2
Rendering was predictable	-0.1
Cross-sections are useful for 3D design	1.8

7 DISCUSSION

The goal of our research was to develop an intuitive interface for 3D environments. The evaluation survey results suggest that users found the interface enjoyable and easy to understand. This suggests a level of simplicity or intuitiveness of the interactions hence making them easy to remember. Additionally the sense of directness of touching the object may have added to the enjoyability compared to the traditional mouse method. Interestingly only a moderate level of naturalness was suggested by the survey despite our attempts to design real-world analogous actions. This may relate to the problem of

2D input. The actions are still not closely enough related to holding and manipulating a real 3D object in one's hands. The main problem is the flat screen being the interaction medium. Another reason for this may be limitations of the hardware, e.g. sensitivity and friction, which reduced the sense of naturalness.

The second goal of our research was to provide a simple interface which doesn't have the steep learning curve encountered with traditional 3D modeling tools. Our implementation contains at most four buttons on the screen at any time and the user is still able to perform a fair amount of manipulation using it. The minimalistic interface has enabled us to free screen space for displaying the modeled object and because of the easy interaction we found that users do not require the multiple views usually encountered in traditional tools. The interface could be minimized further by using gestures or even speech recognition.

Although we considered the input actions to be user friendly, the user study showed that the contour interpolation was not as intuitive as expected. Users were surprised when distant slices did not join together or certain slices could not be rendered. Even for valid user input the predictability was moderate. It seems that users need some experience or a mental model ("soap bubbles") of how the radial basis function interpolation affects objects. Indeed, one user suggested in the survey feedback that intuition would increase with continuing usage.

Although we did not carry out a formal comparative study we were curious about how usability would change with mouse input instead of using a touch screen. Participants commented that they were more used to the mouse which helped them to use it well. This suggests that touch screens may need to reach a greater level of ubiquity in order to reach their full potential in terms of effective and natural user input.

The spatial reasoning of users had an impact on their design skills. There appeared to be little difficulty in performing basic operations involving a few slices such as extrusions, however our observations were that modeling becomes increasingly difficult the more slices are used. This is due to the difficulty of visualizing how a surface can flow through many slices. A way around this could be to create multiple localized surfaces rather than one global surface for all the slices. This would provide greater control of the shape and improve predictability. Objects could be created from positioning together many smaller ones which is one main feature of traditional modeling tools.

8 CONCLUSIONS & FUTURE WORK

Existing commercial 3D modeling applications are complex to use and hence significant training is required before users reach proficiency. In response to this we have designed and implemented a simpler 3D modeling application which utilizes two-touch and sketch techniques. Our solution was enjoyable for users and can be used to quickly design a variety of objects. However, limitations were imposed by the underlying mathematical model and users' ability to create 3D mental models and match them to visual input.

The results of our research indicate that the concept of 3D modeling based on touch and sketch input is promising, but more work needs to be done to make it more effective and natural. One major obstacle is the lack of 3D vision of many users and might only be completely overcome with the emergence of 3D displays and consumer level 3D gesture recognition.

Even with the above limitations there are already a lot of useful applications available. We are in particular interested in medical imaging applications where slice input is natural (x-rays, CT and MRI data sets) and where users (medical professionals) have exceptional 3D vision and 3D mental capacities. We are currently working on tools for user-assisted object segmentation using touch input.

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