Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication

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ABSTRACT
This paper details the design and evaluation of *Being the Machine,* a portable digital fabrication system that places digital fabrication activity outside of the traditional fab lab environment. Being the Machine invites people to (re)consider materials found in their everyday and personal environment as part of the fabrication activity. We expand the design space involving hybrid (physical-digital) fabrication by describing how our system draws from art to support critical and reflective modes of making. In interaction with our system, participants distributed control between human and machine actors to support their preferred mode of making. These patterns reveal new opportunities and challenges for future hybrid fabrication systems, and suggest that designing for qualities of *experience,* like meditation and reflection, could support meaningful making experiences for many different kinds of makers.

Author Keywords
Hybrid fabrication; art; 3D printing; everyday materials.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Digital fabrication has been a growing topic of interest in HCI. The vision of personal fabricators suggested by Gershenfeld in 2007 is looking more like reality as digital fabricators proliferate outside of privileged laboratory settings [6] and become more economically accessible for a wide variety of people. As digital fabrication is poised to enter our schools and homes, it is important to consider the values and assumptions that are implicit and not yet studied in the designs of digital fabrication systems [1,20,28]. The way a fabrication system is designed configures relationships between humans, machines, materials, and digital models, and reflects the ideology of the designers: ideas of who or what should have agency or control in the making process. These configurations can have powerful effects on what people feel, experience, or express while engaging in digital fabrication activities.

We look to the values of art practice to suggest new configurations of humans and machines in hybrid making and present *Being the Machine,* a system that guides users in building 3D models from everyday materials by following instructions typically given to 3D printers. Technically, the system uses a single laser point to communicate the position of a 3D printer head. Much like a 3D version of the game connect-the-dots, users follow the movements of the laser point while "extruding" materials to create a physical version of their digital model.

By inviting the user to become the machine, Being the Machine aims to:

- Elicit active and personal reflections on human-machine relationships by reconfiguring expected roles of humans and machines in hybrid making, exposing tensions between agency and control.

Figure 1: Being the Machine guides people in building 3D models with everyday materials. One user made a pair of glasses using found Magnolia leaves.

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- Engage people with a wide range of materials (beyond typical plastic filaments), allowing for opportunities to reflect on the interplay of low-tech material practices and high-tech mechanical processes.
- Use human hands as the mechanically controlled tool, trading precision and control with the ability to realize surprising and unexpected forms.

In order to evaluate Being the Machine, we invited 14 individuals with different backgrounds, motivations, and styles of making to use our system. We found that our system was able to support aesthetic experiences and critical reflections on the relationship between human and mechanical modes of production. Users negotiated control between themselves, our system, and their materials in order to enter into meditative, reflective, and collaborative modes of making, which they believed to enhance their personal creativity.

By subverting an expected relationship between humans and machines in making, new roles for digital fabricators in physical making practices emerged. This paper contributes descriptions of these roles in order to expand the design space of hybrid-fabrication. Additionally, we reflect on how the values of art that informed our design were enacted in each role and the potential these values hold for future research.

BACKGROUND

A 3D printer can be considered as the emblematic technology of the "maker movement." While some see the movement as revolutionary and empowering [2,6], others criticize it as consumerist and corporatized [13,28]. With Being the Machine, we offer an opportunity to encounter 3D printing in a way that could encourage personal reflections on the 3D printing as a cultural symbol. Existing digital fabrication systems and hybrid-craft tools *could* be used to this critical effect, but we believe that their current designs do not necessarily *invite* such reflections in everyday users.

We looked to art, a mode of making that involves questioning, reflecting, and interrogating technology [5], to inform our design. In the following sections, we present our theoretical framework, which draws from art and material studies. We pair semiology [3] and Ingold's concept of making as *correspondence* [11] to describe the intellectual and physical work performed by artists.

Values in Art Practice

The study of art is often paired with lessons on semiology [3]. Semiology is the study of *signs.* A sign is composed of the signifier and the signified. For example, a tree (signifier) can signify many things like growth, nature, or sustainability (signified). When creating an artwork, artists are relying on cultural interpretations of signs and juxtaposing them in order to articulate and set forth new ideas or questions. For example, Warhol's famous silkscreens of celebrities are meaningful not only because they are visually interesting, but also because they use mass production techniques. By juxtaposing celebrities, aesthetics of advertising, and the processes of mass marketing, Warhol posed a provocative question: What is an art object in the age of mass commercialization?

