

SESAME: Towards Better 3D Conceptual Design Systems

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ABSTRACT

Conceptual design dominates the early stages of most creative design processes. During these stages, the designer makes important decisions about the parameters of a model that are aimed at satisfying a set of design criteria. To do this, the designer produces many sketches of various possible solutions. Meanwhile, computer-aided design (CAD) systems are becoming the dominant visual medium used in design practice. However, these tools evolved as documentation production tools and do not support conceptual thinking. This paper presents a list of guidelines for computer support for conceptual design activities on 3D scenes and presents SESAME (Sketch, Extrude, Sculpt, and Manipulate Easily), a system based on these guidelines. Finally, we present a user study comparing SESAME with a conventional CAD package to demonstrate the effectiveness of SESAME.

Author Keywords: Conceptual design, Sketching interface, 3D design

ACM Classification Keywords: J6 [Computer-aided Engineering]: Computer-aided design, H5.2 [Information interfaces and presentation]: User Interfaces –Evaluation/ methodology

INTRODUCTION

During conceptual design sessions, a designer considers a design problem and generates a broad range of solutions in the form of schemes. Many design decisions are made during this stage and knowledge from various disciplines, such as engineering, production methods, and commercial aspects are incorporated [4].

In the conceptual design stage, sketching is primarily used due to its low use overhead and the informality of the representations. Nowadays, however, designers start to use computers in earlier phases of the design process, as computing power has improved greatly and people are more adept at using computers. Furthermore, for 3D design problems, a 3D representation is much more effective for presentation to people outside the design discipline, and also allows for simulation (e.g. of lighting for a building). However, conventional computer-aided design (CAD) systems do not support

the early design phases well, as they are more tailored towards detail work. Hence, designers sometimes alternate between sketching and the use of computer systems to get the “best of both worlds”.

The goal of our work is to support important operations of the early design process directly in a computer system so that designers can quickly explore different design solutions for 3D problems. For this, we first present a list of guidelines for such systems based on studies of the design process. Then we introduce a new conceptual design system, SESAME (Sketch, Extrude, Sculpt, and Manipulate Easily) and discuss how various features of the system are implemented based on the guidelines. Finally, we present a study comparing SESAME with 3D Studio Max.

RELATED WORK

One approach for creating 3D models is sketch reconstruction, which reconstructs a 3D model from the lines of a user-created 2D sketch. There are many examples for such systems (e.g. [14, 24, 26]). Overall, the problem with the sketch reconstruction is that all algorithms require a set of assumptions about the types of drawing or the types of objects to be reconstructed, and thus can only deal with a fairly limited set of objects [29].

Another approach is gesture-based user interfaces, where users create 3D objects using a set of predefined gestures. SKETCH [31] is one of the main examples. The main disadvantage of this system is that the types of created objects are limited by the “vocabulary” of the gesture interface and the need to train users on this vocabulary. SKETCH’s user interface was adapted in Sketch-N-Make [1], which was developed for designing and manufacturing machined metal and plastic prismatic parts, which provides an example of how an initial design can be transformed into a production system. Teddy [10] extended this gesture-based approach to free-form objects. Chateau [11] also utilizes a gesture interface, but adds 3D suggestion engines to aid the user. These engines suggest possible scene configurations based on common design conventions such as symmetry or parallelism and present them to the user. One downside of this approach is that these suggestions consume a substantial amount of screen-space.

SketchUp™ (www.sketchup.com) is a commercial product targeted at architectural design. It provides a simple user interface to quickly build 3D structures. Based on a push-pull

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metaphor, the system implements an effective extrusion interface, to allow users to quickly extrude 2D shapes into 3D volumes. One drawback of this system is it sometimes requires the user to manipulate individual polygons, which can be cumbersome for rapid design exploration.

Yet another approach is based on the idea of constructing 3D scenes of voxel-like objects. Galyean and Hughes [7] presented a sculpting system based on this idea. They provided a set of tools to modify an object by adding material, cutting away, or smoothing the surface. A polygonal representation was then derived from the voxel representation as needed. DDDoolz [28] is a voxel-based architectural design tool, where the user creates a scene by filling space with blocks or removing some of them. Users can group voxels to form architectural elements by coloring them with the same color. In Virtual Lego [17], people can create and manipulate complex Lego models efficiently using intelligent group manipulation techniques. Since many people are familiar with the idea of volume manipulation this type of systems is quick to learn and easy to use. However, the level of detail that such systems can support is limited by the size of the basic voxel and they are typically bad at representing slanted surfaces.

Finally, some systems focus only on the creation and manipulation of 3D scenes based on a library of predefined objects. For example, in the MIVE system [25], the authors investigated how predefined constraints help users to place and/or rearrange predefined objects. The constraints limit the motion of objects based on simple heuristics, such as the fact that chairs are usually placed on floors and that shelves are usually placed on the floor and against a wall (or some other support). The authors showed that this allows naïve users to quickly populate 3D scenes with predefined objects. The main limitation of this system is that it does not allow for the creation of new objects.

GUIDELINES FOR CONCEPTUAL DESIGN SYSTEMS

This section presents a list of guidelines collected from a review of the design research literature [19], with the main contributions coming mainly from three papers [5, 21, 22]. For each guideline, we detail how we applied it in the design of our new system, SESAME.

It is important to note that we applied all guidelines in the context of a *computer-based 3D design system*. For example, while freehand drawing is a very important property for sketching, designers generally want to have more accurate 2D tools, such as line drawing facilities, when using 3D computer systems.

- *Non-intrusive interface*: One of the reasons that designers sketch is due to the complexity of design problems and the fact that mental resources are limited. Therefore, designers sketch to externalize their vague ideas in their mental imagery and to visually evaluate them. Hence, the cognitive demand for using computer tools should be minimal so that the designers can fully commit themselves to solve the

design problem rather than worrying about the tool interface.

