Enabling the Fabrication of Interactive 3D-printed Objects by Non-Experts and Novices

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ABSTRACT

While digital fabrication has come great lengths since its inception decades ago, the promise of fabricating custom devices is still unfulfilled. Although the literature contains multiple efforts of adding interactivity to digitally fabricated objects, the techniques explored are often reserved for the more technical savvy, as they generally require extra knowledge from the maker. In this paper, we evaluate the current state-of-the-art in the fabrication of interactive objects, analyzing their inherent shortcomings. Inspired by the literature, we introduce an Interactivity Toolkit comprised of mechanisms to add interactivity to 3D-printed objects, in an maker-friendly way, and present our firsts steps in the population of this toolkit in the form of Blowhole, a system that allows the user to acoustically tag 3D-printed objects by embedding blowing-activated tags inside them. We additionally discuss the current and future efforts towards enabling interactions in a maker-friendly way with the introduction of AirTouch, a system that leverages airflow to enable touch interaction in digitally fabricated objects.

INTRODUCTION

Although fabrication technology research may appear to be a recent trend in the Human-Computer Interaction (HCI) and computer graphics communities, this technology has been around for decades. The development of these technologies took place behind closed doors starting in the 1960s as a rapid prototyping technology. The expiration of major patents in 2009 marked the beginning of the transition of this technology from the industry to the hands of the consumers.

The birth of this new category of fabricators (henceforth referred as makers) peaked the interest of researchers. Studies like [16] explore the possible uses of this technologies in the hand of everyday makers, concluding in that one of the most important tasks undertaken by these makers is one of *augmented fabrication* [1]: designing and fabricating objects that work with already existing ones.

We believe that the next natural step in the evolution of these technologies is enabling its users to fabricate fully interactive objects, that in turn can be then used as interfaces to the user's devices. This is corroborated by the numerous efforts published in the literature in the past years exploring novel ways to add interactivity to digitally fabricated objects (see section 3 for a comprehensive literature review).

However, previous work exploring the enabling of interactivity in digitally fabricated devices focus their efforts to the interactivity mechanisms themselves, without taking into consideration how the inclusion of these mechanisms adds more complexity to the fabrication process. The inclusion of electronic techniques, and advanced fabrication processes adds another level of complexity to the already complicated fabrication process [6, 10, 19] and can hinder the acceptance of these new technologies by novice users.

Inspired by these limitations, in this paper we propose to enable interactions in digitally fabricated objects by utilizing naturally occurring properties (e.g. acoustic resonance, fluid dynamics). Rather than sensing the interactions of the user on the object itself, we propose to indirectly sense them by measuring the changes caused by the interaction to these properties using wearable sensing technologies. By externally sensing the effects the user's interactions have in these properties, the objects augmented with our mechanisms can be interacted with immediately after they finish printing, and do not require the addition of circuitry enable interactions.

RESEARCH QUESTIONS

Based on the discussion presented above, we seek to answer the following research questions through our work:

1. What different natural properties can be leveraged to enable interactivity to digitally fabricated objects?
2. How many different interaction mechanisms can we enable by making use of these properties?
3. How does these interaction mechanisms perform against more complex mechanisms?

RELATED WORK

Adding interactivity to 3D-printed objects has been a popular topic in the literature in recent years. While most efforts explore novel and interesting ways to make 3D printed objects more interactive, few concentrate their efforts in adding these interactive capabilities in an maker-friendly way—reserving this process for experienced and knowledgeable makers. Below we present a comprehensive survey of the different methods used to enable interactivity explored by the literature, categorized by the mechanisms used to enable them.

Acoustic

We can find in the literature multiple efforts leveraging acoustic properties to enable interactivity in printed objects.

Stane [11], for example, uses different surface textures that produce distinct acoustic signatures when rubbed with a finger. The sounds generated by these interactions are then captured by a microphone under the surface of the object and further analyzed and classified.

