Interactive Fabrication: New Interfaces for Digital Fabrication

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ABSTRACT
We present a series of prototype devices that use real-time input to fabricate physical form: *Interactive Fabrication*. Our work maps out the problem space of real-time control for digital fabrication devices, and examines where alternative interfaces for digital fabrication are relevant. We conclude by reflecting upon the potential of interactive fabrication and outline a number of considerations for future research in this area.

Author Keywords
Interactive, fabrication, digital, prototyping, embodied, interface, real-time, tangible, interaction, creativity, design.

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Design, Experimentation, Human Factors, Theory.

INTRODUCTION
The once costly and exclusive domain of digital fabrication is already reaching wider audiences under the banners of 'desktop manufacturing' and 'personal fabrication' [3]. Computer output is moving beyond the two-dimensional display and into the world of three-dimensional physical objects. It is clear that most current interfaces catering to digital fabrication remain focused within the graphical user interface (GUI) paradigm. Figure 1 illustrates how the current digital fabrication process closely follows the desktop publishing metaphor: A design is created using a GUI interface, saved to file, fed to an output device, and finally manifested in physical form. This process is overly complex, requiring numerous disparate steps to go from design idea to physical prototype. It is far removed from traditional craft where the artist or designer interacts directly with the material using tools such as brushes or chisels to paint or sculpt. Generative, code-driven, and algorithmic approaches to fabrication are an important area of creative exploration, but are not always applicable for general design scenarios. Empowering users with purpose-built tools for digital fabrication opens up a range of new creative possibilities.

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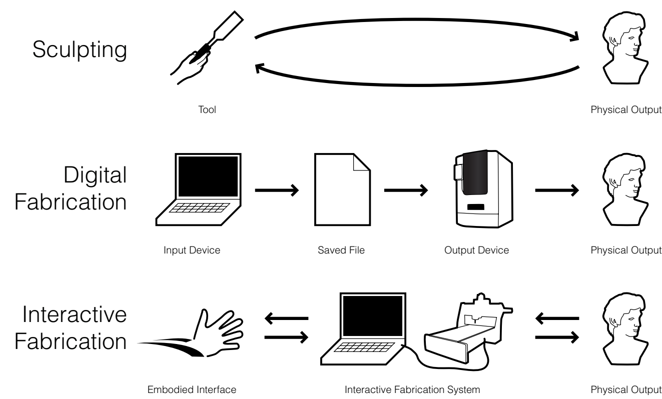

Figure 1. *Interactive Fabrication* contrasts with existing approaches by allowing real-time input to digital fabrication.

We present a series of prototype devices that take real-time input to fabricate physical form: *Interactive Fabrication*[1]. We do not suggest that these tools are a ready replacement for the current digital fabrication process; rather our work seeks to map out the problem space and understand where alternative interfaces are relevant. We conclude the paper by contextualizing our work within the broader framework of *Direct Manipulation* [8] and outline a number of considerations for researchers looking to explore this space.

MOTIVATION
Despite recent advances in digital tools there remains a considerable divide between the *designer* and the *constructor* of artifacts. We believe bringing physical input and output closer together can aid in recapturing the creative process seen in earlier forms of direct making. This has the benefit of establishing a closer relationship with materials and allows designers to better understand their properties and nuances.

[1] http://www.interactivefabrication.com

Key to bringing together physical input and output are interfaces that support embodied real-time interaction and fabrication. By situating the interface with the fabrication device the user can view the material directly to understand the spatial relationships and structure of the form. Real-time feedback from the fabrication process can then directly inform the design. We envision this direct form of interaction will foster experimentation, improvisation, and an exploration of the medium's capacity [6].

RELATED WORK

Research in the separate fields of non-GUI interfaces and digital fabrication is currently flourishing. Despite the work done in each field, few projects cross the divide between embodied input and embodied output. A noteworthy early example of a computational interface bridging between physical input and physical output is Frazer's *Flexible Intelligent Modeling System*, developed in 1980 [1]. The system is intended to support the architectural design process and consists of sensor embedded blocks able to determine their configuration and output a 2D representation to a plotter. While there has been considerable research on tangible modeling systems as input devices, research crossing over into tangible output has to date been limited. The automated construction of architectural designs as physical models has been explored by Howe [7]. He outlines a number of principles aimed at allowing scale models to be constructed using a robotic arm and interlocking components. Gramazio and Kohler [4] have made extensive use of robotic arms as a fabrication technology to design prototype architectural structures and manufacture large scale building facades.

