Spatial Sketch: Bridging Between Movement & Fabrication

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ABSTRACT

Spatial Sketch is a three-dimensional (3D) sketch application that bridges between physical movement and the fabrication of objects in the real world via cut planar materials. This paper explores the rationale and details behind the development of the *Spatial Sketch* application, and presents our observations from user testing and a hands-on lamp shade design workshop. Finally we reflect upon the relevance of embodied forms of human computer interaction for use in digital fabrication.

Author Keywords

Sketching, drawing, creativity, design, 3D interfaces, fabrication, embodied interaction, rapid prototyping.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): User Interfaces: Input devices and strategies, Theory and methods.

General Terms

Algorithms, Design, Experimentation, Human Factors

INTRODUCTION

The broader goal of our research is to develop computational systems that cultivate the creativity of a wide audience of people and support self-expression through the fabrication of real-world entities. While graphical user interfaces (GUI) are the prevalent interaction style for systems focused on everyday creativity and self-expression, non-GUI interfaces have proven to be a powerful tool to engage a wide range of people with the possibilities offered by computation. In particular, *embodied interaction,* grounded in our real experiences [4], allows even those unfamiliar with current interface paradigms to interact with computational systems. Such systems open up a range of possibilities for supporting the creativity and self-expression of new audiences – adults and children alike. Much research in this field has focused predominantly on developing novel input systems to support the creation of digital artefacts (such as imagery and sound) or to be used in a performance context. Research into how non-GUI interfaces can aid the creation and fabrication of real world entities has thus far been limited.

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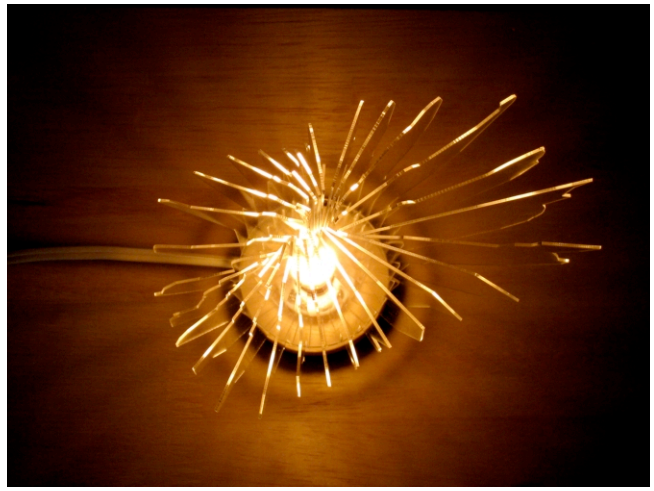

Figure 1. A lamp shade designed and fabricated from physical movement using the *Spatial Sketch* application.

Current trends suggest that the once costly and exclusive domain of digital fabrication will soon be pervading into the lives of computer users under the banner of 'desktop manufacturing' and 'personal fabrication' [7]. The increasing prevalence of technologies such as laser cutters, three-dimensional printers, and computer-controlled milling machines shows a clear direction towards computer output moving beyond the display and printed page and into the world of three-dimensional physical objects. It is equally clear that current software catering for these technologies remain set within the GUI paradigm of interaction. In many cases software for digital fabrication is merely an output method from existing CAD applications, without specific consideration given to interface design.

Embodied interaction, with its relationship to the real, tangible, physical world, undoubtedly shows promise as an alternative interface for the design and fabrication of physical objects. We believe that embodied interaction techniques utilising body movement and the physical attributes of our bodies [3, 12] offer one approach for designing interfaces for digital fabrication. If our physical movements in the real world can be mapped directly to digital fabrication, we can establish an immediately understandable relationship between the interface and real-world output.

The aim of our research has been to develop a spatial sketching system that bridges between gestural movement and digital fabrication output techniques. Our focus has been to simplify the process of personal fabrication to allow a wide range of people to actively participate in the design and creation of everyday objects. In this paper we introduce the *Spatial Sketch* software application and present a case study demonstrating how gesture and movement can be utilised for the design and creation of functional and unique lamp shades.