Conversely, an effort similar to Stane is Lamello [14]. Here, the authors leverage a series of components that, when interacted with, produce singular acoustic fingerprints by strumming fabricated comb-like structures that generates an identifiable signature. These tones are captured by contact microphones placed under the surface of the object, and identified using a classification pipeline. Notably, in this effort, the authors compiled a library of different interaction techniques that can be enabled using this mechanism, comprised of different types of buttons, sliders and dials.

Continuing, efforts like Acoustruments [9] enable more elaborate interactions by leveraging more elaborate fabrication processes. Here, the authors create acoustic pathways to route the audio emitted from a smartphone's speaker to its microphone, making use of physical controls to modify the signal going through this path. These controls can enable an abundance of interactions, from tilt to pressure sensing, and can be leveraged to create numerous application, as the paper presents.

Although these efforts enable an abundance of interesting interaction possibilities, they do it at the expense of complex fabrication techniques. While digital fabrication technologies are becoming ubiquitous, most novice makers are not experienced in complex fabrication techniques, limiting the reach of the interactions presented above.

Electric

Using electronic components to add interactivity to objects has been thoroughly used in manufacturing processes for decades. Thanks to advances in commercially available printers, makers can use a combination of conductive and nonconductive materials to enable new interaction modalities to their objects.

An example of the efforts carried out leveraging electronic mechanisms to enable interactions is Steel-Sense [18]. In this effort, the authors leverage dielectric materials between two surfaces to create a hinge between two conductive surfaces, effectively sensing the angle of rotation of said surfaces.

Continuing, in Liquido [15], the authors leverage capacitive sensing and dielectric liquids (such as water) to augment the printed object with tilt and motion sensing. Using a dual extrusion printing process, the authors add conductive filament to the walls of a cavity, where the fluid is to be poured into. This cavity is then closed, and, when the liquid comes in contact with a sensor, capacitance increases. These changes in the position of the liquid inside the object can be then translated to movement and orientation.

Adding, the authors of PyzoFlex [12] created a proprietary, printable, ferroelectric material, that, relying on the piezoelectric effect [4], can be used to add touch, pressure and bend sensing capabilities to 2D surfaces. This material also has pyroelectric characteristics, allowing it to sense changes in temperature in the printed object.

Even though these new interaction capabilities enabled by the aforementioned efforts can unlock a wide variety of applications, they all require the user to possess certain electronic knowledge to fabricate these augmented objects. Not every maker has an electronic background, therefore these mechanisms are limited to a selected few.

Optic

Other researchers have explored enhancing printed objects using optical mechanisms. Notable efforts include Printed Optics [21] by Willis et al., where the authors are able to sense user input my using light pipes and custom optical sensors. In this paper, the authors present different examples of augmented objects using this technology, like sliders, touch pads, and buttons.

Another interesting effort is Sauron [13], where the authors make use of a camera, with an accompanying light ring, embedded to the inside of the printed object to detect the movements of areas of interest. This setup is augmented using a system of mirrors to allow the camera to "see" around corners and bocks inside the object. This mechanism enabled a variety of interaction methods, like buttons, sliders, scroll wheels, etc.

While both of the aforementioned efforts make use of optic mechanisms to enable very different interactions, they do so by increasing the complexity of the fabrication pipeline. In [13] the maker is required to assemble the interactive components on the printed shell, as well as cameras and mirrors to sense the interactions, while in [21] requires the use of intricate and expensive fabrication equipment and materials.

Metamaterial

3D-printing technologies enable the production of new types of metamaterials, since the properties of the material can be outlined throughout different sections of an object. By modifying the microstructures that compose the object, the maker can influence properties like strength, weight and flexibility, enabling different ways to interact with the fabricated object.

Ion et al. explore these concepts in their work titled Metamaterial Mechanisms [7]. Here, the authors employ different metamaterial structures to create mechanical interfaces in digitally fabricated objects. In their work, the authors introduce what they refer as *cells*, that allow deformation in one direction, but not on other. The authors then use these metamaterials to fabricate common mechanical interfaces like a door knob, a pair of pliers, among others.