Accordingly, one value of art practice is the **ability to explore the semiotic effects that are produced when different materials, contexts, and processes are brought into juxtaposition with one another**. As 3D printing takes on increasing cultural capital, it can be valuable for makers to bring different materials and contexts into dialogue with this particular process.

Another value is **the ability to understand a medium on both symbolic and technical levels**. To understand the symbolism of 3D printing, it is important to situate it within a particular culture and reflect on how that symbol is represented and understood by that culture. To understand it technically, one must be able to open the black box of 3D printing and ask what else the mechanical motions and actions of the machine could symbolize.

Correspondence with Materials

The physical work of art making can be conceptualized by Tim Ingold's view of making as *correspondence* [10,11]. Ingold argues that making is often incorrectly understood as the translation of an idea in the mind to material form. In this "hylomorphic" view of making, "Form came to be seen as imposed by an agent with a particular design in mind, while matter, thus rendered passive and inert, became that which was imposed upon" [10]. Alternatively, Ingold argues for a non-hylomorphic view of making where a maker "joins forces" with "active materials" and works with them "in anticipation of what might emerge" [11]. He describes making as *correspondence* between the desires of the maker and the desires of the materials. In correspondence, active materials "speak" to makers through their physical properties, how much they are willing to bend or fold for instance. While the maker may begin with a form in mind, form ultimately emerges from the interplay of human and material forces. In correspondence, the maker grows with a set of materials and practices, becoming attuned to their properties or forces and generating knowledge that carries through their practice.

Ingold might describe the current state of 3D printing as hylomorphic because of the way it imposes form on materials that have been engineered to be passive or easily molded into any form. A 3D printer designed through the lens of correspondence would allow for the building materials to play an influential or "active" role in shaping the form that is produced. Where existing 3D printers attempt to precisely determine the outcome, a non-hylomorphic system would place a premium on the human experience of working with the machine as one of many material forces to be negotiated in making activities.

RELATED WORK

Design Tools

Designers and artists often use technology to guide their work. For instance, some muralists use projectors to enlarge an image onto a wall to be traced and painted. Design tools tend to serve an instrumental purpose, offering a means to an end rather than the symbolic presence of a particular practice. We align Being the Machine with practices like IKEA hacking [19], where standard guides or tools, like instructions for assembly, can be engaged and reinterpreted by makers to create new structures. In these practices, the very act of subverting or reinterpreting the instructions becomes visible and meaningful in the resulting work.

Hybrid Craft

Work studied as “hybrid” craft [8,27] explores forms of making that blend digital and physical practices. *FreeD* [26] and *Haptic Intelligensia* [22] draw from existing craft practices to design tools that allow users to sense and react to digital models in physical space. We contribute additional insights to this area of research by using art values to add a symbolic layer to hybrid interactions. By asking people to build in the style of a 3D printer, and not as a human might normally work, we aim to provoke reflection on a specific process with cultural relevance.

Another trend in hybrid craft is to increase efficiency and precision. *Sculpting by Numbers* is a system that offers projected feedback to assist users in precisely recreating models with common materials like clay [17]. Rivers et al. also developed a table router that allows a user to guide the machine along a general path while the machine cuts the fine details [18]. In both projects, the machine acts as a helper that allows a user to create precision models. Mistakes or “happy accidents” can be a resource for new inspirations and creative insights [12]. Accordingly, we make room for human inaccuracy by withholding feedback on human actions. By using a minimal interface (single laser point) rather than a projector system, we intend to shift focus from a pre-defined outcome and towards the materials in order to offer a more reflective and potentially surprising making experience.

Interactive Fabrication

Researchers in the area of interactive fabrication look to create real-time links between the actions and movements of one’s hand and the actions of a machine [14,23,24]. In this line of work, the machine responds to human action. In our system, the machine *steers* but does not determine human action. In a way, we limit the freedom of human movement by turning it into the machine’s movement. It is this very constraint of mechanical movements we wanted humans to feel and experience. By creating a visceral connection between body and machine, we aimed to provoke a user to reflect on the tension between controlling and being controlled.