SESAME: Current CAD systems have many modes, which impose a burden on the users' mental resources, as they have to keep track of the current mode to avoid mode errors. We believe that during conceptual design, users need only a small repository of operations to develop ideas rather than the full functionality of a CAD system. Hence, SESAME provides only a minimum set of modes: a 2D mode for drawing contours and a 3D mode for manipulating solids. For 2D drawing, the system facilitates efficient drawing with a set of techniques – e.g. suggestions, automatic segmentation of freehand drawings, and recognition of closed structures. In 3D manipulation mode, the system provides natural and efficient manipulation techniques based on physical properties, such as gravity and collisions.

Similarly, many conventional CAD systems use multiple views or wire-frame images to depict a scene. This forces the user to continuously “translate” the images on the screen to a different mental representation to understand the arrangement of a scene. SESAME allows the user to perform all operations in a single perspective view of the shaded scene representation, which is easier to perceive.

- *Easy creation*: The design process is dialectic and cyclic [22]. Solutions are repetitively created or refined while (mentally) testing them against the desired criteria. This means that the cost to visualize a solution should be minimal. Therefore, any computer tool has to provide efficient ways to create design solutions quickly.

SESAME: Previous work has shown that solid modeling is more appropriate for early design phases compared to other approaches, such as polygon based modeling, since solid modeling facilitates the efficient creation of rough models [6]. Most of today's CAD systems are based on the manipulation of polygons, edges, and vertices. In contrast, SESAME supports solid modeling directly, via the metaphor of the extrusion of 2D contours, as well as sculpting and direct manipulation of 3D objects.

- *Easy combination and restructuring*: The recognition of individual parts and their relationships aid a human in the interpretation of a whole object [3]. Based on this, some design researchers [27] observed that the combination and restructuring of parts are the main activities in creative invention. Furthermore, combination is a simple mental activity, while restructuring requires the aid of externalizations. Therefore, the user must be able to combine components of objects easily as well as to be able to restructure the result of a combination.

SESAME: The design of SESAME is based on the hypothesis that solid modeling combined with a direct visualization makes it easier to combine objects and restructure a scene. Hence, we provide object manipulation schemes that use a single viewpoint and match the users' expectations about the most probable object motion. This allows

users to evaluate the results directly, instead of having to check the correctness of each operation separately. Similarly, group manipulation techniques behave in a way that is consistent with the real world.

- *Tolerance to ambiguity and incompleteness:* Although design decisions are not well formed in the conceptual design session, sketchers can still express their ideas, and the visuals naturally exhibit the ambiguity and incompleteness of these ideas. Hence, computer tools should not always expect fully legitimate input from users, and provide a way to externalize ambiguous forms. In addition, the visual output has to reflect the tentativeness of a solution, so that the designers can easily identify newly created problems or defects from intermediate forms.

SESAME: Sketching naturally supports ambiguity and incompleteness. This manifests in several aspects: 1) the viewpoint for a sketch is defined by the designer's sketch itself, instead of the paradigm of drawing into a 3D scene from a particular viewpoint, 2) sketches visualize both 2D and 3D shape (from a single viewpoint) descriptions as well as annotations [12], and 3) the character of line drawings impart informality and implies incompleteness, which in turn invites modification [23].

Sketch reconstruction systems (e.g. [14, 24, 26]) are able to address the first aspect. However, these systems are quite restrictive in that users have to provide "clean" drawing with "correct" shapes from a single viewpoint, which is often hard in the early design stages.

In SESAME, we provide some level of flexibility in 2D drawing. Users can draw 2D contours on any surface via common 2D primitive shape tools and freehand sketching. The user input for freehand sketches is smoothened by segmenting it into primitive 2D shapes. As this user input usually contains jitter, smoothening is usually a positive thing. However, to preserve important details while removing unwanted noise, the level of detail for the segmentation varies depending on the viewing distance. That is, if the user is viewing the drawing surface from far away, the system segments drawings in more gross detail than at a closer distance. Segmentation provides another advantage in that the users can later select and manipulate the segmented parts. Furthermore, design researchers identified that shapes that are created by (seemingly) random intersecting figures are often used for the exploration of design ideas [8, 27]. Hence, SESAME automatically recognizes closed contours from intersecting contour elements. Then, the user can quickly create 3D objects from these 2D shapes.

Concerning the second aspect, in principle, SESAME supports the coexistence of 2D drawings and 3D shapes, as it facilitates the "exchange" of ideas across dimensionalities. However, this facility is imperfect due to limitations of the current implementation; it is explained in the user evaluation section.

The third aspect is related to the "expressiveness" of ambiguous drawings. Traditional computer graphics techniques require a high degree of accuracy. Non-photorealistic rendering (NPR) tries to address this issue (e.g. [15]). While this is a good idea for artistic visualization or presentation purposes, many NPR techniques are not a good choice for interactive systems as the choice and behavior of a rendering style depend on the choices of the designer of the system, and not on the user's choices and/or design intent.

In SESAME, we choose a compromise and provide thick outlines rendered on top of shaded objects. This is a middle ground between the expression of informality and the accuracy required for interaction with computer systems.

- *Range of levels of abstraction:* There is a range of levels of abstraction that designers commonly move within, since they can only deal with a limited set of problems at any instant. Experienced designers tend to shift more fluently between overall and detailed aspects of design [5]. This range, however, is different between different disciplines of design, that is, one designer's concern might not be the concern of another. For example, an urban designer may not consider details of the way a door is closed or opened, and it is likely that he would choose some existing mechanism. On the other side, a building architect will closely focus on this aspect of a door. Certainly, there is no universal tool that works for every design specialization. However, any computer tool has to match to the range of detail that a designer works with.

SESAME: For many years, snapping has provided a convenient bridge between the inaccuracy of a users' input and the accuracy required by computer system. With this, designers can quickly generate a rough scene configuration and the system can display it accurately (enough). However, snapping can restrict the level of detail a user can work at, as users may not be able to work on details smaller than a fixed snapping distance, as objects will always snap to nearby anchors. Hence, many systems provide the option to configure this snapping distance via some dialog. However, this complicates the user interface.