This work was then extended in Digital Mechanical Metamaterials [8]. Here, making use of bi-stable mechanisms, the authors add logic to their designs. The authors were able to augment their previous designs with logical gates and switches.

Even though these presented efforts are truly pushing the boundaries of what is considered a 3D-printed object, they rely on very complicated printing techniques to enable said interactions. As we mention beforehand, most novice makers are not well versed in such complicated techniques, and such should not be required to add interactivity to objects.

RESEARCH PLAN

Although the literature presents a wide variety of mechanisms to add interactivity to 3D-printed objects, the big majority of these rely on some form of extra knowledge from the maker, either as a background in electronics, or complex printing techniques. These aforementioned techniques and mechanisms are in fact adding more complexity to an already complex process [6, 10, 19]., in turn raising higher the barrier for users to fabricate their own interactive devices.

INTERACTIVITY TOOLKIT

Inspired by the limitations in the literature mentioned above, we propose an Interactivity Toolkit where the maker can augment its three-dimensional models by leveraging naturally occurring properties, and wearable computational capabilities and sensing.

The different mechanisms that will constitute this interaction toolkit must possess the following common qualities. They must be able to be printed in commodity printers, thus guaranteeing that these mechanisms are able to be fabricated using all kinds of printers. Additionally, these mechanisms must be ready to use right off the printer, requiring no post-print assembly or cleaning, ensuring that even the most novice of users can augment their objects using them. Lastly, while the objects must be modified to enable interactions, these modifications must be minimal, preserving the objects form.

Blowhole

We have already taken steps in populating this interactivity toolkit. The first addition to it is Blowhole [17]. Blowhole enables users to tag sections of 3D-printed objects by embedding blowing-activated tags inside them. In this section, we present and describe how Blowhole works.

Overview

Blowhole is based on the principle of acoustic resonance: the same principle that makes a bottle whistle when blown across its mouth. Blowhole embeds cavities into 3D models with tubular openings to the surface. The variations in the volume of said cavities and lengths of the tubes produce changes in the fundamental frequency of the sound generated when these cavities are gently blown on. This sound is then identified by our system, effectively linking the produced sound to a location on the model. Using our design tool, a user can select an arbitrary location on a 3D model to embed openings on; associating actions to each location. After optimizing the cavity sizes, the software provides a printer-ready file for fabrication.

The cavities used in Blowhole must possess certain qualities: they must allow enough variation in their parameters to generate a wide enough range of frequencies when blown into; their size must be small enough to be embedded into handheld objects; and they should be printable in any orientation. After experimenting with numerous cavity shapes (spheres, tubes, cubes, pyramids, cylinders, and their combinations), the geometry that resulted in the best combination of clear sound and multi-orientation printability was a sphere with a tube connecting to the surface of the model.

Leveraging the principle of acoustic resonance, where particular frequencies are amplified or attenuated due to the physical properties of a cavity, we embed spherical cavities inside a 3D-printed model with straight pipes openings onto the surface. The resulting frequency is tied to the area, and length, of the opening to the surface and the volume of the embedded cavity. This is commonly modeled using the Helmholtz [5] resonance equation:

$$f = \frac{cd_t}{\pi}\sqrt{\frac{3}{8(L_t + .75d_t)d_s^3}} \quad (1)$$

where c represents the speed of sound, d_s the diameter of the cavity, and d_t and L_t the diameter and length, respectively, of the tube connecting the cavity to the surface of the model. Figure 1 provides an illustration of these parameters in a Blowhole cavity.

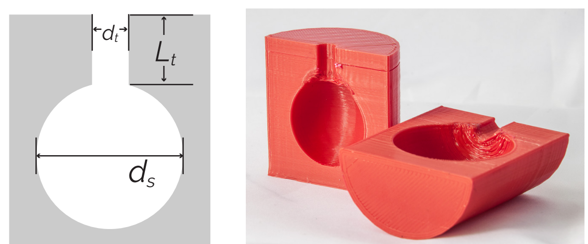

Figure 1. Left: an ideal spherical Helmholtz resonator, with tube diameter d_t, tube length L_t, and sphere diameter d_s. Right: cross-sections of two Blowhole test objects, showing the resonator structures.

