Surface Drawing: Creating Organic 3D Shapes with the Hand and Tangible Tools

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Abstract

Surface Drawing is a system for creating organic 3D shapes in a manner which supports the needs and interests of artists. This medium facilitates the early stages of creative design which many 3D modeling programs neglect. Much like traditional media such as line drawing and painting, Surface Drawing lets users construct shapes through *repeated marking*. In our case, the hand is used to mark 3D space in a semi-immersive virtual environment. The interface is completed with tangible tools to edit and manipulate models. We introduce the use of tongs to move and scale 3D shapes and demonstrate a magnet tool which is comfortably held without restricting hand motion. We evaluated our system through collaboration with artists and designers, exhibition before hundreds of users, our own extensive exploration of the medium, and an informal user study. Response was especially positive from users with an artistic background.

Keywords: artistic shape creation, 3D modeling, tangible user interface, hand-based interface, semi-immersive environment, repeated marking, fine art, design prototyping

INTRODUCTION

Many users, from architects and industrial designers to fine artists and modelers in the entertainment industry are focused on the task of creating 3D shapes. Popular 3D modeling systems require artists to create shapes out of B-spline patches, using mathematical controls such as curves and control points. We observe that many artists have difficulty conceptualizing with this tool,[1] and begin the modeling process with pencil sketches. Later, when their ideas are developed, they turn to 3D modeling software. This dual-interface system uses the traditional sketchpad for artistic expression and the computer for specification, not creation.

Our goal is to integrate these two processes and develop a way of creating three-dimensional shapes that is as free-flowing, organic, and natural as traditional artistic processes such as line drawing and painting. Moreover, we are interested in allowing this expression in the three-dimensional space intrinsic to these models, extending sketching in a manner that is uniquely appropriate to immersive interface hardware.

We have developed a medium, which we call *Surface Drawing*, that facilitates conceptual exploration by giving artists an emotional relationship with their tools and a physical understanding of their workspace. This is accomplished by bringing marks, already popular in traditional 2D line drawing, to 3D space. The path of the hand in space is directly realized as geometry, in a manner analogous to the path of the pencil on a page making a line. Much like its 2D counterpart, our system is immediately physically understood, and the level of control grows with a user's expertise and practice. Complex organic shapes come quite easily while a shape like a perfect sphere is difficult to construct. Thus the strengths of this tool are markedly distinct from those of traditional 3D modeling systems such as Maya. We are not focused on creating numerically precise or perfectly smooth models; we place emphasis on expression and communication.

The interface uses the semi-immersive virtual environment of the Responsive Workbench [13]. As illustrated in Figure 1, all viewing and interactions occur in the user's physical space. This 3D interaction aids the user's spatial understanding of the model. In addition to the hand, a number of tangible tools complete the interface: tongs that move and scale the model, a squeezable eraser, and a magnet tool which deforms a shape. The magnet tool is specially designed to be held lightly without restricting the ability of the hand to bend. Using these few tools to repeatedly mark 3D space, complex shapes can be constructed. Structure and process are left to the artist's own choosing within this paradigm.

Our system offers a number of contributions to the field of human-computer interface. First, we introduce the use of the hand to make strokes in space and the thumb as a built-in toggle switch for the hand. Secondly, we investigate tangible tools in semi-immersive environments. We develop tongs that move objects in space and a magnet tool which is comfortably held without limiting the hand's flexibility.

Figure 1: *Hand motions create shapes which float above the Responsive Workbench.*

[1] Our observation is based on extensive interaction and collaboration with industrial designers at Designworks/USA and with art students at the Art Center College of Design over a period of several years.