In SESAME, the idea that the level of detail is proportional to the viewing distance is used in many interaction techniques. This is based on the observation that designers generally work on an overall idea by viewing the scene from a farther distance and work on detail by zooming into the part of interest. E.g. 2D shapes and 3D objects snap to features in the scene with a snapping distance that is proportional to the viewing distance and the smoothening of 2D freeform drawings is also dependent on the distance.

- *Ability to edit various forms of information:* The representations used in the design process are not only geometric shapes, but also different free-form strokes that stand for size, ratio, or trajectory. By putting figural and conceptual information together, a designer can reflect on different dimensions of a design problem at once. Therefore, the

goal of sketching is to organize the problem/solution via different kinds of symbolic representations in the course of producing a final geometric shape. Many tools overlook this factor by focusing overly on various geometric representations.

SESAME: Currently, the system does not address this in a significant way.

- *Supporting evaluation (simulation)*: Designers explore a solution/problem space by generating many solutions and testing them, asking ‘what if’. Sketching visualizes a situation on paper, and designers perform simulation of the situation in their mind. On the other hand, computer tools can conduct the simulation directly, instead of the designers. This should be beneficial, if the system can support spontaneous creation, modification, and re-simulation. However, simulation is closely task-specific, so one cannot count this as a criterion to judge computer tools for the design process.

SESAME: We support this via the export of scene geometry to a simulation package and then running that simulation. In the future, we may integrate this better.

SESAME USER INTERFACE OVERVIEW

The user interface of SESAME consists of a main 3D scene view and a menu panel on the right side. The menu offers a color/texture palette, a 2D and 3D primitive shape selection palette, an undo button (which is a variation of the common undo icon from modern GUI systems), a navigation mode switch button, and a recycle bin (Figure 1).

In the top right of the menu panel is a color/texture palette. A user can switch between color or texture palettes by pressing on either of the top two buttons. On the left hand side of the menu panel, the first group of buttons is the 2D drawing tool palette, with common 2D tools such as lines and arcs, and a freeform drawing tool. These freeform drawings are automatically segmented into a sequence of lines, circular arcs, and ellipses. Once they are segmented into primitives, these segments can be manipulated as if the individual drawing tools would have created them. For segmentation, the system uses the mean shift algorithm presented by Yu [30], which employs the mean shift to find the slope and curvature of a stroke to decided between straight segments and curved ones.

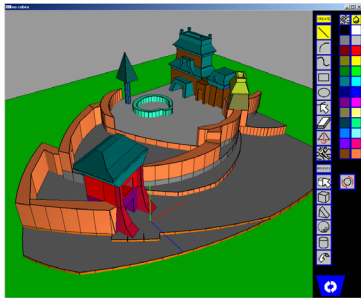


Figure 1. SESAME interface

The next set of menus on the left hand side provides 3D operations such as the 3D manipulation of objects and the instantiation of primitive 3D shapes, such as boxes, triangular prisms, spheres, and cylinders.

The user interface utilizes only a 3-button mouse and a few modifier keys. All actions such as sketching a contour or moving objects can be accomplished with them. From a high level, the system has two main modes: 2D and 3D. If the user selects one of the 2D shape manipulation tools such as lines, arcs, or eraser, then he/she is in 2D mode. The user then manipulates 2D shapes using the left mouse button and modifier keys. If the user selects one of the 3D tools, he/she is placed in 3D mode. Then the user can move or add 3D objects using the left mouse button and modifier keys. Other mouse button functions are independent of the selected mode. The overview of the mouse function assignments is shown in Table 1.

| Input command | Mode | Function | Realization |
|--|------|--|---|
| Left click | 2D | Select 2D shape | On release |
| | 3D | Select or add 3D object | |
| Left drag | 2D | Draw 2D shape | On press |
| | 3D | Move 3D object | On dragging more than a threshold distance |
| Shift + left drag | 2D | Clone 2D shape | On dragging more than a threshold distance |
| | 3D | Clone 3D object | |
| Ctrl + left drag | 3D | Rotate 3D object | During dragging |
| Right drag towards outside of a volume | Both | Extrude a 2D contour or a face | During dragging |
| Right drag towards inside of a volume | Both | Subtract an extruded shape from a 2D contour or a face | Extrude during dragging, subtract after release |
| Shift +right drag | Both | Scale object | During dragging |

Table 1. Mouse and keyboard commands.

Dragging the mouse with the shift button held down realizes cloning. This operation provides a powerful way to create repetitive patterns in combination with the grouping technique explained below. It is implemented as a (continuous) dragging action. That is, once a user drags the selected source object more than certain distance, a cloned object is instantiated. The cloned object will continue to move in the scene, until the user places it on the target position by releasing the mouse.

Additionally, SESAME provides a simple navigation interface so that users can assess the 3D structure of the scene rapidly. Camera rotation, pan, and zoom are accessible through middle mouse button dragging, shift-dragging, and scrolling, respectively.

ENHANCED SUGGESTIVE 2D DRAWING INTERFACE

In SESAME, a user can draw lines, arcs, or free-form curves onto any planar surface. As the user draws 2D shapes in the perspective view, it is crucial to provide proper visual guides to compensate for the perspective distortion. For example, a rectangle drawn on a plane that is tilted relative to the viewer will look like a trapezoid. While the user draws a line (or an arc) in SESAME, the line (or arc) is visualized with the well-known rubber band technique. Additionally, a white circle

centered on the origin of the line is displayed. The shape of the perspective distorted circle provides a cue about the orientation of the base plane as well as the real length of the line relative to the rest of the scene (Figure 2). Such circles are also used in perceptual experiments to investigate the perception of surface orientation (see e.g. [13]).