We do not claim that *Spatial Sketch* offers a definitive solution to the general problem of non-GUI interfaces for digital fabrication. Rather we introduce the lessons we have learnt through our research activity in hope that they will be useful for others working in this field. Most importantly we show that embodied interaction for digital fabrication can create engaging experiences; an encouraging sign for future work in this area. Finally we hope that some of the more technical implementation details and specific observations will be useful for the development of similar systems in the future.

RELATED WORK

In this section we present a summary of sketch systems that explore interaction in physical space and examine how their sketch output is utilised. One of the earliest examples of sketching in physical space can be found in a series of long exposure photographs of Pablo Picasso drawing with a light bulb. Taken by Gjon Mili for Life Magazine in 1949, they capture the physicality of the sketch process remarkably well as Picasso navigates his way through the space around him. These photographs hint at the potential for extending computer based sketch interactions into physical space.

Interaction techniques for sketching in physical space begin with the 'Digital Drawing' module of Myron Krueger's *Videoplace*, developed from 1973 onwards [14]. The *Videoplace* participant is situated in front of a screen that displays their silhouette, and computer vision techniques are used to locate their fingertip and draw a two-dimensional line following its movement in space. The result is an immediately comprehensible and natural style of embodied interaction.

There has been a significant amount of research into spatial input sketch systems beginning with Sach's pioneering *3-Draw* system utilising a pen and palette input device to control orientation in 3D space [15]. Other direct 3D input based sketch systems include the Brown University developed ErgoSketch [5], as well as the virtual sculpting environments *CavePainting* [11] and *Surface Drawing* [16]. The primary focus of these systems is addressing the many challenging issues related to the usability of free-space 3D user interfaces. However once 3D geometry have been created, no specific consideration is given to how this geometry will be manifested in the real world. By contrast our research sought to take a holistic approach that covered the design process from input right through to the output stage.

Translating 3D sketch information into physical objects has been explored outside of a research context by artists and designers working with out-of-the-box 3D motion capture systems. Artist Claude Heath in collaboration with the University of Leeds explored the use of 3D sketches as an extension to his own work creating paper structures with 3D-like sketch markings [8]. The *Sketch Furniture* project by Swedish design company FRONT shows perhaps the closest link so far between spatial 3D input and actual fabrication [6]. Using a complete motion capture system the designer firstly sketches in physical space to create 3D geometry for a furniture design. This geometry is then manually processing in *3D Studio Max* before being outputted to a 3D printer for full-sized fabrication. While we admire these works in their own right, from a user interface perspective they require a significant amount of skill, equipment, and time to be used efficiently. Making the *Spatial Sketch* application accessible to as wide an audience as possible meant not only creating a user-friendly interface but also designing a system that could be implemented without excessive technical requirements. This design perspective would guide many of the technical decisions made during the development process.

SPATIAL SKETCH

The *Spatial Sketch* application covers the process of capturing gestural movement as a 3D sketch and translating that sketch into a series of 2D slices for fabrication using planar materials with a laser cutter.

Spatial Input

To capture user movement *Spatial Sketch* utilises a simple stereo-vision 3D input system consisting of two infrared cameras. The user is provided with an infrared pen light that has a single button for toggling on and off. As the user draws with the pen light, its location is tracked by the two infrared cameras and triangulation is used to locate the depth of the light. Depth information is then used to construct freeform sketch lines in 3D space.

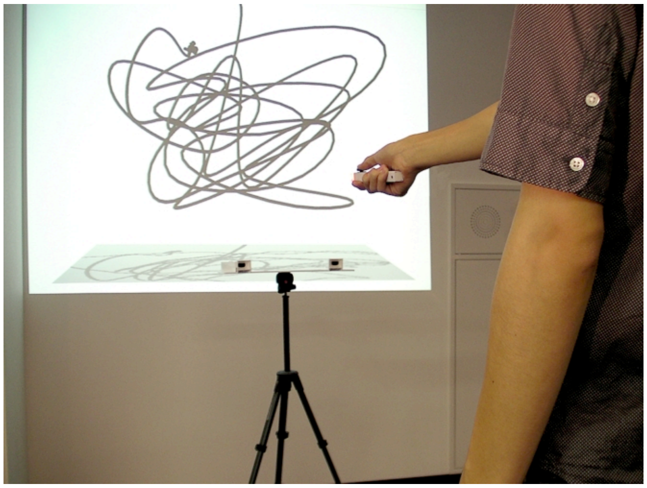

Figure 2. Sketching with the *Spatial Sketch* application.