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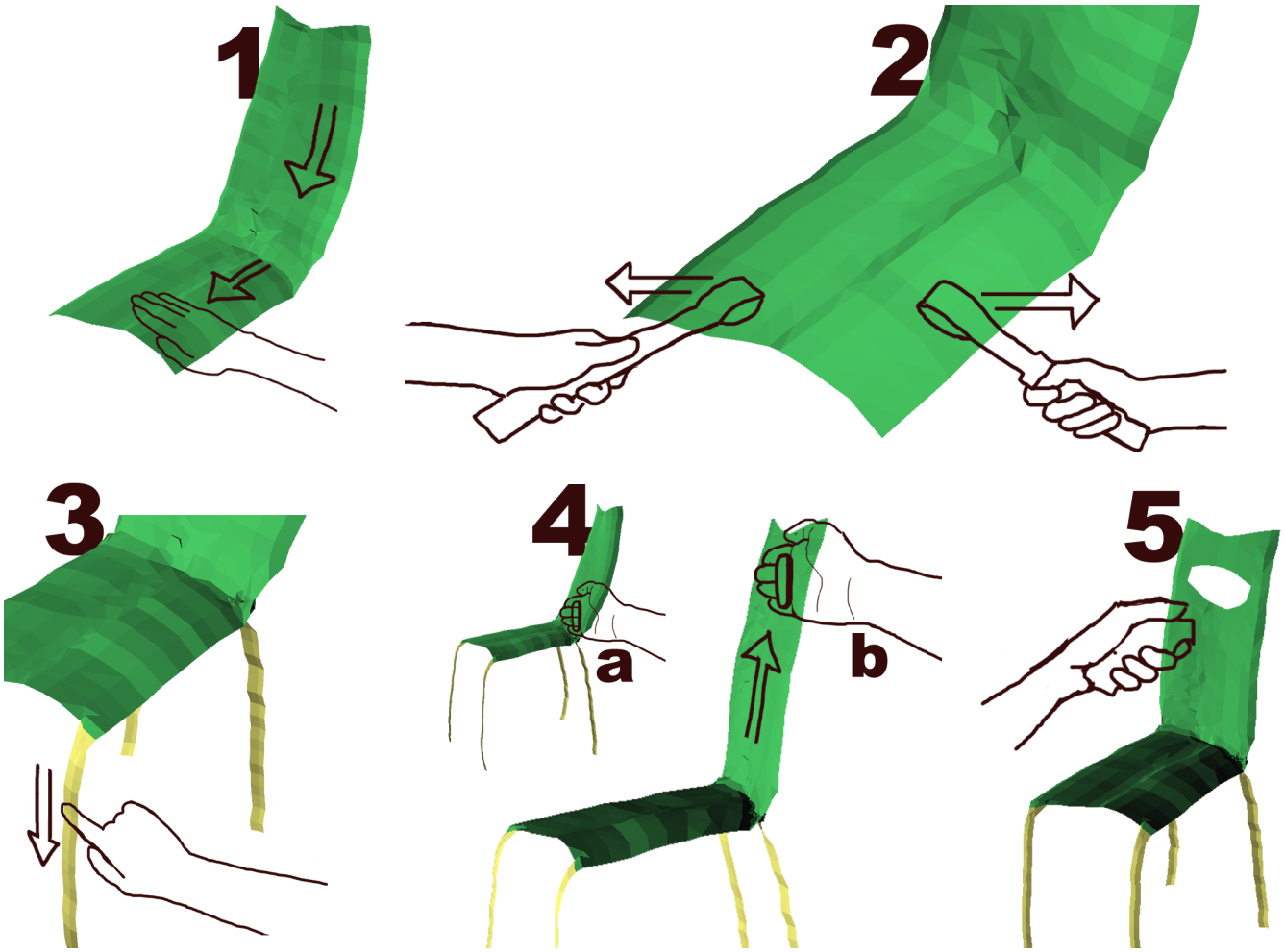

Figure 2: *Drawing a chair illustrates all of the features of our interface: (1) A hand gesture defines the body of the chair. (2) The tongs are used to scale the model. (3) The fingertip is used to draw the thin chair legs. (4) The magnet slightly bends the chair's back. (5) A carrying handle is added with the eraser.*

Thirdly, Surface Drawing brings to the forefront the importance of marks in artistic creation. The free marking of 3D space is not possible in the physical world; we thus take particular advantage of a gravity-free semi-immersive environment. We demonstrate a comprehensive system that is easy to learn, attractive to artists, and capable of generating a wide range of sophisticated shapes. Our claims are based on the observation of the reactions of approx. 1000 novice users through on-site demonstrations, exhibitions, and an informal user study. Additionally we have analyzed the long-term use of the medium through the extensive experience of one of the authors, the application of Surface Drawing to fine art practice, and our collaboration with an industrial design firm.

RELATED WORK

The most popular way to create 3D shapes with computers is with NURBS-based modelers such as Maya or 3D Studio Max. These tools have sophisticated B-spline structures which the user can manipulate through control vertices and other high-level handles. The precision of these schemes is important in engineering applications, but the accompanying complexity ultimately interferes with artistic expression. After the initial control structure is specified, it becomes cumbersome to add, remove, or alter large features. In Surface Drawing users do not negotiate a complex internal structure but rather directly create geometry with a structure that is dependent on their choice of process. New products such as Maya's Artisan allow some parts of the design process to be free from complex structure. Although similar to Surface Drawing, this manipulation is accessed through a 2D interface, ultimately lacking the immersiveness and freedom of expression which we aim to foster.

Other 2D interfaces such as Teddy [11] and Sketch [19] translate 2D gestures into 3D geometric manipulations. These tools fill the gap between 2D and 3D by making assumptions about the types of shapes being created. In contrast Surface Drawing's recording of gesture provides a direct and immediate control of shape.

Traditional clay sculpture, in which a volumetric lump is deformed by the hands or with tools, is an ancient form of creation that much research [7, 18] aims to recreate computationally. Surface Drawing is *not* an emulation of clay. Our medium works with surface, not volume. Users start with blank space instead of a large mass. Basic shapes are generated by direct creation instead of carving. Thus Surface Drawing facilitates a type of doodling and free creation which is difficult with clay.