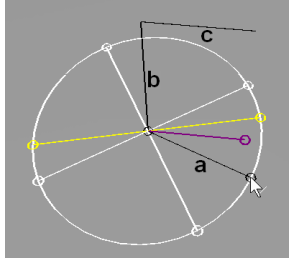


Figure 2. A circle is used to visualize the orientation of the current plane in SESAME. The user is currently drawing line *a*. Additionally, multiple colored guides are displayed based on other connected lines (*b* and *c*). The yellow line is perpendicular to *b*, the purple line is parallel to *c*, and the straight white lines are parallel to the coordinate axes.

Within this circle, three types of suggestive guides are displayed (see Figure 2): 1) lines that are parallel to the coordinate axes – as many objects are oriented along these, 2) lines that are perpendicular to another line that is connected to the start of the line that is being drawn, and 3) lines that are parallel to other lines. These suggestions help the user in creating common configurations. If the user moves the cursor close to the end of any guide, then the current line snaps to it. By displaying all mentioned options, the user is made aware of possible configurations and has the choice to select any of those guides.

When there are many curves drawn on the current plane, there can be too many guides (in particular type 3) and hence too many features to snap to, which may confuse the user. To prevent this, SESAME implements a new technique that prunes guides that are less likely to be relevant to the current drawing context – effectively showing only suggestions that are “reasonably” close to the cursor. Figure 3 shows a visual comparison of an interface that shows all (or too many) suggestions with our optimized display.

Compared to our suggestion engine, Pegasus [9] beautifies a 2D drawing with parallel, symmetric, and orthogonal configurations. However, the system displays all the possible beautification candidates, which can be often confusing to the users. Furthermore, the system does not deal with perspective distortion. Another system, Chateau [11] presented suggestive engines for 3D. There, possible scene configurations are displayed in thumbnails along the border of the screen, which takes screen real estate and also diverts users’ attention from the main design task.

In addition to guides for lines and arcs, all primitive drawing shapes can snap to any other existing shape. The end point of a line or arc can snap to any vertex or edge of another shape (e.g. a corner or side of a rectangle or an ellipse), or an important feature of them (e.g. the center of an ellipse). The

snapping distance increases as viewing distance increases. This feature allows users to work on various levels of detail, as discussed above in the guidelines.

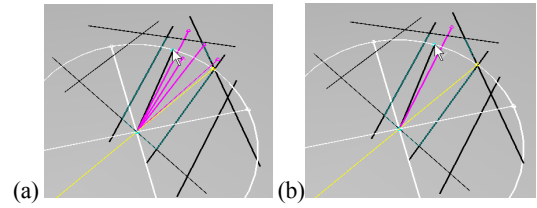


Figure 3. (a) Showing all suggestions, and (b) the optimized technique that shows only suggestions close to the current cursor position.

Identification of Closed Contours

Whenever the user adds a 2D shape, the system analyzes the current drawing and detects all closed contours created by the added shape. This is achieved by searching for connected components in a depth-first manner.

Users can also draw straight or curved segments, which cross other closed contours, effectively dividing them into multiple closed contours (Figure 4a). This feature was implemented to accommodate emergent shapes that can be created by multiple sketching strokes, as emergent shapes are one of the factors that facilitate creative thinking during the design process [8,27].

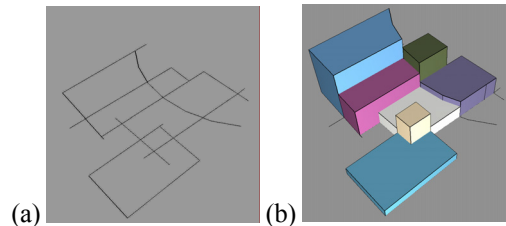


Figure 4. Intersecting contours and their extruded volumes.

EXTRUSION INTERFACE

Once a closed contour is detected by SESAME, the user can extrude it into the third dimension with a right mouse button drag operation starting inside the contour. Depending on the dragging direction, the user can access two different operations: either the creation of a new volume or the subtraction from an existing volume. If the user drags from the inside of the contour towards the outside of the volume, then an extruded volume is created and its extrusion height changes proportionally to the mouse movement (Figure 5a,b). If the drag direction is towards the inside of the volume, the extruded volume is used to sculpt the volume (Figure 5c,d). More precisely, the current extrusion height is the distance between the plane and the intersection point with the mouse ray along the plane normal during the drag operation. Positive height means that the user is dragging outwards from the plane, while negative height means that he/she is dragging inwards.

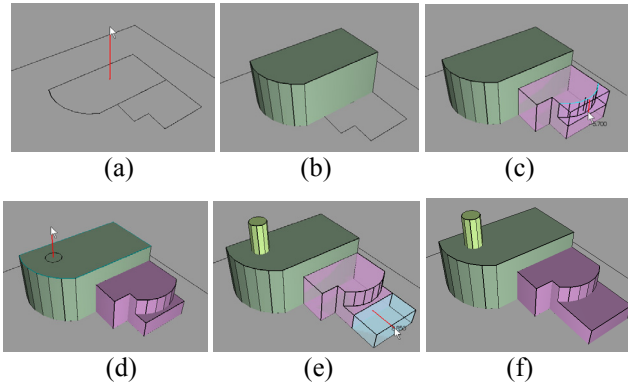


Figure 5. Sketching interface. (a-b) Dragging outwards from a closed contour creates a volume. (c-d) Drawing a contour on a face and dragging inwards sculpts the volume. (d-e) The user creates a new shape by dragging outward. (e-f) The user can also “stretch” a face by dragging the face directly.

(The red lines and mouse cursors were added to the images to clarify the concept. In the real system, the height of the extruded shape follows the mouse cursor motion directly.)

Dragging outwards results in two different behaviors, depending on whether the user is dragging inside a face or inside of a contour on top of a face. When the user drags a face of a 3D object without drawing a 2D contour on it, the system extrudes the face (Figure 5e,f), effectively resizing the volume in an orthogonal direction. In contrast, if he/she drags inside a closed 2D contour, the system creates a new volume (Figures 5a,b and d,e).