Humans, Machines, and Fabrication in Artwork

The relationship between human and machine has been explored extensively over the last century through performance art. Our design was inspired by turn of the century Futurist “mechanical performances” that used mechanical technologies, like the printing press and the steam engine, to choreograph human movements [7]. While traditional theater of the time attempted to represent modern life through realistically painted sets, Futurists felt that the sounds and movements of modern machines offered a better representation of the chaos and dynamism of modern life. A tradition of contrasting body and machine through performance has continued through contemporary art [7] and demonstrates how the symbolism of objects, human actions, and machines can be juxtaposed to produce provocative and critical statements.

3D Printing with Everyday Materials

Designers, hobbyists, and researchers are developing 3D printers that work with everyday materials from felt [9] to concrete [29]. Shewbridge et al. studied potential uses of 3D printing in the home and found that participants in their study were interested in using common materials like ceramics and metals to make household tools or to repair meaningful objects [21]. Their study focused primarily on practical usage of 3D printers. Our study looks to compliment this work by exploring how 3D printing can be encountered creatively in the home as well as in and out of everyday life.

DESIGN PRINCIPLES

Drawing from values in art practice and Ingold’s notion of correspondence, we derived the following principles for our design of Being the Machine:

Passive Machine / Active Materials

In order to support the ability to combine different processes and materials, as well as bring the concept of “correspondence” to the fore in digital fabrication activities, we invite human bodies and hands, and not the machine’s “body,” to take an active role in working with materials. Ingold uses the terms “passive” and “active” to reflect the degree to which an entity enacted in a making activity (human, machine, material) determines the form that emerges. In traditional 3D printing, plastic filaments are molded into predefined shapes. In terms of correspondence, the 3D printer is *active* as it imposes form onto materials and the materials are *passive* as they receive the form. Our system places the human between the machine and the materials in order to activate the materials while limiting the control of the machine. Working with one’s hands allows for more visceral and direct interaction with a wide variety of materials, thus leading to more personal experiences and insights. The goal of our machine is to guide human hands to reach this experience.