A real-time view of the sketch is shown on the display to provide visual feedback and help the user navigate their way through physical space (Figure 2). To make the *Spatial Sketch* application as accessible as possible, we choose to implement the 3D input system using infrared cameras found on the *Wii* gaming console's remote controller. This hardware is both affordable and commonly available, and only requires the user to position the cameras at the correct angle using a printed template or custom stand. No calibration stage is necessary, making system set-up a trivial matter. This simplified approach does result in slight noise and minor loses in accuracy, however the greater precision of a full scale motion capture system was not deemed necessary for our purposes. Noise and accuracy errors can be largely overcome using simple line smoothing. Figure 3 shows a sketch created using the 3D input system with line smoothing applied in real-time.

When sketching at a distance of 150cm from the camera system, the user has an approximate drawing window size of 80cm x 80cm. This accommodates a comfortable range of side to side and up-down arm movement as well as considerable depth movement. The pen light must however remain within camera view at all times so that the spatial location can be tracked. As a result sketching outside of the camera view-plane or moving the pen light behind objects causes the location information to go unregistered. The system is therefore designed for tracking arm-movement through space from a fixed location, rather than the significantly wider physical range of full body movement through space. This approach addresses the technical limitations of the 3D input system while still allowing for an embodied sketch experience. The approximate bounds of the sketch area are represented onscreen by a flat 'floor' plane that also serves to display the shadow of the sketch and better represent its volume and depth. An auto-rotate setting also aids in previewing the sketch solidity without having to return and interact via mouse and keyboard.

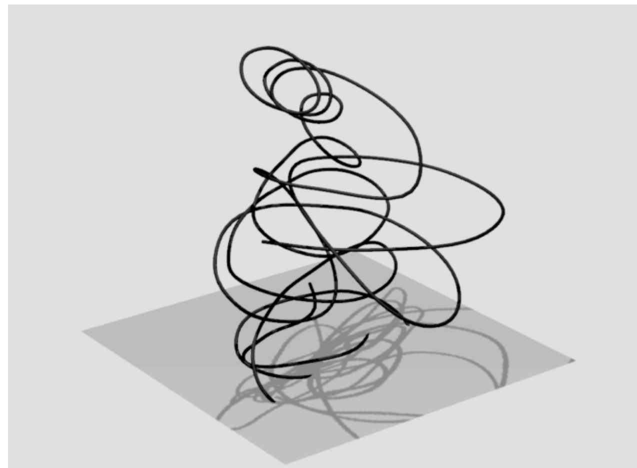

Figure 3. A sketch created using the *Spatial Sketch* 3D input system with line smoothing applied in real-time.

Sketch Soup

Once the sketch has been drawn the next step in the process is to transform the sketch data into a series of slices for digital fabrication using planar materials. These slices must represent the overall outer shape of the sketch as accurately as possible. Exactly how we perceive a series of arbitrary points or lines as a whole shape is a complex topic related to the Gestalt principles of form perception [13].

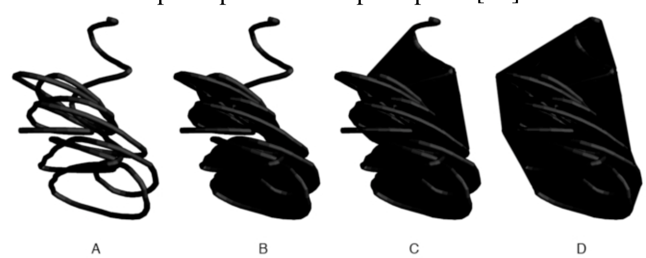

Figure 4. The process of transforming line forms (left) into an appropriate solid shape, depends heavily on individual perception.