3D OBJECT MOTION

SESAME provides a novel way to smoothly and predictably move objects in a 3D scene. Unlike many other systems that use various widgets to implement this, we believe that the user should simply be able to grab any object and slide it across the scene to the desired position to visually assess the impact of a change. One of the main ideas behind this is that this will greatly facilitate exploration. As almost all objects in the real world are attached to other objects, we based the design of our interaction technique on the idea that, unless special actions are taken, objects should *always* stay connected with another part of the scene. This conforms better to the way *most* people think about the real world (i.e. people who do not have a background in computer graphics). Based on the same kind of arguments we also believe that objects should not interpenetrate other objects, again, unless special actions are taken.

To support this, objects follow the mouse cursor closely while they slide objects on any surface in the scene. The most common approach for this is to compute the object position based on the surface that is first hit by the ray from the eye through the mouse position along the viewing direction. Object Associations [2] and Mive [25] use this approach along with predefined semantic information that describes the expected object behavior. The main limitation of this is that users only can create a scene based on a library of predefined objects. Another, more serious problem

is that motion solely based on the mouse cursor position results in unpredictable and jumpy object motion. In particular, a small mouse cursor movement on the screen can result in a huge movement of an object in 3D.

In informal observations of users moving objects in a 3D system, we noticed that users seem to consider the entire area of the visual overlap of a foreground object with the (potentially complex) background. This observation is further supported by research into vision in primates, in that the perceptive field for an object that is being held in the hand covers the whole object [16]. Based on this, we select the movement plane that is foremost to the viewer in the region that is occluded by the moving object. The implementation of this idea results in visually smooth and predictable movement of an object across a scene [18]. It is interesting to note that this technique can exploit graphics hardware to perform all computations (including collision detection) in real time even for very complex scenes. More details and an evaluation comparing it with axis-widgets are presented in [18]. The evaluation showed that this new technique is significantly more efficient for novice users and showed that our technique conforms very well to users’ expectation about the position of objects relative to a scene.

Finally, SESAME allows objects to move freely in 3D space, when an object is seen over the background (i.e. there is no visual overlay with other objects). In this case, the movement surface is chosen to be the axis-aligned plane that is most orthogonal to the viewing direction. This provides users with the option to quickly create “floating” objects, if necessary.

GROUP SELECTION

In the real world, objects that are on top of another one generally follow the motion of the object underneath. A small user study with naïve users showed that this type of gravitational hierarchical grouping has the potential to make 3D group selection significantly more efficient [20]. In this test, we compared conventional rectangular selection with a modified rectangular selection scheme, which is based on the concept of a gravitational hierarchy. In other words, any objects on top of an object inside the rectangular selection region are also added to the selection. For example, if the user selects the two desks in the Figure 6, then all the objects on top of them are also selected into the group. We observed that this modified scheme outperformed the conventional rectangular selection scheme significantly.

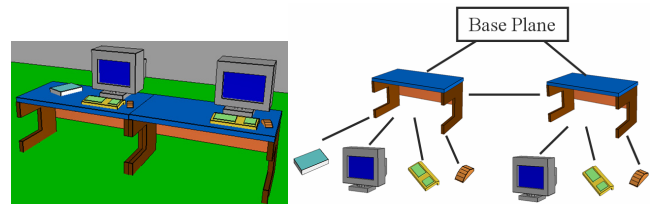


Figure 6. (a) Example scene, (b) corresponding contact graph

Based on the results of a user study [20] we also provide another group selection scheme to facilitate grouping of connected components via repeated clicking. The first click on an object selects the object itself and all other objects on top of it (gravitational hierarchy), the second click on the object selects all connected objects (connectivity grouping), and the third click on an object selects only that object. The fourth click loops back to the first selection. This is analogous to the word and paragraph selection scheme in MS Word. To implement the selection of connected objects, the system dynamically builds a contact graph starting from the base plane and updates it whenever an object is moved. Figure 6 illustrates this graph, which represents both the gravitational hierarchy as well as the contact relationship between sibling nodes. Together, these techniques make restructuring and combinations easier.

COMPARISON WITH 3D STUDIO MAX

To evaluate SESAME, we performed a study to compare it with a conventional CAD system. The main objectives of the experiments reported in this section are to analyze whether designers can produce a reasonably complex design in a given amount of time, whether they can become creative with a new system, and whether they can perform necessary operations during a given task. We consider a design to be reasonably complex if it fulfills a set of constraints that was specified in the design assignment. We believe that SESAME can be considered to support creativity if designers can experiment with different forms during the design process. For this, we analyzed video data recordings of the experiments to check if SESAME supports all necessary operations.

3D Studio Max (3DS Max) was chosen as a representative conventional CAD system. The main reasons for the choice of 3D Studio Max were: 1) it supports full 3D modeling, 2) it has one of the largest user groups, 3) it *is used* in conceptual design in practice, and 4) it provides an extensive number of operations that enable the user to create support a broad range of 3D shapes. We assume that trained 3D Studio Max users will be able to produce a model in a reasonable amount of time. Hence, we are able to use it as a reference to investigate the design efficiency of SESAME, as well as to assess how well users activate desired operations in a current CAD system.

Task

The task was chosen from a set of urban design problems. In this task, participants were asked to undertake a preliminary building massing and form study typical of that performed at the start of the design process. The goal was to produce possible design solution(s) for commercial and residential space on a property owned by a charitable organization as depicted in Figure 7.

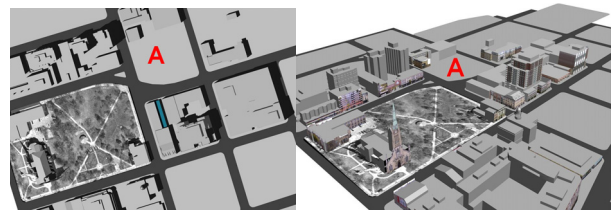


Figure 7. The design task. (a) Top view and (b) oblique view of a city. 'A' indicates the site of the new building.