Early work in 3D shape creation using tracked tools was ex-

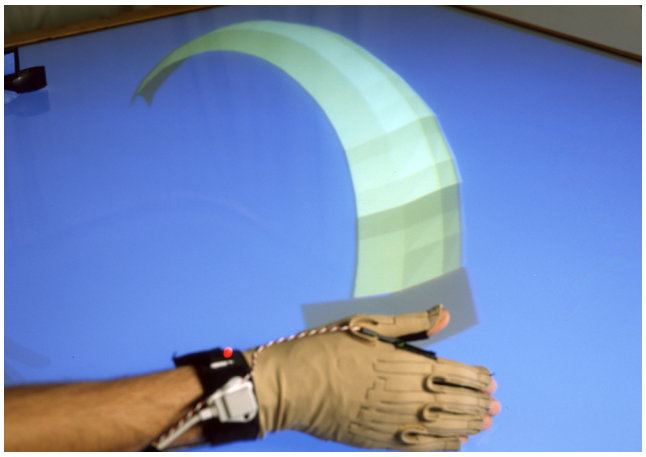

Figure 3: *The path of the hand defines a stroke. Closing the thumb starts a stroke; opening the thumb completes it. The contact sensors can be seen as black patches on the inside surface of the thumb and the base of the index finger.*

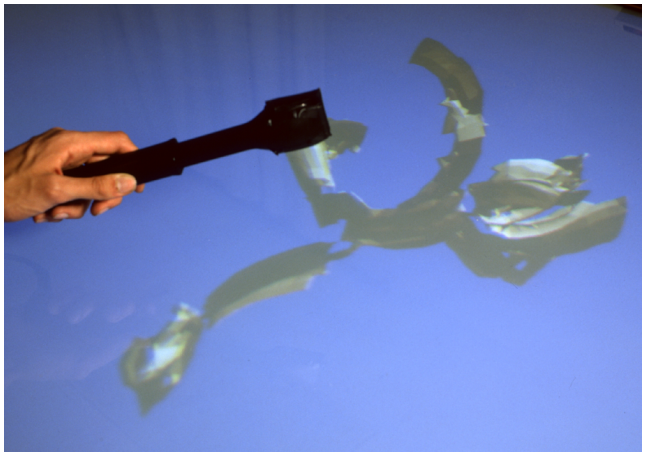

Figure 4: *A pair of kitchen tongs moves a drawing (two pairs of tongs are used to scale a model).*

plored in 3-Draw [14]. Their work allows curves to be drawn in 3D space using a tracked stylus. The results were viewed on a standard monitor. 3-Draw focused on engineering design, allowing networks of curves with constraints. Deering followed up on this work with HoloSketch [5], which allows the drawing of tubes of toothpaste by moving a tracked stylus through 3D space. A standard monitor and a pair of head-tracked stereoscopic shutter glasses are used for display. HoloSketch's interface includes a 3D menu system for selecting the cross-section of the wand. Surface Drawing builds upon these methods, providing greater model complexity (by using the hand instead of a wand), a simpler interface, and a more immersive display.

Our interface uses ideas first developed in previous research in tangible user interfaces including Bricks [6], which adds physical handles to 2D widgets; Hinckley's work [10] on surgical simulation with physical props; the metaDESK [17], a general-purpose 2D space which is controlled with tangible tools; and Iwai's *Composition on the Table* [12] which graphically reacts to physical knobs. These interfaces all involve 2D, non-immersive environments (although Hinckley's task is 3D). Surface Drawing explores the interaction of tangible tools with a 3D, augmented-reality space.

SYSTEM OVERVIEW

The basis of the interactive environment is the Responsive Workbench [13]. The artist's hand moves in free space above the table, defining a surface strip, or *stroke*. Strokes are combined to form a three-dimensional *drawing*. This drawing can be manipulated by a number of tangible tools: tongs (Figure 4) allow the user to move the drawing around in space, an eraser tool (Figure 5) removes geometry, and a magnet tool (Figure 6) produces small deformations. An example of these tools being used together to create a simple chair is shown Figure 2.

Drawing As shown in Figure 3, a stroke is the geometric realization of the path of the hand in space. Creating a stroke in 3D space is similar to drawing a line on 2D paper.

This extension of line-creation in 2D to surface-creation in 3D motivates our work, and is the reason for calling it Surface Drawing. Bending the hand changes the cross-section of this stroke. In two-dimensional drawing strokes are started by placing a marker on a surface, but there is no such analogy in three dimensions. Hence, strokes are begun by sensing when the user's thumb closes.

In two-dimensional drawing it is rather easy to make lines touch. This is more difficult in Surface Drawing due to both the complexity of three-dimensional stroke boundaries and the noticeable error (especially latency) of the tracker system. To lower the precision required of the user, we automatically merge strokes onto the drawing in a smooth, continuous fashion. We discuss our algorithm for merging strokes in an accompanying technical report [15].

Thinner strokes are made by pointing with the finger and drawing. In this mode, geometry emanates from the fingertip instead of the palm.