To better understand the limitations of the frequencies we could detect and differentiate between, we took an experimental approach by printing 48 objects enclosing different sized cavities between them (a subset of these objects is presented in Figure 2). These objects were replicated in multiple FDM[1] printers (Qidi Technology X-One, LulzBot Taz 4, and LulzBot Taz Mini) to compare the differences in the resulting frequency, if any. We then asked 10 people to blow on each cylinder, while we recorded the data using a laptop computers' built-in microphone. Figure 3 presents spectrograms from one for a series of blows into different cavity configurations.

Implementation

Blowhole is comprised of three main parts: a design software to modify existing 3D models; the objects augmented with resonant cavities; and a software that recognizes the sound caused by the user blowing into an augmented object, triggering the corresponding action.

Design Software

Our software is built on top of Autodesk Meshmixer, making use of its Python API to remote control the suite, and execute commands. After the user has tagged all the desired positions in the model, and linked them to their corresponding action,

[1] Fused Deposition Modeling—the most-common consumer printer technology

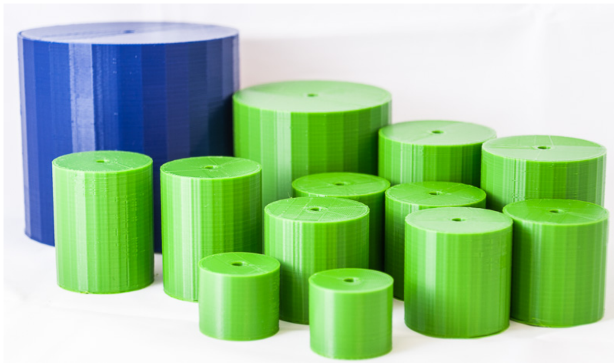

Figure 2. A subset of our test cylinders with varying cavity volumes and tube lengths.

we find a set of L_t and d_s that can fit in the requested locations without cavities colliding, using a depth-first search algorithm with backtracking.

Blowhole-enabled Objects
Because our system embeds resonant cavities in existing models, the printability of said model is not affected. Thanks to the capabilities of most hobbyist 3D-printers to print up to a 45° overhang without the need of support material, embedding Blowhole cavities does not cause any extra cleanup on the augmented object (aside from removing some "3D-printer spaghetti", some of it can be seen in Figure 1). The little to none cleanup and the complete lack of assembly required to interact with a Blowhole-enabled object means that the maker can interact with his fabricated object directly off the printer.

Blowhole-enabled objects can be used for a different number of applications. In our paper we present six different uses for Blowhole-enabled objects that illustrates the potential for Blowhole, from those, we present three:

Music Controller. We built a "music box" comprised of raised controls, each augmented with a Blowhole cavity inside, capable of controlling the music playback by blowing. Blowhole is robust enough to background noise that its performance was not affected by music playing in the background.

Cell Model. We augmented a model of an animal cell[2] by adding Blowhole tags to different parts of the cell. When the user acts on the tags, Blowhole launches the accompanying Wikipedia cell for the corresponding cell component.

Interactive Animals. We fabricated three different cetaceous: a dolphin[3], and two whales[4], and set the position of the cavity to the animal's blowhole. When these objects are interacted with, a corresponding video is played on the user's computer.

Blow Sound Recognition
While exploring new wearable interactions in Bitey [2], we learned very useful concepts on acoustic signal processing and machine learning. We employ these concepts in the recognition of the sounds produced when the user blows into the Blowhole cavities. We window the 44.1 KHz signal in 0.1 second, non-overlapping segments. After computing the RMS value for each segment, we look for 0.5 seconds of contiguous windows that exceed an empirically set threshold, representing the presence of sound. Using Welch's method [20], we extract the power spectrum of the signal and use the strongest frequency as the resonant frequency of the sound. We then match this frequency to the frequencies generated by the set of cavities configurations (d_s and L_t) to determine which hole the user is interacting with. Once classified, we execute the associated action present in the configuration file created by the design software.