In the field of industrial design, the *Sketch Furniture* system uses a professional motion-capture system to create 3D geometry from sketches in physical space [2]. This geometry is then processed into a mesh that can be fabricated at full scale using a 3D printer. *Spatial Sketch* takes a similar approach with a 3D sketch interface that outputs patterns of slice forms for construction using a laser cutter and planar materials [9]. While these works bridge between embodied input and embodied output, the process suffers from a level of indirection: fabrication only begins once the design has been completed. Our interest lies in exploring direct real-time control of fabrication devices to integrate design and fabrication into a single process.

INTERACTIVE FABRICATION

We have developed several prototype devices that use real-time sensor input to directly affect fabricated output.

Shaper

Shaper is a prototype device that uses a three-axis computer numerical control (CNC) machine to interactively dispense expanding polyurethane foam material (Figure 2). The user controls the device via a translucent touch screen to create physical artifacts with sketch-like gestures. *Shaper* challenges the conventional process of digital fabrication by allowing direct interactive control. The translucent touch surface is situated above the fabrication area, so that users can directly see the physical output. The gesture interface is projected onto the rear of the touch surface and a depth map is stored to allow multiple layers to be built up into three-dimensional form. The software detects when sketch lines intersect and raises the dispenser head to the appropriate height; material can then be built up layer by layer. The polyurethane foam dries into a lightweight and smooth material. Figure 2 illustrates the type of physical 'pixels' that can be created with expanding foam. We chose expanding polyurethane foam to enable quick fabrication. Unlike other additive 3D printing processes, foam quickly expands to a substantial volume.

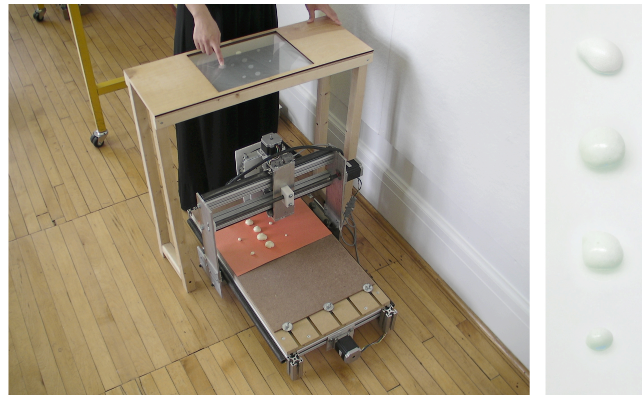

Figure 2. *Shaper*, a prototype device for interactive fabrication (left) using expanding polyurethane foam (right).

A number of factors contribute to the fidelity and controllability of the fabricated foam design: the speed at which the machine moves, the amount of pressure inside the canister, the nozzle shape, and the dispensing surface. By observing and interacting with the material, designers can better understand how the material behaves and 'talks back' during the creation process. Despite the speed at which the foam could be dispensed, the speed of the CNC machine proved to be a bottleneck. The speed of user interaction was far beyond the response speed of the machine, meaning commands had to be placed in a queue for delayed execution. Future work on the project will involve developing the software interface further and trialing alternative materials. For example, using subtractive fabrication techniques opens up a variety of different materials that can be interactively milled by the user.

Speaker

Speaker interactively sculpts wire forms based on sound input. The user stands in front of the device and speaks into a small microphone. An Arduino micro-controller embedded in the device then begins to calculate a simplified contour from the sound wave. Two motors are used to push and bend the metal wire into a shape. Sounds are thus physically 'encoded' into the wire, creating a tangible manifestation of an intangible sound (Figure 3). The device explores the immediacy of the fabrication