Moving, Scaling, Erasing It is rather difficult for a user to move around the Responsive Workbench, due to the large size of the table and the constraint of the wired glasses and glove. We thus provide tongs that enable artists to move a shape and access all regions of it. Structurally, the tool consists of a pair of ordinary kitchen tongs outfitted with magnetic trackers and sensors to detect when they are closed. When a pair of tongs is closed, the current drawing transforms with it, mimicking the traditional function of tongs. A second pair of tongs has the same action. Using both pairs in concert scales an object: closing them and moving them apart increases the model's size,[2] in the fashion of Tangible Geospaces' building anchors [17].

Once a drawing has been made, portions of it can be removed with an eraser. The eraser is made of soft molded silicone. The shape is designed to fit naturally and comfortably within the hand, as shown in Figure 5. The eraser has a 6DOF magnetic tracker inside of it and a pressure sensor that is activated by the thumb. Its small spherical region, represented by an avatar, is erased when this tool is squeezed.

Magnet Drawing Small modifications are useful when users want to refine their shapes with subtle details. While erasing and redrawing is a viable option in some circum-

[2]The two tongs can also be used to rotate and move a model, although individual tong rotations can be in conflict. We thus ignore individual tong rotation when moving objects with two tongs.

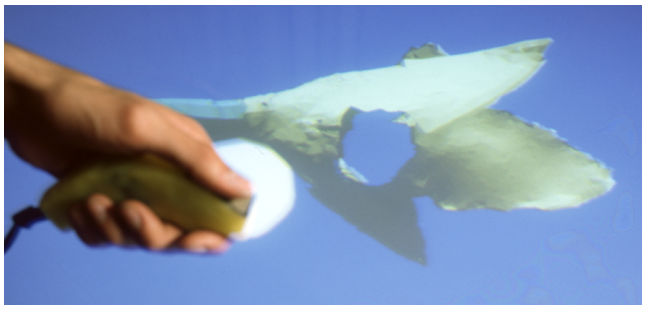

Figure 5: *The eraser removes a small spherical volume from a flower model. This tool, made of soft silicone, fits ergonomically in the hand. A pressure switch is embedded in the tool, just below the thumb in the above photograph.*

Figure 6: *The magnet is used to deform geometry slightly. This stroke was flat before the magnet added a slight bend to it. The magnet tool itself can be seen poking between the fingers (and in its nest in Fig. 7). This prop can be easily held without restricting the bend of the hand.*

stances[3], the ability to make slight modifications is often useful.

We devised a magnet tool which, when held, changes the meaning of a drawing action to that of altering existing geometry. We view this as a method of 'overdrawing,' in the spirit of Cohen's work on overdrawing screen-space curves [3]. Waving the magnet near a region of a drawing pulls the drawing closer to the magnet (see Figure 6). The effects of this tool are somewhat akin to pushing and pulling a surface sculpturally, although the semantics are those of waving instead of pushing, making the motion close to that of a repeated drawing.

We created a small prop, shown at rest in Figure 7. The magnet, like the eraser, is made of soft silicone and it is quite lightweight. Friction allows this prop to stay in the hand without being squeezed. This shape does not interrupt the bending of the fingers and hence does not constrain the motion of the artist.

INTERFACE PHILOSOPHY

The path of the hand in space forms a mark. Marks are characterized by Buxton [2] as continuous streams of uninterpreted coordinates in space representing the user's movement. In Surface Drawing, a series of these marks form a shape. This process of *repeated marking* is the foundation of our interface. The eraser makes marks of negative space, and the magnet marks the surface with small deformations. In our immersive environment the marking tool coincides physically with the mark. The sense of immediacy is thus heightened, and the languages of body and shape are unified. This is a form of direct manipulation [16], in which the body physically mimics the change in model state. This proprioception adds intimacy.

Surface Drawing presents users with a number of tools that affect this surface locally. Global control is not represented in the interface but is rather a decision of the artist. The methodology of creation can thus be approached in ways that were not envisioned by the interface designer. Moreover, this philosophy enables Surface Drawing to support a wide variety of modeling approaches *without* a complex interface to manage this complex structure. For example, a shape like the head in Figure 8*l* is drawn by sketching a head and slowly adding detail; the flower in Figure 8*i* is created by tracing the borders of the petals and filling in the centers; a simple shape like the chair in Figure 2 is created in one pass; figures such as those in Figures 8*h* are created by mimicking the gesture of a pose; and the figures in Figure 8*a* are created by tracing the bodies of human subjects. There is little interface to be learned, instead the artist learns to control the surface. This approach yields a more intimate artistic medium; learning Surface Drawing involves gaining control of one's body and understanding 3D space. Like other rich media, Surface Drawing takes a minute to learn but a lifetime to master.