Figure 4 shows a projected 2D view of a 3D sketch, and illustrates the problem of transforming line forms (A) into an appropriately shaped solid form for fabrication. From a visual approach we can firstly fill in the holes to create a more or less solid form, but are still left with gaps and stray lines (B). We can then begin to fill in sections of the outer area (C) over and over until the definition of the shape is lost and it begins to form a convex hull (D). The difficulty arises in knowing exactly where in this process we perceive the shape as being both solid and true to the original form.

The problem of creating solid form from arbitrary point data is related to work on surface reconstruction from point clouds, of which there has been a significant amount of research [1, 2, 10]. Our problem however, differs in two ways: firstly, surface reconstruction typically assumes the point cloud lies on or near the constructed surface. The input from the *Spatial Sketch* application forms a kind of 'sketch soup' and is more akin to a spatial sampling of the expected volumetric shape. Only a small sample of the sketch points will be considered to belong to the surface, and the rest of them will be discarded as they lie on the inside of the shape. Secondly, surface reconstruction typically assumes the point cloud is very dense and provides abundant information for reconstruction, point information from the 'sketch soup' is rather sparse and is at times difficult to infer a concrete shape from the given information.

To solve this problem in a lightweight way we implemented an algorithm that works much like the visual filling in process shown in Figure 4, only in reverse order. Firstly we construct a series of projection planes using settings specified by the user (Figure 5). The original outline is formed by Delaunay triangulation of the projection area and is therefore a coarse approximation of the shape the user expects (Figure 6A). In the second step we perform trimming of the outline to remove areas of the outline triangulation that satisfy several conditions: guarantee topology (avoid the creation of islands), maintain the relative smoothness of the outline, and finally never remove areas that belong to the original sketch (Figure 6B). For the final stage we clip the outline with the cross section of the 3D convex hull to ensure that no slice is ever bigger than the 3D convex itself (Figure 6C-D).

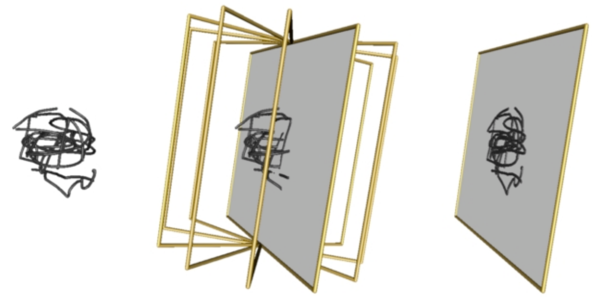

Figure 5. Slices are created from the original sketch by projecting the sketch on to a series of planes.

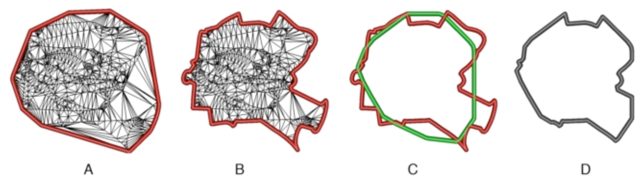

Figure 6. Trimming the slice outline by removing sections of the triangulated area, then clipping the outline with the cross section of the 3D convex hull.

Using the above process it is possible for the user to construct an arbitrary number of slices projected either radially across the sketch or running in parallel to it. The user can also specify the projection axis so that a range of vertical or horizontally projected combinations can be created (Figure 7). To allow for differences in perception and add control over how the solid slices are derived from the original sketch, the amount of trimming to be performed can be controlled manually by the user.