Subjects

Six participants were recruited from the set of Master's students in Architecture and Landscape Architecture at the University of Toronto (one female and five males, age 25-35). Participants' experience in architecture or landscape design ranged from one year to more than ten years including academic and professional experience (avg. 6 years). They rated their skill with 3DS Max between average to excellent. More precisely, four out of six subjects stated that they could use 3DS Max well enough to perform all (or at least most) operations required for their profession. Two people stated that they could only perform basic operations. Only one participant had beginner knowledge of SESAME, but the other participants had never seen SESAME beforehand.

Procedure

The test session was composed of an introduction session, a SESAME training session, two task sessions, and a qualitative evaluation session. After the introduction, the written description of the design problem was presented to participants. The time for reading the description was not included in the task time. The order of the two systems was counter-balanced to address potential learning effects. Immediately before the design session with SESAME, the experimenter trained participants with SESAME for thirty minutes. Since we set up the design task to be rapid prototyping for the conceptual design stage and because it is subjective to judge whether a design is finished or not, each task session was limited to thirty minutes. However, participants had the choice to stop when they felt that their design was finished. After the task sessions, participants filled out a questionnaire and discussed the system with the experimenter.

Results

Design Quality

To evaluate the results for each participant quality, creativity, practicality, and overall quality were rated. These ratings were performed by one of the authors of this paper, who is the leader of a design studio and has many years of experience in urban design. Ratings ranged from 0 to 10. Creativity was measured to judge if a design was inventive and expressive. The practicality measure aimed to judge if a design was buildable and fulfilled the design requirements. The overall rating provided a balanced judgment between creative exploration and reality.

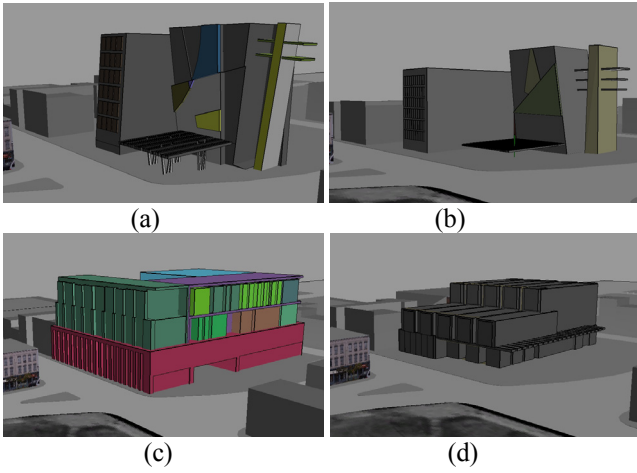


Figure 8. Scene example from User 1 from (a) SESAME, (b) 3DS Max, User 4 from (c) SESAME (d) 3DS Max

Several example results are depicted in Figure 8. Results from SESAME sessions were rated significantly higher in terms of creativity and overall quality. Table 2 shows the ratings per user.

| | | #1 | #2 | #3 | #4 | #5 | #6 | Avg. | p^* |
|--------------|---------|----|----|----|----|----|----|------|--------|
| Creativity | SESAME | 9 | 2 | 3 | 8 | 10 | 4 | 6 | 0.03** |
| | 3DS Max | 7 | 2 | 2 | 8 | 8 | 2 | 4.83 | |
| Practicality | SESAME | 7 | 6 | 6 | 6 | 6 | 5 | 6 | 0.74 |
| | 3DS Max | 7 | 5 | 5 | 6 | 8 | 4 | 5.83 | |
| Overall | SESAME | 8 | 4 | 4 | 7 | 8 | 5 | 6 | 0.04** |
| | 3DS Max | 6 | 3 | 3 | 7 | 8 | 3 | 5 | |

* Probability level resulted for paired t-Test

** Term significant at $\alpha=0.05$

Table 2. Ranking of designs

Analysis of Tasks

To examine the task characteristics further, we analyzed the individual design operations of each user. The goal of this analysis was to evaluate if a participant could explore design problems well enough and to determine if SESAME supports efficient modeling.

The characteristics of the design tasks were examined by decomposing them into unit modeling operations as shown in Table 3. Due to space limitations, this is only an abbreviated version of the full table presented in [19]. The modeling operations were enumerated by observing the videotaped user sessions several times. In this scheme, we also counted “failed” operations to check if designers could perform their desired operation well enough. We determined an operation to have failed whenever the user encountered unexpected results due to user interface problems.

Table 4 shows the total number of operations. The average number of operations per user for SESAME is 75.5, for 3D Studio Max is 52.5, and these values are significantly different ($t_5=2.78$, $p<0.05$).

| Category | Code | Operation |
|---------------|------|--|
| Navigation | N | Navigation for better view of the model, assessment of a scene, or walk-through. |
| 2D Drawing | D | 2D drawing activities, e.g. drawing, selecting, or editing 2D. |
| 3D Creation | C | Add 3D primitives, extrude 2D contours, or clone existing ones. |
| Modification | O | Sculpt or extrude to change shape. |
| Manipulation | A | Resize, rotate, move, or remove. |
| Material | T | Apply or change texture or color. |
| Miscellaneous | I | Any activities that are not directly related to changing the geometry. |

Table 3: Categories of modeling operation

The relatively high number of failures for draw operations in SESAME (28) is due to an implementation problem that erases previously drawn 2D contours whenever the user clicks on a new 3D face. Hence, when the user clicked near a 3D edge, sometimes previously drawn contours were erased. To account for effect of each system correctly, all further analysis was conducted only on the successful operations.

| | N | D | C | O | A | T | I | Total |
|---------|----|-----|----|----|----|----|----|-------|
| SESAME | 75 | 172 | 76 | 68 | 61 | 24 | 13 | 489 |
| | 0 | 28 | 3 | 2 | 5 | 0 | 0 | 38 |
| 3DS Max | 57 | 39 | 84 | 6 | 84 | 23 | 15 | 308 |
| | 1 | 2 | 3 | 3 | 0 | 0 | 10 | 19 |

Table 4. Total number of successful operations across users (upper row per system) and failed operations (lower row).