Surface Drawing forges a deep connection between the artist's body and the shapes that are created. The hand, as a body part, is inherently natural to control. With a large number of degrees of freedom, the hand makes sophisticated marks with ease. To use Gorbet's terminology [8], Surface Drawing *couples* physical motion with the creation and manipulation of geometry. The medium is an extension of the body, understood through physical memory and proprioception. The state configuration is not remembered or accessed linguistically but rather part of the physical state of the world.

DESIGN ISSUES

Display System: The Responsive Workbench Surface Drawing relies upon a one-to-one correspondence between motion in 3D space and resulting geometry. Thus it is crucial that Surface Drawing be implemented in an immersive or semi-immersive VR-style environment. The Responsive Workbench's head-tracking and stereoscopic display present the illusion that objects are floating in space. The table is a familiar workspace metaphor which also serves as a convenient storage location for physical tools. Fully immersive environments such as the CAVE [4] and head-mounted displays such as the n-Vision Datavisor are too virtual—fully immersing the artist in a space instead of directing focus on one object. These fully immersive systems also inhibit the merging of the physical and the virtual that we seek. Surface Drawing is less of a virtual reality experience and more of a 3D computing environment.

The usefulness of adding active haptic feedback to the system is unclear. In line drawing, artists do not feel their strokes after they are drawn. In Surface Drawing, users often draw through existing geometry, and force feedback might interfere with this action. Currently full-arm-range haptic devices are only available in large exoskeletons that restrict motion, while the SensAble Phantom provides 3DOF feedback at a single point within a $7.5" \times 10.5" \times 15"$ region. Such

[3] In fact this is often all that is used in traditional drawing, and in many circumstances artists forgo erasing altogether.

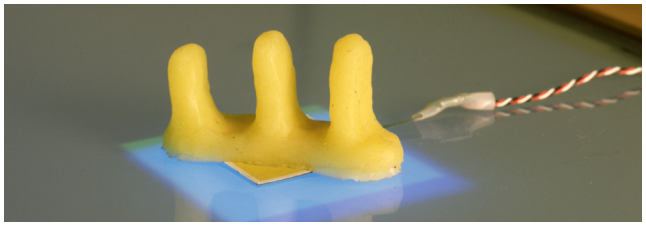

Figure 7: *The magnet tool, molded out of silicone, rests in its nest. The nest is a wired pressure sensor which rests on the Responsive Workbench.*

hardware would severely limit the freedom of movement of Surface Drawing.

Strokes Translating the action of the hand into geometry is greatly aided by the chunking [1] of a hand motion into a stroke. An initial implementation updated the surface one sample at a time, incrementally growing it. Grouping into strokes chunks the act of drawing at a higher level. Algorithmically, it adds coherence to the model's structure, resulting in better models.

Delimiting Strokes An important interface consideration is the method of signaling the beginning and end of a stroke. Using the non-dominant hand or a foot pedal shifts the focus of a drawing action away from the center of geometry creation. Our use of the thumb on the dominant hand (pressing the thumb against the base of the index finger starts a stroke) enables the entire mark to be encapsulated in one action. While this concept was easily understood by users, it proved difficult to sense with input hardware. Users had different ways of closing their thumbs, and bending the hand causes further variation in this posture. We address this issue by putting a contact sensor on the thumb and inner index finger. This solution is certainly an improvement, but there are still occasional errors. Although the gesture is successful, we are still exploring devices to sense it more accurately.

Stroke Properties *Width*: Details of different sizes demand different drawing actions. We are averse to having a control knob to affect the width of a stroke, as this dial is not physically related to stroke width. Scaling with tongs allows variation in detail size by changing the size of the model with respect to the hand. Drawing with the fingertip allows very small details to be added without a large amount of scaling. This mode is activated by putting the hand in a pointing posture, which is easily sensed. The thumb is still used as a toggle switch. This mode has no curvature and is useful mainly for patching small holes or extending a surface border slightly.

Curvature: The hand naturally bends in one direction, which we will call positive. When the hand is completely flat, our software makes a stroke that is bent slightly in the negative direction. Bending the hand backwards increases this curvature, allowing a small range of negative curvatures to be input quite easily.

Color: The color of strokes is changed with a physical knob on the workbench surface that points to different colors on a color wheel. Ultimately, we would like to see a more sophisticated control of color and texture in this system, although at present we focus on geometry creation.

Tongs and Eraser Tongs are used to grab and rotate objects in everyday life, so they were a natural choice for moving drawings in 3D space. They implicitly represent the orientation of an object with their position, and provide tactile feedback when they close. The tongs allow a coordinate frame to be set with the non-dominant hand, as suggested by Guiard [9].

The eraser was designed to fit in the hand in a low-profile fashion; users feel somewhat as if they are bumping away geometry with their hands. An earlier prop took the form of a ball that was activated when squeezed. In comparison, the new tool places the hand closer and in a more relaxed position relative to the surface. The ergonomic eraser affords the ability to fit in the hand in a low-profile fashion, placing the thumb naturally over the toggle button.