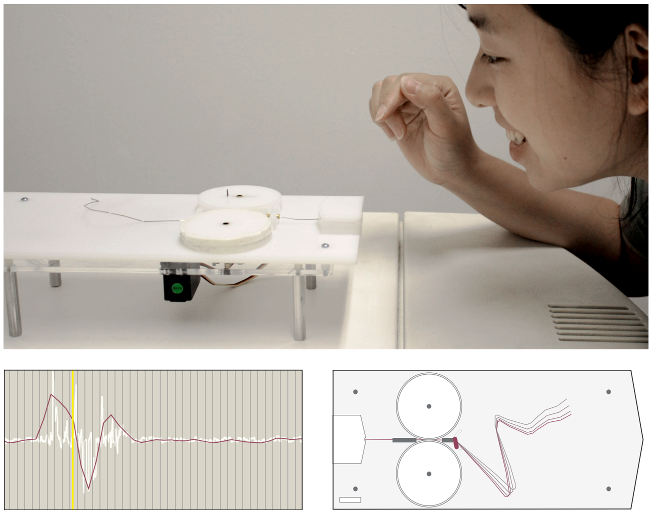

Figure 3. ***Speaker*** **sculpts wire forms from user sounds (top). Wire is bent to form a simplified sound wave (bottom).**

process by linking an ephemeral passage of sound to a physical entity. It furthermore acts as a means for the spoken word to be transcribed into an artifact of meaning. Figure 4 shows a pair of earrings constructed with the words ‘I love you’.

Due to the physical actuation involved in shaping the wire, we found latency was again an issue. We experimented with two modes of interaction. In ‘echo mode’ the device echoes user input immediately, sculpting the wire with the minimum amount of latency possible. In ‘replay mode’, the device records a few seconds of speech, then immediately starts bending a section of wire. We observed that the latter mode would almost draw users into a conversation with the machine, transforming the waiting time into a playful experience. In future work we would like to explore how other qualities of sound can inform the shape. For example, a higher pitch can be mapped to sharper turns, while a lower pitch can appear smoother. This can give the voice of a child a very different visual style than that of an adult.

Figure 4. Earrings shaped with the words ‘I love you’.

Cutter

Cutter is a tangible interface for generating three-dimensional digital models by hand crafting polystyrene foam. The user pulls, pushes, and rotates a custom hotwire cutter to sculpt, cut, and shape foam cubes. The position of the cutting path is processed in real-time by a computer to visualize the cutting process and generate a 3D model. *Cutter* aims to provide an intuitive way to explore physical form by combining traditional craft with digital fabrication.

Cutter consists of a hotwire cutter, a holder, and a visualization program. When the hotwire cutter comes into contact with the foam it cuts a path that is processed by the computer into a 3D model. The cutter is constructed using thin wire heated by electrical resistance, a linear potentiometer to measure the distance the cutter has been pushed or pulled, and a rotary potentiometer to record the tilt angle (Figure 5). The foam holder can be set in a stationary position or rotated via stepper-motor to allow more intricate and unpredictable forms. A real-time visualization shows the cube position, orientation, and cutting path on screen (Figure 6). Geometry is reconstructed based on sensor data and can be saved as an STL mesh file for immediate reproduction with a 3D printer or edited and revised using 3D modeling software.

The polystyrene foam material was chosen because of its

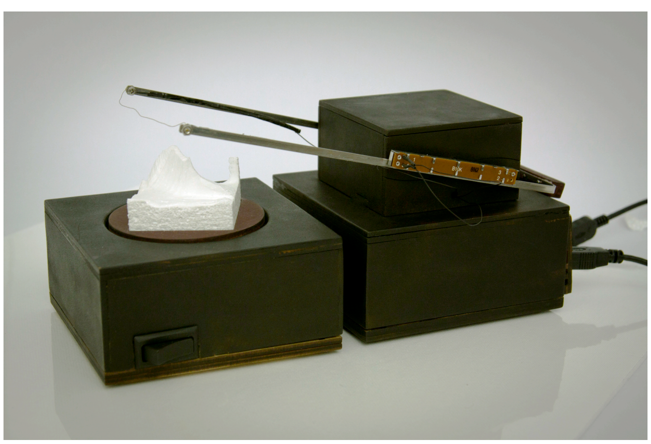

Figure 5. ***Cutter*** **is a tangible interface for generating three-dimensional digital models by hand crafting polystyrene foam.**