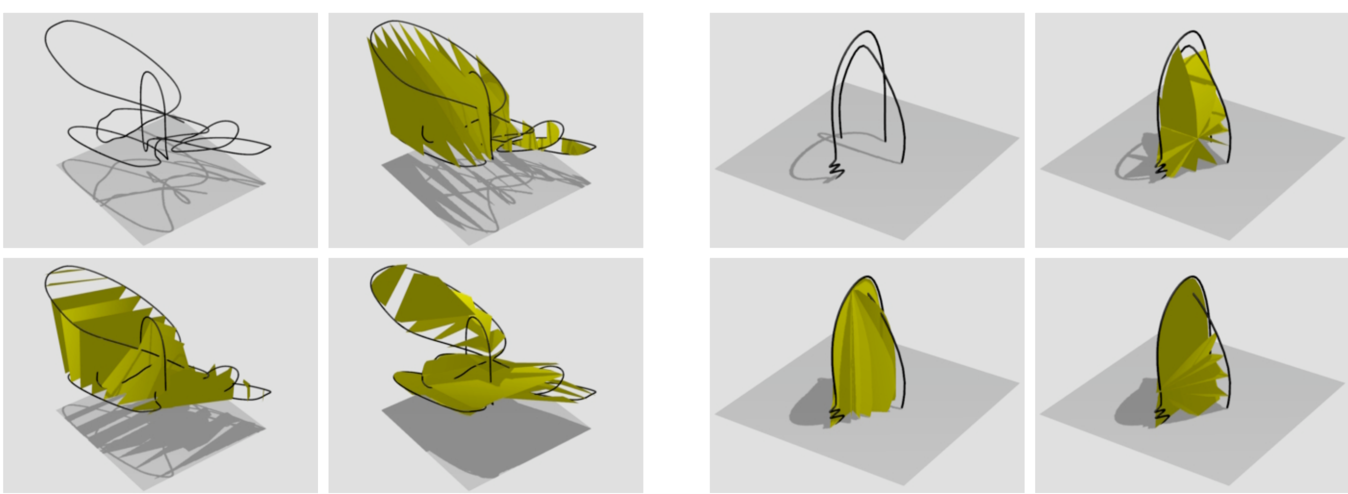

Figure 7. Slices projected from the original sketch in parallel (left) and radial (right) mode.

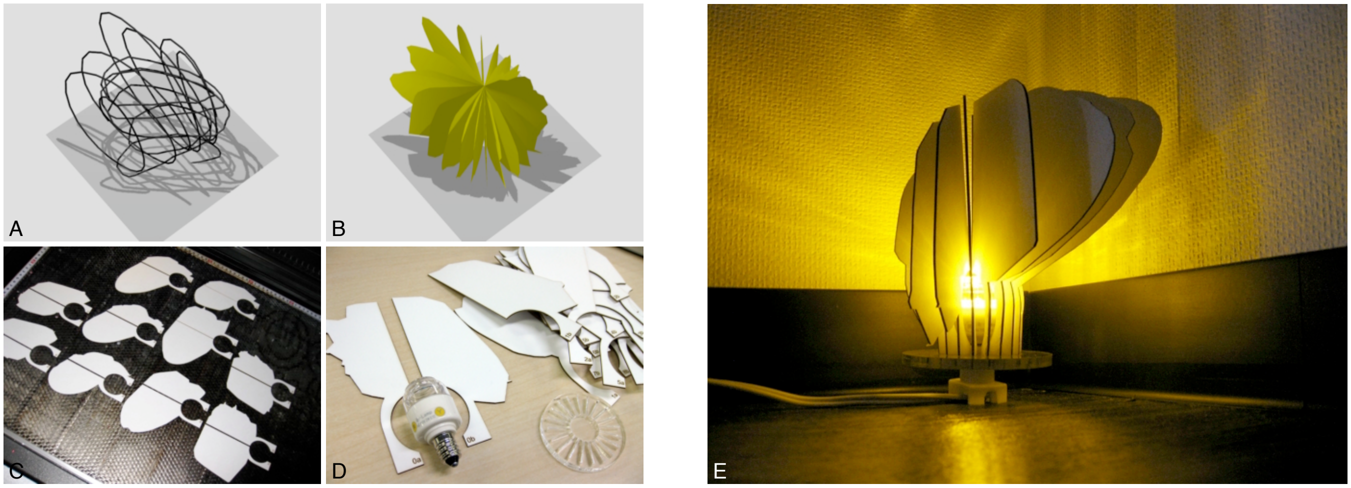

Figure 8. Creating a lamp shade with *Spatial Sketch*, (A) The original 3D sketch (B) Radial slices of the sketch (C) Laser cut slices of card, (D) The final set of parts before assembly, (E) The final assembled lamp shade.