Modification Achieving subtle effects is greatly aided by a refinement tool. The magnet provides a function, called *overdrawing*, that changes a shape. The idea behind overdrawing stems from watching artists draw small variations on a line, gradually getting darker, to get a desired mark. The magnet tool not only refines shapes, it also smoothes the rough geometry that often results from a quick sketch. An example of a shape before and after the magnet is shown in Figure 8.

Initial experiments with overdrawing used no prop, beginning the mode when a stroke was started near a drawing. This proved difficult to control. The magnet prop explicitly signifies a state change and reminds the user that they are in the overdrawing state. While holding the magnet, the hand is fully flexible while the magnet is held between the fingers.

The magnet has no sensors. It has a nest on the workbench where it is stored when not in use. Its position is derived from that of the hand. Although a user can accidentally violate this convention by putting the magnet down away from its nest, it is less constraining to have a wireless tool.

EVALUATION

We have informally evaluated this work through on-site demos, exhibitions, collaborations with fine artists and industrial designers, and a small user study. Judging this work objectively is difficult due to the inherently subjective nature of the artistic process. We feel that we have made some astute observations in our informal analysis largely because our design iterations led to improved user feedback. For example, our exhibit at SIGGRAPH 1999 used hand postures that proved difficult, and the props-based interface was better received in our second exhibit. The artists we were collaborating with became much more comfortable when we chunked the drawing process into strokes.

Exhibition Surface Drawing has been exhibited twice, first in August 1999 at SIGGRAPH's Emerging Technologies. This version of Surface Drawing did not have any custom props. Hand postures turned the hand into an eraser or smoothing tool, and a stylus was used to translate and rotate. The exhibit gave users the opportunity to try the system, starting with a blank canvas. The response to this exhibit, especially among artists, was very enthusiastic. Most users were impressed by seeing their motions directly captured in 3D space. This reflects the immersive nature of the Responsive Workbench and the interactivity of the drawing process. Such a large sampling of users—over 500—revealed difficulties in the postures we chose (many users found them un-

comfortable), calibration (even after re-calibrating the glove, some users had trouble), and hand variation (some users, especially elderly ones, could not even make the postures). This exhibit also showed a cultural difference in the acceptance of Surface Drawing. Artists took readily to the tool and began doodling freely and playing, while computer scientists were less comfortable with the blank canvas and with spatial intuition, sometimes asking for control points or other mathematical shape handles.

The second exhibit was in June 2000 at the Mostra da Realidade Virtual in Rio de Janeiro, Brazil. The exhibit was conducted in the same manner, with an updated system including the tangible tongs and eraser. The advantage of the physical tools was noticeable: some users were more interested in using the tongs than drawing, and would move a simple shape around, playing with it for minutes. This exhibit took place in a Portuguese-speaking country, enabling us to view the effects of a language barrier on learning. A Portuguese-speaking assistant helped most of the attendees, but we explained the system to many users with no verbal communication whatsoever. By first moving the user's hand to make a stroke, and then demonstrating the tongs, users understood the interface and immediately started making shapes on their own. Surface Drawing was rapidly learned through physical demonstration even though the users had no experience with semi-immersive environments. The ease of learning is testimony to the intuitiveness of the interface.

User Study These exhibits were informative, although slightly biased by crowds and our own enthusiasm. We ran a small controlled user study in June 2000 to get more feedback. Eight art students with experience in pencil drawing, 3D modeling, or both were recruited. After being briefly introduced to Surface Drawing, they were asked to draw a practice doodle (5 minutes), a flower (5 minutes), and a human (20 minutes). Examples of flowers that users drew are shown in Figures 8*f* and 8*g*. A human is shown in Figure 8*e*.

Our observations should be tempered by consideration that these users had no prior experience with Surface Drawing. They were given the task of learning the interface and constructing some very demanding shapes in a short amount of time. Indeed, most subjects were intimidated by the task of drawing a human figure in this brand-new creative space. Like an artist picking up a pencil for the first time, these novice users could not make many of the mature observations that require experience. This user study tests the freshness and intuitiveness of Surface Drawing at first glance.

The subjects were given a survey in which they rated the usability of the interface. The tongs were found to be very usable (average rating 4.6 on a scale of 0–5). The display was rated fairly usable (average rating 3.9). The glove and eraser were found to be moderately usable (average ratings 2.8 and 2.6, respectively). Participants in the study found the magnet difficult to use (average rating 1.5).

Artists with a background in traditional media seemed to appreciate the system the most. One artist described his experience with the system as "Fun. Takes a while to get some tactile fluency but one senses with plenty of practice one could get to be quite capable. The tools supplied are really quite versatile, and one appreciates that with greater familiarity one would be able to make some good art."

An artist who was most familiar with pencil drawing and had additional experience with Maya enjoyed the Responsive Workbench: "I was completely amazed at how quickly I interpreted and understood the canvas and model to be existing in space. It was immediate."

Users who were most familiar with spline-based 3D modeling software sought their familiar control handles, as exemplified in the response of one seasoned Maya user, stating that Surface Drawing "needs finer control (or long-term training) for anything to be done seriously."