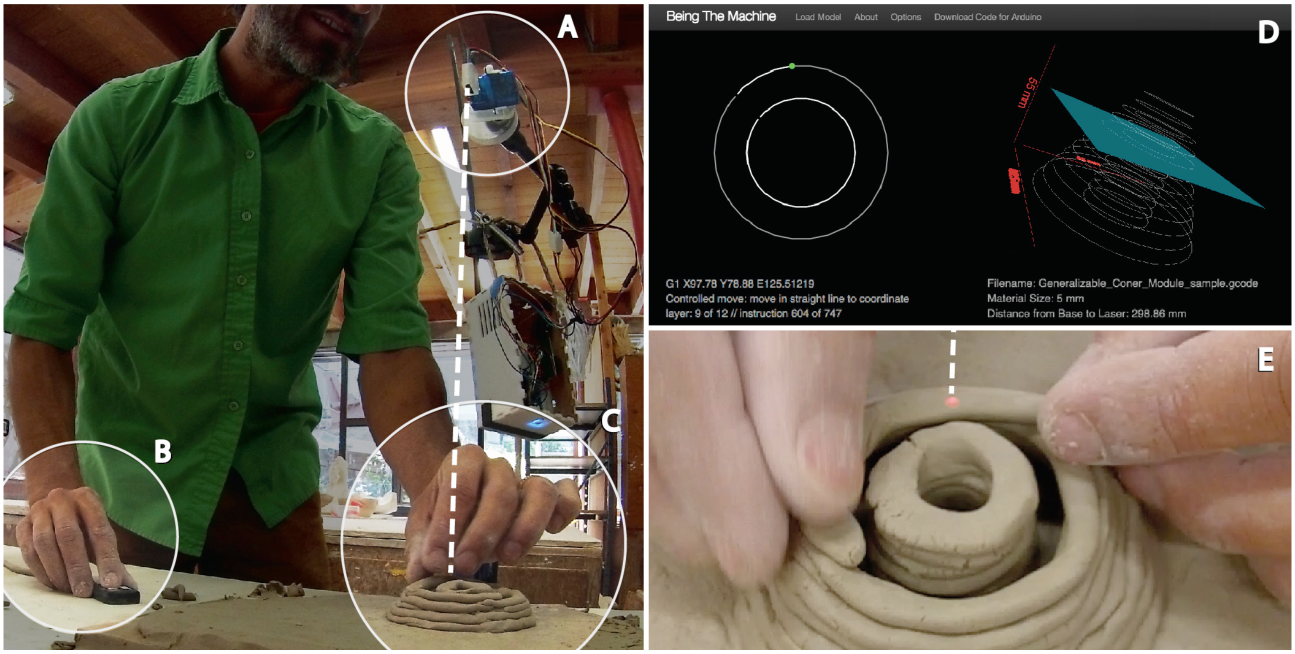

Figure 2: An overview of Being the Machine. A) A laser guide draws a point on a 2D plane. B) A user pushes next and back buttons on a wireless key fob to move the laser point to the position of the next or last G-Code instruction. C) The user moves her materials to follow the path of the laser. D) Our G-Code visualization software allows the user to see the paths of her model in 2 and 3 dimensions. E) A close-up view showing what the user sees (a laser dot) when building their model with Being the Machine.

Guide Rather than Instruct

Not only should the machine take a passive role in terms of manipulating materials, but the machine should also take a more passive role in determining human actions. Like Ingold, we see form as emergent rather than predetermined, which makes the idea of designing a system to show a user the "right" or "correct" way to build something irrelevant. Instead, we present the machine as a guide, framing it as one way to go about building while inviting the user to reinterpret its instructions as they please.

In order to play with artistic juxtapositions, it is important to leave room for makers to bring their own building strategies and materials to the system. Designing a system to instruct users would require constraining the machine in order to address a limited set of predefined material practices. Rather than constraining material practices, we chose to constrain the machine by only allowing it to communicate a minimal unit of information needed to guide a user in building a 3D model, a single laser point. A laser point makes very few demands except to be seen, and invites users to follow with any method they see fit.

BEING THE MACHINE: TECHNICAL IMPLEMENTATION

Being the Machine translates G-Code instructions (step-by-step functions that tell a 3D printer what to do) into a form that the user can follow by hand. In order to accomplish this, we developed our own software and hardware components. The G-Code visualization software we developed allows the user to see the paths specified by a G-Code file in two and three dimensions [Figure 2d]. Using arrow keys on her computer, the user can navigate through the instructions or layers in order to visualize the overall shape of the paths and the order in which they will be drawn.

The hardware consists of an actuated laser guide, a laser pointer attached to two servo motors in a pan-tilt configuration [Figure 2a]. The guide can point to nearly any position on a 2D plane and we use an Arduino to move the laser to point to the position indicated by a G-Code instruction. All of the building instructions are stored on the Arduino and the user is able to tell the system to move to the next or last instruction using buttons on a wireless key fob [Figure 2b]. We used a magic arm tripod mount affixed to a 24" clamp to mount the laser guide above a building surface (table, floor, etc.). The software interface tells the user how far she should position the laser from the building platform in order to generate a model with the specified dimensions. While a projector system could have performed many of the same functions as our laser guide, the low power usage and high light intensity of our guide offered increased portability.

To use Being the Machine, the user locates a digital model and the materials with which she would like to print. Any standard digital model, like those found on thingiverse.com, can be used with our system. Next, the system converts the digital model into G-Code. This conversion typically takes place within 3D printer software, but freely available tools allow us to generate G-Code files independently of owning a 3D printer. In our examples and studies, we used *Slic3r* [16] to generate G-Code for RepRap 3D printers because it allowed us to customize building parameters like layer height and material width and generated simple files that used only straight-line moves (G1 instructions). The user measures her building material and enters those measurements to Slic3r in order to generate G-Code specific to her building materials

Once the user prepares a G-Code file, she imports it into our G-Code visualizer, which parses and displays the paths that are described by the file. At this moment, the user can make judgments about the structural integrity of her model. For example, if she is building a tree with branches that extend out from the base, she can look at the visualization to see if each layer will have enough support from the layer below to remain structurally sound. If not, she can go back to Slic3r and adjust the settings to add additional perimeters or scaffolding. Once the user is satisfied by what she sees in the visualization, she can upload the code generated by the G-Code visualization software to the laser guide for building.

To begin building, she positions the laser at the correct distance from the base (as indicated on the visualization) and pushes "next" on the key fob to queue the first instruction. This moves the laser guide into the position specified by the first G-Code instruction. She places her material on the laser point and hits "next" to advance the laser point to the next spot specified by the G-Code instructions. She connects the current location of the laser pointer and the previous point by filling the space with her material. She follows this pattern until the laser turns off, indicating that she has reached the end of a path. The process of following the laser and building path by path and layer upon layer continues until the model is complete.