The robustness of this algorithm was evaluated against the data gathered from our participants, obtaining a 98% average accuracy (please refer to the paper for a complete discussion of these results).

Future Work
We believe that some of the main strengths of Blowhole is its playfulness and its capabilities to translate a physical location on an object to an acoustic signature. Therefore, we are interested in exploring how Blowhole is used by children and sight impaired users in a controlled user study. This study will help assess the experience of these two populations while using Blowhole.

New Interaction Mechanisms
We continue to explore the different mechanisms we can utilize to enable interactivity in 3D-printed models in an maker-friendly way. As we did with Blowhole, we aim to leverage naturally occurring properties to enable interactivity in fabricated objects. In this section we will present our current, and future, efforts in adding interactivity to 3D-printed models.

AirTouch
For the next addition to our interactivity toolkit, we draw inspiration from Blowhole, as we continue to leverage sound generated by air currents to enable interactivity in 3D-printed objects. We focus our efforts, this time, to augment the fabricated objects by adding touch interactivity. As all future additions to our toolkit, AirTouch must satisfy the aforementioned qualities to guarantee maker-friendliness.

To enable touch interactivity in 3D-printed objects, we will make use of Bernoulli's principle for fluid dynamics [3] to design a system of pipes with openings to the surface, which will be embedded inside the fabricated object. When connected to an air source (e.g. air compressor), this structure will route the airflow through the object to the different places of interest identified by the maker. These ducts will be configured in a way that they afford air to flow to these openings, but when the opening is covered (e.g. by a finger) the air corresponding to that opening is then rerouted through an exhaust pipe. Each corresponding exhaust pipe will be corrugated with a unique pattern that translates the flow of air into predictable, identifiable, sounds. Figure 4 presents a simplified model of how these air ducts will look inside a 3D-printed elephant, where the airflow begins in the elephant's trunk and is then propagated using previously described structure.

These structures can enable a variety of touch interactions on the 3D-printed object, ranging from simple touch interactions,

[2] http://www.thingiverse.com/thing:689381
[3] http://www.thingiverse.com/thing:1121803
[4] http://www.thingiverse.com/thing:232247
http://www.thingiverse.com/thing:665571