The tongs were universally appreciated. "Tongs are super cool for providing quick access to all parts of the figure drawn," one artist opined. "Surface Drawing is unique in speed of creation and control over figures once drawn. Other media are slow and awkward to manipulate in comparison."

We were surprised by how few artists worked three-dimensionally. For example, many of the figures were not poses, but rather people standing as if they were lying against a wall. The flowers, which were perceived by the subjects as a less daunting task, exhibited more three-dimensionality and playfulness.

The tongs were successful because of their analogy to a tool which most people have used before. The primary difficulty of the glove was sensing the thumb's closing, which still required a little bit of practice for users, showing that this sensing needs further refinement.

The magnet tool was undoubtedly the most difficult feature. Many users did not use it very much. Those who did appeared to be spending most of their time figuring out what it did and not using it constructively. Without accurate handling of the magnet, it is easy to make a mess. The magnet is also most effective on large connected surfaces, which few of the subjects constructed. The magnet clearly frustrated the beginners, and we would like to study it in a body of experienced users.

The user study shows that Surface Drawing works in a way that artists appreciate and find comfortable. Many users acknowledged that they need more time to become accomplished with the system, although they did not have problems mastering the basic interface. Many of the users wanted to spend more time using the medium. (Some asked when they could have one in their own homes.)

Our Experiments The user study examines how artists respond to Surface Drawing, but it does not examine the extent of the medium. It is certainly useful for sketching, but what is the range of shapes that can be created? To explore this space, one of the authors has worked with the system extensively. Figure 8*k* shows an intermediate step in the creation of a human head. Once the basic form was in place, extensive use of the magnet created the refined shape shown in Figure 8*l*. This process of working from rough to detailed is used in pencil-based figure drawing as well. Figure 8*h* shows three one-minute gesture drawings. These images illustrate the quick gestural communication which a more experienced user has with this system. More refined shapes are shown in Figure 8, including furniture prototypes and the especially challenging form of a ballerina.

Working with this system has made us realize that a big part of Surface Drawing is deciding how to construct things. The process is the choice of the artist and can affect greatly what

is made. We also noticed that many aspects of the interface become subconscious after much learning. For example, it is important to use the tongs to view and access different parts of the model. We quickly reached a level where the tongs were constantly used in conjunction with the hand to ensure stroke accuracy. This manipulation is not a focus but rather occurs fluidly, allowing concentration on the structure of the model.

Fine Art We have worked with several artists who are excited about the possibility of using Surface Drawing to explore 3D visual space. An early adopter of the medium, davidkremers, learned how to control the system by practicing figurative drawing. As his abilities matured, he began using the system to conceptually explore four-dimensional flower shapes that would be almost impossible to envision without the higher-dimensional sketching ability that Surface Drawing provides.

Artists Jen Grey and Sheriann Ki Sun Bernham worked with Surface Drawing for one day a week for a period of three months. These artists pushed Surface Drawing into a direction for which it was not designed. They quickly became interested in drawing on a subject who would lie on a table near the workbench. Their work has met with preliminary success: one of Grey's prints (see Figure 8*a*) was featured in the SIGGRAPH 2000 art show.

These artists are very excited about the possibilities of this new medium: "To see abstract images pour like water from my fingertips is sensational," states Grey. "Even more amazing is to see what touch looks like!" Bernham found that Surface Drawing enabled her to "think in a completely new way. Much like when paint programs liberated drawing in 2D on a computer, this system liberates the normally rigid/structured process of building computer models in 3D space. Gesture becomes important again."

Industrial Design Applications of Surface Drawing are being investigated in collaboration with Designworks/USA, an industrial design firm. Designworks is interested in using Surface Drawing to create conceptual prototypes of products, which, in their case, range from automobiles to cellular phones. "We are interested in capturing the emotions that drive gestural descriptions of form," states Senior Designer Gary Fitzgerald. Surface Drawing is a tool to explore "the world of subtleties and nuances that only this type of rapid capture enables. This is a story-telling experience illustrated as geometry."

Working closely with Designworks has helped us understand how much gesture and motion affect design aesthetics. For example, their designers can visually tell the difference between a line drawn 'from the elbow' (with the elbow on the drafting table) and one drawn 'from the shoulder.' Surface Drawing adds a new way of moving and hence a new aesthetic to the design space. Designworks' process is heavily oriented in the sketch, often drawing with pen on top of a printout of a 3D model to better conceptualize. Their experiments with Surface Drawing show new avenues of design, new aesthetics, and new ways to explore space. A second system has been deployed at Designworks to give their designers more access to the Surface Drawing process.

CONCLUSION

Surface Drawing is a powerful medium for creating three-dimensional form and for interacting with three-dimensional space. The path of the hand is directly realized as geometry, providing a physical coupling between body and shape. Tangible tools complete the interface: tongs for moving and scaling, an eraser, and a magnet tool for refinement.