Lamp Shade Design

Slices created from the sketch can then be used to create real world objects through digital fabrication. Planar materials such as wood, cardboard, and acrylic can be cut with a laser cutter to quickly create a real world manifestation of the 3D sketch. As part of our research we conducted a case study using *Spatial Sketch* to create slice based lamp shade designs. As lamp shades can take almost any form we envisioned the organic nature of human movement would be well suited and accentuated by illumination. To create a lamp shade the user specifies variables such as the type of material, dimensions of the light fitting, and the desired size to quickly output a lamp shade pattern for fabrication. The form of the lamp shade is based on a series of radial slices following the outline of the sketch as derived by the aforementioned 'sketch soup' algorithm. This method provided a convenient and structurally sturdy way of wrapping around the light. The inside area is then hollowed out to fit the light inside, support tabs added, and a base plate pattern created to combine the individual parts. Figure 8 illustrates the lamp shade creation process and Figure 9 shows a selection of lamp shades created during the development process.

Figure 9. A sample of different prototype lamp shades created using a range of materials.

USER EXPERIENCES

In the process of developing *Spatial Sketch* we conducted several user experience sessions, including a presentation and participatory demonstration of the system at an arts university, a user study to determine the value of visual feedback, and a hands-on children's workshop.

Initial Presentation

The initial presentation of the *Spatial Sketch* system took place at the Tokyo University of the Arts before a group of fifty students with a shared interest in using digital technology in their creative practice. Following a short presentation of the *Spatial Sketch* system, the students were invited to participate by sketching and sharing their ideas.

What followed was a very interesting session of exploration as the students first came to grips with navigating in 3D space, and then proceeded to draw in a number of unexpected ways. With help from a faculty member one student proceeded to trace around the outline of their body, another student drew a series of circles as if constructing the outline of a flower vase, while another student attempted to write characters along the depth axis.

This initial presentation provided some valuable insights into how people would approach drawing with *Spatial Sketch*. It also underlined some of the deficiencies and shortcomings of the system. The most apparent issue was that sketching directly in 3D was difficult. As traditional sketching is a 2D activity with strong visual and tactile feedback, it took some time for users to grow accustomed to navigating 3D space without concrete feedback. Artist Claude Heath notes his own experience adjusting and the subsequent shift in spatial comprehension:

> Once you have overcome the temptation to conform to the lifelong habit of making marks across a flat drawing surface, it then becomes very apparent just what it means to have the capability to make a 'mark' that can be placed anywhere within a given space [8].

It further became apparent that while the visual feedback on the display aided in navigating 2D space, it seemed to offer little or no benefit for navigating depth in 3D space. Some students became over-focused on the 2D display and seemingly forgot that full spatial movement was being captured. This experience prompted us to explore the relationship between visual feedback and 3D input in a subsequent user study.

However despite these difficulties in growing accustomed to spatial drawing we received some very positive feedback from this initial trial run. Students shared their thoughts on a form handed out after the presentation, with many expressing their interest in the project and enjoyment in participating. A range of possible applications were suggested ranging from the use of more expressive sketching tools such as a gymnastics ribbon or small ball, to creating some form of spatial music notation system. As the initial presentation did not cover the output and fabrication stage, most of the students ideas and feedback focused on the sketch input alone.

User Study

Based on our observations during the initial presentation of *Spatial Sketch*, we decided to conduct a simple user study to establish if the visual feedback provided by the application aided the user in navigating 3D space. We are aware of a considerable amount of research addressing issues of spatial input [9], and hoped this basic study would assist us in addressing the *Spatial Sketch* input system specifically.

The current *Spatial Sketch* implementation displays a front-on view of the sketch so that a line drawn from left to right by the user appears onscreen from left to right in the same manner. This approach allows the user to locate themselves in 2D space and provides a very direct and understandable form of visual feedback. However when sketching a line away from your body and towards the input device, the feedback is not nearly as useful. We hypothesised that this feedback could in fact be detrimental to the user and distract them from sketching in full 3D space.