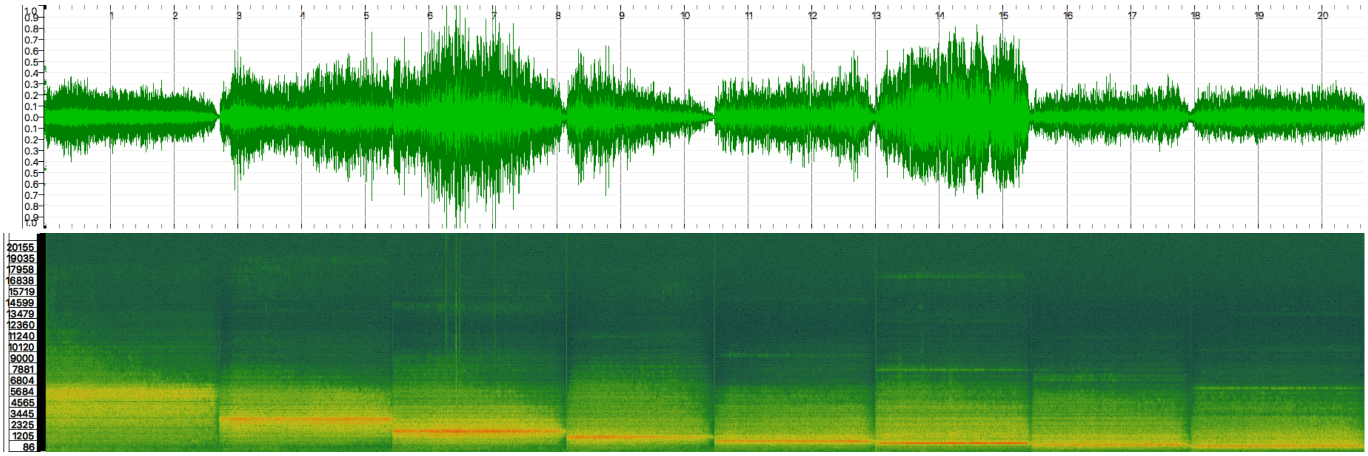

Figure 3. Waveform (top) and spectrogram (bottom) of blows into holes with a tube length L_t of 2.5 mm, with the cavity diameter d_s varying in steps of 2 mm from 4 mm on the left to 18 mm on the right.

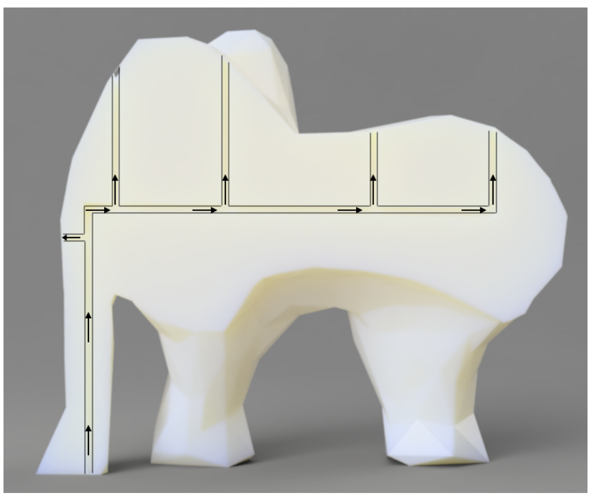

Figure 4. A simplified example of the pipe structure inside a 3D-printed elephant.

to more complex gestures like sliding and long-presses. We will enable these interactions by analyzing the duration of the already identified signal.

Similarly to Blowhole, AirTouch will be made up of three main components: a design system that allows users to modify existing three dimensional models, the AirTouch-enabled objects, and a wearable-based recognition software that identifies the emitted sound, triggering the corresponding action.

Once we finish developing AirTouch, our next step will be to evaluate the usability of our system. To do so, we will recruit up to 15 novice makers from the local makerspace and carry out a user study. In the study, we will observe how the participants use AirTouch to augment existing designs with touch interactivity, noting all their comments throughout the process.

CONCLUSION

In this paper we presented and analyzed the obstacles that plague the current state-of-the-art in the fabrication of interactive objects. In response to said limitations, we introduce our effort to lower the complexity on adding interactivity to fabricated objects by leveraging natural properties. Our solution takes the form of an Interactivity Toolkit where the maker can choose which mechanisms to augment its object with. As a first addition to this toolkit, we introduced Blowhole, a system that allows the maker to tag its three dimensional models using blowing-activated tags. Additionally, we present our current efforts in populating our Interactivity Toolkit with AirTouch. Here, we will embed a system of air ducts inside a three dimensional model to leverage touch interactions and enable a variety of gestures.

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APPENDIX

This work was performed in the Future Everyday Technology Research Laboratory (FETLab) under the supervision of Dr. Daniel Ashbrook, the director of this space. The FETLab focuses its work in the democratization of digital fabrication technologies (e.g. 3D printing, laser cutting, CNC milling). The premise behind their work is that, although digital fabrication equipment are now reasonably priced to be afforded by enthusiasts and hobbyists, the tools and process accompanying these still present high levels of difficulty which not all novices can reach. The work presented on Blowhole was carried out by the Acoustic Interfaces group comprised of Zhiyuan Li, Osamu Fujimoto, and myself, where Zhiyuan was responsible for the implementation of the design software, Osamu focused on experimenting with the different cavity shapes and sizes, and I was responsible of the development of the sound recognition section.