Since each user conducted a different number of operations, we computed the percentage of each type of operation relative to the total number of operations (shown in Figure 9).

It is also illustrative to examine the difference in the patterns of operations in the two systems. In general, users performed more 2D drawing (D, 31.79%) and modification operations (O, 14.57%) in SESAME. However, they performed more creation (C, 25.71%) and manipulation operations (A, 26.67%) in 3DS Max. In SESAME, a user must first draw a closed contour and then can extrude it to create a volume or carve into an existing volume. In addition, adding primitive shapes is not as flexible as in 3DS Max, as SESAME does not directly allow specifying the desired size of a primitive during its creation. Consequently, users drew (D) more contours to create (C) or to modify (O) objects. For example, user #4 (Figure 8c) performed 61 drawing operations out of 141 total operations. With this, the user was able to express the detailed facade of the building using carving and extrusion of drawn contours.

Modification of shapes (e.g. subtraction) is generally considered to be an advanced feature in 3DS Max. Only one user changed the form of an existing shape with such an operation (User #1, 5 times, Figure 8 b). 3DS Max users relied mainly on their ability to create new volumes by extruding closed contours or adding primitives and then rearranging the created objects. For example, user #2 created three separate volumes in 3DS Max, instead of creating one volume and carving it to create the desired object as in SESAME. User #4

created completely different models in each system (Figure 8 c,d). In 3DS Max, the user created a model composed of many cloned boxes, while in SESAME, the user created a model with many carved details.

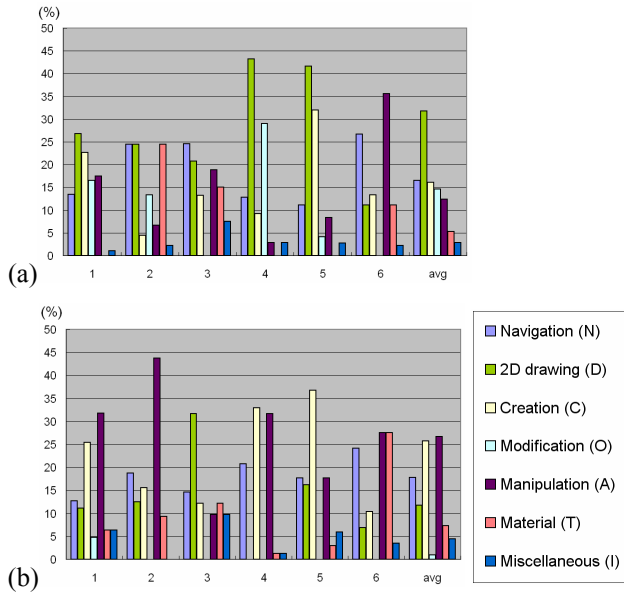


Figure 9. Percentage of operations by user (a) with SESAME, and (b) with 3DS Max

Users' Opinion

In general, participants stated that SESAME is well suited for the exploration of design solutions during a conceptual design session. They pointed out that the rapid activation of basic functions, such as extrusion, subtraction, and easy navigation, are the most useful features of the system. One user added that it is friendly for novice users and it may be useful for educational purposes.

When asked to compare SESAME with 3DS Max, users mentioned that SESAME has a shorter learning curve, is more intuitive, and gives more freedom to design artifacts. They stated also that it is a good system to create initial shapes before more elaborate work, saving time in the conceptual stage. Further comments were that the system would be useful to examine the relationship among building elements and explore various compositions of forms. On the other hand the participants stated that 3DS Max is a better tool for a final product, as it provides greater precision with numeric inputs, and has more functions to build an extensive range of objects.

As for problems with SESAME, participants commented that the system might not be able to support users if they needed to elaborate the model for more detailed development. Also, participants complained that there were no dimensions, no grids, and no numeric input facility. Also, they found that object movement is not as “easy” as in 3DS Max, which meant that they could not always position objects in the exact place they intended. Since our users had already extensive experience in 3DS Max and its user interface for moving

objects, we recognize this comment as typical for an expert user group that needs control of every parameter of a design.

Discussion

The user evaluation demonstrates that SESAME was preferred to 3DS Max for conceptual design sessions, even though users were much more familiar with 3DS Max. Using SESAME, users could try more design operations and were more creative. This is due to the fact that SESAME has more flexible drawing tools and that they are directly related to creation and modification operations. The detailed observations are:

First, SESAME had shorter mode switching times and users spent less time in menus. The analysis of the data for 3DS Max revealed relatively long menu searches and mode switching times before users actually started an operation. This significantly lowered the total number of operations people could perform during each task session. SESAME does not need to rely on menus, since it provides only a limited set of operations while 3DS Max has to provide an extensive number of modeling operations. Interestingly, even in 3DS Max, participants used almost exclusively the readily available operations to produce the initial design. Hence, we conjecture that the small set of operations available in SESAME did not hamper the design task. Conversely, this underlines that it is important to avoid user interface overhead in a system aimed at conceptual design, as stated in the guidelines.

Second, the flexibility of the 2D drawing interface helped users to be more creative in SESAME than in 3DS Max. SESAME provides a number of basic drawing tools to draw curves, but also analyzes line drawings to automatically detect newly created closed contours. Consequently, even though there were small implementation issues around the drawing tools, people made extensive use of the drawing operations. Some users sketched randomly crossing lines, resulting in interesting contours, and then used the contours to carve or extrude 3D shapes. This kind of activity was something very difficult to do in 3DS Max, where users even drew intersecting lines first and then traced closed loops *over* them to create contours for extrusion. Given that creativity often comes from playful, opportunistic exploration, we argue that SESAME follows the “easy creation” and “tolerance to ambiguity and incompleteness” guidelines much better.

Third, the participants could effectively use the new features provided by SESAME, such as suggestive guidelines, snapping distance proportional to the viewing distance, and the freeform drawing tool. These facilities were based on the guidelines we mention above and we observed that those facilities worked naturally and actually helped users to produce designs with an interesting level of complexity within the short design session.