We designed a simple experiment where we asked ten members of our lab to create sketches with and without the onscreen display. Each participant had not used the *Spatial Sketch* system before and was allocated a short period of practice time to grow accustomed to the system. Participants were then asked to draw a cube and sphere first with the display visible, and then again without the display.

We analysed the sketches to determine differences in drawing style, shape rendition and the overall time taken. Our first observation was that overall time taken to complete the task differed noticeably. Participants took on average approximately 58% more time when sketching with the display visible. Rather than one interface being more efficient than the other, this difference in time taken is more likely a result of using visual feedback as an aid to 'perfect' the sketch, thus consuming more time. Next we analysed the depth of each sketch to determine if the visual feedback distracted participants from sketching in full 3D space. We found that there was no noticeable difference in the depth of sketches created with the display visible or not. Of the 20 shapes sketched, 11 were deeper with the display visible versus the 9 that were deeper without the display. This result suggests that the predominantly 2D visual feedback provided does not distract the user from drawing in full 3D space as we have predicted.

Finally we analysed each sketch visually to determine if either method produced more accurate renditions of the shape requested. Of the 20 shapes, we judged 12 cases drawn without the display and 8 cases drawn with the display, to be overall better renditions of the original cube and sphere. Figure 11 shows sketches created by a user study participant. The left side shows the cube and sphere drawn with the display visible, and the right side shows the cube and sphere drawn without the display. Noticeable differences in drawing style include the slower more jagged lines created when the display is visible, as the participant utilises the visual feedback and attempts to create a more accurate rendition. While the lines drawn without the display are more fluid, they often do not meet up correctly due to the lack of a visual reference point onscreen.

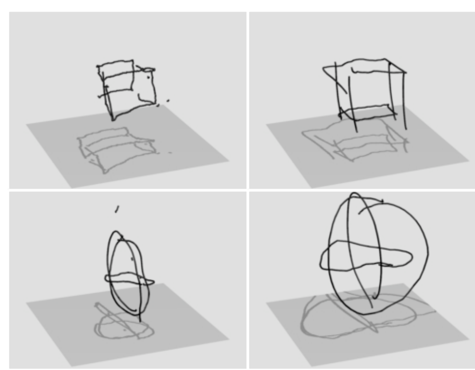

Figure 11. Sketches created by a user study participant. The left side shows shape drawn with the display visible, and the right side those drawn without.

The user study has shown us that there is a definite change in drawing style when the visual feedback provided by *Spatial Sketch* is taken away. The lack of visual feedback encouraged participants to sketch more fluid lines and focus more on the physical space as opposed to the flat 2D display. This led to noticeably faster sketches that overall were judged to be slightly more accurate renditions of the original shapes. On the other hand, sketching with the display visible did not seem to distract participants from using the full 3D space and did provide a useful visual reference for connecting or matching up lines.

Workshop

The next step in gauging user experiences focused on the full design cycle from sketch input to output and fabrication. As the *Spatial Sketch* application is intended for use by a wide range of people, we decided to run a small workshop for children where they could sketch, design, and construct their own original lamp. Workshop participants ranged in age from 8 to 11 years old and were introduced to *Spatial Sketch* with a series of simple exercises. Firstly sketching simple circles and squares in 2D, then sketching again along a different axis moving in and away from the camera input device. This helped participants understand the type of movements that produced specific shapes. Participants were then invited to sketch freely and experiment with the different types of planar forms that *Spatial Sketch* can create. Once they had decided on a form they liked, we began the process of creating the lamp shade. Each participant selected a piece of coloured card from which the lamp shade form would be cut using a laser cutter. They were then provided with the lamp base, a light bulb, and the freshly cut slices to assemble on their own. Each participant managed to quickly and efficiently assemble the lamp shade and then began 'customising' it with marker pens to bring their design to life further. One participant created a tree like form with green card and then added apples into the tree with his marker (Figure 12), another participant transformed an abstract shape into a bird by drawing its eyes and beak.