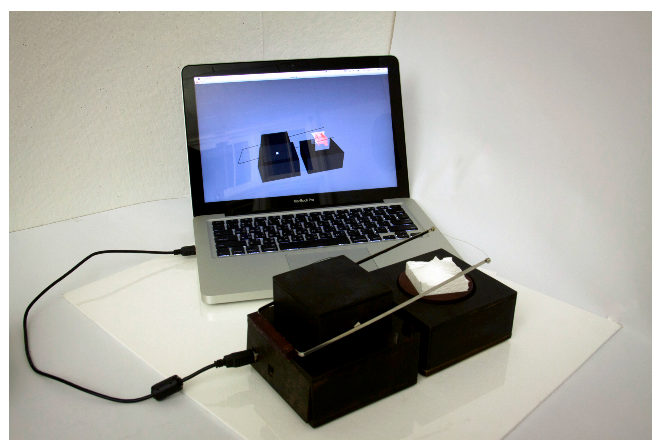

Figure 6. Potentiometers are used to sense the cutting path and visualize the shape of the material on screen.

malleability and the speed at which it can be molded. Due to the nature of the material, the foam can melt when overexposed to heat from the hotwire and cause unpredictable melting patterns. *Cutter* enables designers to play with the material and the randomness and unpredictability it brings. By enabling the physical process to be recorded and transferred into the digital realm, designers can gain from the immediacy of the physical and the flexibility of the digital. The next steps for the project are to replace the potentiometers with actuators that can control the physical position of the hotwire cutter. This enables the device to sense, record, and replay path movement. It opens up possibilities for editing cutting gestures to fabricate a remixed or refined physical object.

DISCUSSION

Shneiderman's concept of *Direct Manipulation* focuses on how screen-based interfaces can benefit from a 'what-you-see-is-what-you-get' approach [8]. Interactive fabrication systems that directly manipulate and produce physical form share many of the same aims.

Continuous representation of the object of interest. Our interactive fabrication prototypes avoid a 'representation' of the object of interest, but instead allow the user to look directly at the fabricated form. Additional information can be added to augment the user's view, but the main area of interest remains the fabricated form itself.

Physical actions. With each of our prototypes the user interacts through an embodied interface where their physical actions are sensed and interpreted in real-time. Physical action again determines the embodied output in the form of digital fabrication.

Rapid, incremental, reversible operations. Optimizing the speed and response time of our prototypes has been a major challenge. Due to the amount of actuation required and the speed of user interaction we have been unable to produce satisfactory fabrication speeds. Our approach has been to incrementally buffer user input and create a delayed response. This approach works well for short segments of interaction, as in the case of *Speaker*, but begins to break down when continuous interaction is required, such as with *Shaper*. The ability to reverse a physical action requires considerably more technological complexity. However, gestures that make up the final form can be digitally stored to allow the user to revisit a design, remove unwanted gestures, and fabricate the form again.

Layered or spiral approach to learning. We strived to create an interface like the pen or piano that is *instantly knowable* and *indefinitely masterable* [5]. We found the directness of interactive fabrication lent itself to accessible interfaces and the complexity and variety of materials provided a considerable range for expression.

Encountering *Direct Manipulation* interfaces in the physical world introduces a number of new considerations for research in this space.

Unexpected Results. The direct nature of interactive control introduces the potential for unexpected results that cannot easily be reversed. In the early stages of the design process it may be desirable to experiment with form, or have a roughly produced early prototype. However when crafting a final form factor, maintaining fidelity to the design idea is of upmost importance.

Waste. Unexpected results leads on to the issue of increased waste. Subtractive fabrication processes already suffer from large amounts of waste material. This could become an even greater problem for fabrication devices that function in real-time and do not require rigorous training to operate.

Disconnect between physical and digital. We have found that there are numerous subtleties to fabrication materials that complicate the process of digital representation. Regardless of how good a simulation can perform, there are numerous sources of variability in materials that can quickly make a digital representation unstable.

CONCLUSION

Although there are numerous advantages to the current GUI approach towards digital fabrication, by more closely linking *input* to *output* we can allow designers to benefit from computer controlled machinery and at the same time re-establish a relationship with the physical fabrication process. The prototypes presented in this paper have only scratched the surface of a much larger area of exploration. Interactive fabrication will not be appropriate for all circumstances, but we foresee a range of new creative possibilities for early stage prototyping, experimental form, improvisational fabrication, and many others. With the rapid growth of digital fabrication upon us, now is an ideal time for reimagining how we create physical form.

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