Forth, subtraction of volumes in SESAME is much easier than in 3DS Max. Subtraction in 3DS Max is considered to be an advanced operation. Hence, with this system, people

could not just casually create an object and elaborate on it. Rather, they needed to have a clear idea from the start what they wanted to design and then create separate parts to compose the desired form.

Lastly, the manipulation schemes such as object motion and gravitational grouping were not as actively used as we previously expected. One possible reason is that the building area was relatively small and did not require active composition of a scene. Also, the other operations, drawing and extrusion/sculpting operations seemed to satisfy the participants' need for creation and modification in this task. However, this may work out different if the scale of the task were larger, e.g. town/park planning.

CONCLUSION AND FUTURE WORK

This paper presented a set of guidelines for 3D conceptual design systems and a new conceptual design system, SESAME based on these. Then, we explained how the interaction schemes of the system are based on our understanding of the task of 3D conceptual design sessions, and then discussed details of the interaction techniques. Finally, we compared the system with 3D Studio Max in a study. The results show that SESAME supports the early design phase efficiently and effectively via the simple 2D drawing interface, common modification operations – extrusion and sculpting, as well novel movement and grouping techniques.

For future work, we are interested in creating even more flexible sketching interfaces and systems that can handle a more extensive range of 3D shapes. The challenge here is to keep the interface straightforward enough so that even novice can quickly create 3D scenes.

REFERENCES

- Bloomenthal, M. *et al.* Sketch-N-Make: Automated machining of CAD sketches. *Proceedings of ASME '98*, (1998) 1-11.
- Bukowski, R., Séquin, C. Object associations: a simple and practical approach to virtual 3D manipulation, *Symposium on Interactive 3D Graphics '95*, (1995) 131-138.
- Chambers, D. and Reisberg, D. Can Mental Images be Ambiguous? *Journal of Experimental Psychology: Human Perception and Performance* (1985) 11: 317-328.
- Cross, N. *Engineering design methods: Strategies for product design*. Wiley, 3rd Ed, 2000.
- Cross, N. Natural intelligence in design. *Design Studies*, (1999) 20: 25-39.
- Deisinger, J. *et al.*, Towards immersive modeling challenges recommendations, *EGVE '00*.
- Galyean, T., Hughes, J. Sculpting: An interactive volumetric modeling technique, *SIGGRAPH '91* (1991) 267-274.
- Gross, M.D. Emergence in a recognition based drawing interface. *Proceedings of the 2nd International Conference on Visual and Spatial Reasoning* 2001.
- Igarashi, T. *et al.* Pegasus: a drawing system for rapid geometric design, *CHI '98*. 105-114 (1998).
- Igarashi, T., Matsuoka, S. and Tanaka, H. Teddy: A sketching interface for 3D freeform design. *SIGGRAPH '99*, (1999) 409-41.
- Igarashi, T., Hughes, J.F. A Suggestive Interface for 3D Drawing, *UIST '01* (2001) 137-181.
- Jung, T., Gross, M.D. and Do, E. Y.-L. Sketching annotations in a 3D Web environment, *CHI '02*, (2002) 618-619.
- Koenderink, J., *et al.* Surface Perception in Pictures, *Perception*, 1992, 22: 487-496.
- Lipson, H. and Shpitalni, M. Optimization Based Reconstruction of a 3D Object From a Single Freehand Line Drawing. *Journal of Computer Aided Design* (1996) 28 (8): 651-663.
- Markosian, L. *et al.* Real-Time Nonphotorealistic Rendering, *Computer Graphics*, 1997.
- Obayashi, S. *et al.* Functional brain mapping of monkey tool use, *NeuroImage*, 2001, 14:853-861.
- Oh, J.-Y., Stuerzlinger, W. A system for desktop conceptual 3D design, *Virtual Reality '04* (2004) 7: 198-211.
- Oh, J.-Y., Stuerzlinger, W. Moving objects with 2D input devices in CAD Systems and Desktop Virtual Environments, *Graphics Interface '05* (2005) 141-149.
- Oh, J.-Y. *Desktop 3D conceptual design systems*, Ph.D Thesis, 2005. York University.
- J.-Y. Oh, W. Stuerzlinger, D. Dadgari, Group Selection Techniques for Efficient 3D Modeling, *IEEE Symposium on 3D User Interfaces '06* (2006) 95-102.
- Purcell, A.T. and Gero, J.S. Drawings and the design process. *Design Studies* (1998). 19: 389-430.
- Schon, D. *The Reflective Practitioner: How Professionals Think in Action*, Basic Book, 1983.
- Schumann, J. *et al.* Assessing the effect of non-photorealistic rendered images in CAD, *CHI '96* (1996) 35-41.
- Schweikardt, E. and Gross, M. 1998. Digital Clay: Deriving digital models from freehand sketches. *Proceedings of ACADIA '98* (1998) 202-211.
- Smith, G. *et al.*, 3D Scene Manipulation with 2D Devices and Constraints, *Graphics Interface '01* (2001) 135-142.
- Tano, S. *et al.* Godzilla: Seamless 2D and 3D sketch environment for reflective and creative design work, *INTERACT '03* (2003) 311-318.
- Verstijnen, I.M. and Hennessey, J.M. Sketching and creative discovery. *Design Studies* (1998) 19: 519-546.
- Vries, B., Achten, H. DDDoolz: designing with modular masses. *Design Studies* (2002) 23: 515-531.
- Varley P., Martin, R. R., Suzuki, H. Can Machines Interpret Line Drawings? *Sketch-Based Interfaces and Modelling Eurographics Symposium Proceedings '04* (2004) 107-116.
- Yu, B. Recognition of freehand sketches using mean shift. *Intelligent User Interfaces '03* (2003) 204-210.
- Zelevnik, R.C., Herndon, K.P. and Hughes, J. F. SKETCH: An interface for sketching 3D scenes. *SIGGRAPH '96* (1996) 163-170.