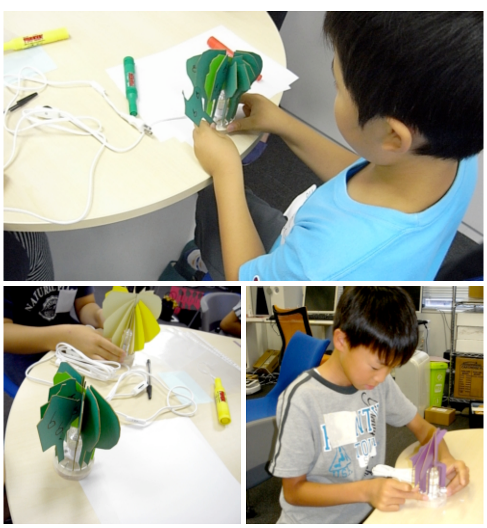

Figure 12. Creating lamp shades with *Spatial Sketch* during a children's workshop.

We asked the workshop participants to complete a short survey asking how they enjoyed the experience and what areas they thought could be improved. While each participant really enjoyed the process of creating their lamp and loved the final lamp design, there were mixed results about how difficult the overall process was. Their feedback leads us to believe that subtle improvements to the 3D sketching system along with more accurate translation into physical form will go some way towards overcoming these difficulties.

DISCUSSION AND FUTURE WORK

A major point that separates sketching in physical space from traditional 2D sketching is the presence of a physical surface to push a pen or pencil against. As this surface is absent when sketching in physical space, the marks created tend to wrap around the body in a curved fashion – directly reflecting the mechanics of the arm. Interaction with *Spatial Sketch* is primarily via arm movement so this was an interesting observation that has implications for creating geometric forms and straight lines. Sketch interactions involving full body movement through space would again have a separate set of considerations.

Sketching in physical space still remains a challenging interface design issue to be addressed. In our case the primary goal was to express human movement as form, so high levels of accuracy were not required. However, the transformation of sketches into planar forms would often further abstract the sketches in unexpected ways. While many of the unexpected forms were aesthetically pleasing, refining the transformation process to be more faithful to the original sketch is an important next step. The current implementation of *Spatial Sketch* used planar materials for output and fabrication due to the common availability and range of different materials available. More complex fabrication devices such as a 3D printer would no doubt offer much greater fidelity to the original sketch, but at a significantly higher production cost. Higher fidelity planar-based forms could be partly achieved using more complex multi-directional inter-locking planes, similar to the work of Sharp [17].

With further improvements we envision *Spatial Sketch* could be used to quickly fabricate a range of different everyday objects from planar materials. Custom craft items such as decorations, mobiles, costume masks, and paper forms would be well suited to the organic shapes and one-of-a-kind nature of the *Spatial Sketch* system. We also envision more focused professional uses such as the creation of stage props, lighting fixtures, costumes, furniture prototypes, and set designs would also be ideal for quick fabrication at a range of scales.

CONCLUSION

Despite the inherent difficulties in navigating physical space, there are numerous indications that the 'unencumbered full-body participation' [14] envisioned very early on by Krueger will become an HCI reality. The trail blazed by Krueger has been followed in the gaming world by the Sony *EyeToy*, the Nintendo *Wii*, and more recently Microsoft's *Project Natal*. The language of embodied interaction is becoming more widely understood as new audiences are increasingly exposed to forms of physical interaction. The challenge remains to push non-GUI interfaces into new fields that can build upon this platform and create richer forms of interaction.

This paper has explored one possible avenue by seeking to bridge between spatial movement and digital fabrication. *Spatial Sketch* does not offer a definitive solution to the general problem of non-GUI interfaces for digital fabrication. Rather it contributes an initial realisation by providing a way for real-world planar-material objects to be constructed using real-world human movement. Most importantly, through our research we have found that users become readily engaged with the *Spatial Sketch* creation process. There appears to be something inherently satisfying in the integrated process of creating and realising a design in physical form; we see this as an encouraging sign for future work in this area.

This project marks only the start of what we believe to be an exciting line of future research and exploration. As technologies for tactile feedback, computer controlled machinery, and shape-changing materials develop, the combination of embodied interaction with responsive, realtime digital fabrication will have a very real impact upon how and what we create in the future.

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