This medium gives artists, architects, and designers a new way to create three-dimensional objects. Surface Drawing allows sketching and doodling, scaling gracefully to more complex organic shapes. The simple, physical interface allows users to define process according to their creative needs.

Surface Drawing has been shown to approximately 1000 users in public exhibitions and on-site demonstrations, virtually all of whom took readily to the medium. The acceptance of Surface Drawing by artists was further illustrated by a small informal user study. Fine artists and industrial designers are currently heavily invested in working with the system, developing their skills and pushing work in directions that would not have been possible without Surface Drawing.

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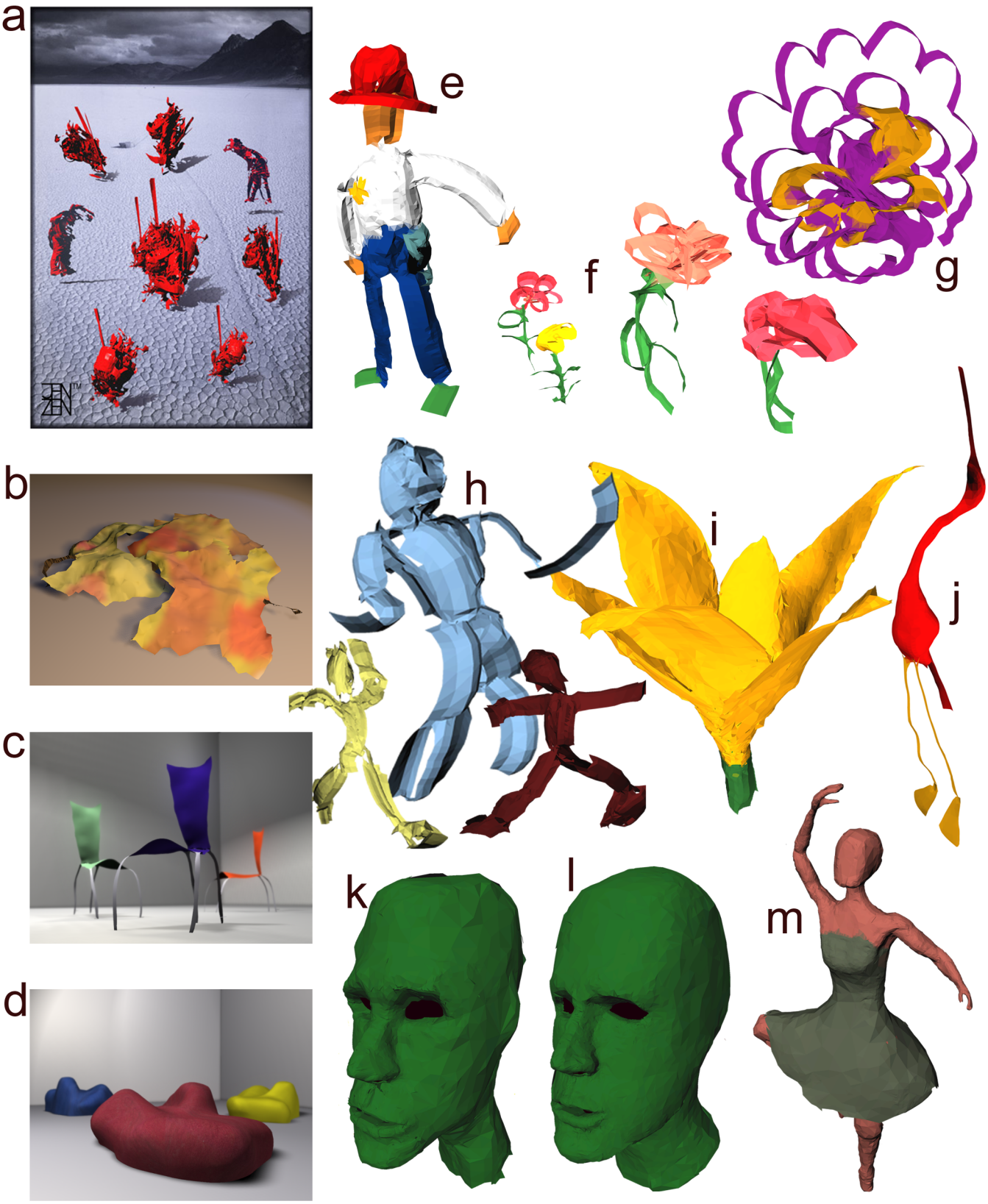

Figure 8: *A variety of shapes created with Surface Drawing: (a) Final Spin, by Jen Grey, as exhibited in the SIGGRAPH 2000 art show, (b) fallen leaves, drawn by davidkremers, (c-d) furniture prototypes, (e-g) a man and some flowers, created by artists during our user study, (h) three one-minute gesture drawings, (i) a flower, (j) an expressive bird, (k) an early version of a human head, (l) a version of this head after being refined with the magnet tool, (m) the full body of a ballerina.*