STUDY

In order to observe the range of engagements with the tool, we invited participants to select the models they would build, the materials they would build them with, and the location in which fabrication would take place.

Methods

We sent email calls to local arts groups, maker spaces, and university lists. We also sent a short video to interested participants that explained how a 3D printer works and how it related to Being the Machine. The video included time-lapse videos of a researcher building three example models: a hand made of pipe cleaners, a vase made of live flowers (with additional images of the vase decaying over time), and a gun made of "Good & Plenty" candies [Figure 3]. We carefully chose this particular set of examples to invite curiosity and demonstrate the variety of materials the system could accommodate. Prior to meeting, we asked prospective participants to watch the video and send a list of materials and models that they would like to use with our system. Participants were not screened based on their responses; we simply wanted to prepare a selection of materials that might be of interest to the participants. We

Figure 3: We showed examples of constructions produced with Being the Machine to prospective participants.

also invited participants to bring materials of their own to the study.

We conducted fourteen one-on-one study sessions in various locations including participants' homes, studios, and indoor and outdoor spaces on a university campus. When participants arrived to the study, we asked them to complete a 15-minute introductory activity (following the laser with a pencil to draw paths on paper) to become familiarized with the process before they embarked on their own project. After they felt comfortable following the laser with a pencil, we asked them to select materials and a 3D model to build. The participants were free to choose the order in which these items were selected. In some cases, participants took short walks to survey the local environment for interesting materials. The participants selected a 3D model using thingiverse.com. We used the 3D model, information about the user's desires (e.g., hollow, bigger, less complex), and information about the materials to generate a G-Code file. We helped with scaling the chosen models and identifying specific G-Code options to allow the model to be completed in a relatively short amount of time (about 90 minutes in most sessions).

Before building their 3D model, we told participants that there was no "right" way to use the system and that they were free to follow (or not follow) the laser point however they pleased. We also made the laptop with the visualization of the paths available for the participants to reference as much as they wished. We asked participants some questions about their approach, ideas, feelings, and thoughts while they built their models. When their model was completed, we asked participants about their experience with the system.

FINDINGS

Fourteen individuals from ages 22 to 43 participated in our study. The sessions varied in length between 2 to 4 hours. While some participants identified themselves as a single kind of maker (e.g., "I'm a knitter"), others felt they took on multiple roles and sought different experiences in each role. As Matt put it, "as a maker I strive for efficiency, then as an artist I see that efficiency sometimes gets in the way of really great things." Five participants had previous experience creating prototypes, custom parts, artworks, and/or create figurines with 3D printers. Nine participants knew something about 3D printers but had never used one.

Participants used the system to make many different objects: Nina created a pair of wearable glasses using leaves from a Magnolia tree [Figure 1]; Vanessa used the

system to make a squirrel shaped treat for her dogs from stacks of peanut butter and bread; and Josh created a musical score for a string trio based on the model of a gun.

For most participants, material choice was primarily based on the aesthetics ("this leaf has a nice shine"), the properties it offered ("I want something that layers well"), or supply ("I've always wanted to know what I could do with all these leftover corks"). Others came to the study with materials they had been working with for some time and saw Being the Machine as an opportunity to subject these materials to new forces. For example, Ellen was an artist who worked with discarded plastic bags. She was interested in using our system to try something entirely new with these familiar materials. Model choice was primarily dependent on personal interest (e.g., "I want to build a spaceship" or "I want to make something wearable") or how well they thought the machine could help (e.g., "I want to make something simple to get a feel for the system" or "I want to make something complex because this system is helping me").

Participants had different strategies for using Being the Machine. Terms like "trust," "control," "time," and "meditation" emerged regularly in their discussions and they experienced them in different ways. As we analyzed our transcripts and videos following the methods outlined by Charmaz in *Constructing Grounded Theory* [4], we identified four roles that participants cast for the machine during their making process. We discuss each of these roles in the following sections.

Machine as an Omniscient Helper

Participants who encountered the machine as an omniscient helper expected the system to show them the "right" way to build their model.

For Jack, the "right" way to do something was connected to the right way to use the materials. Jack was fixated on the onscreen visualization of the paths and kept checking his model to make sure it looked the same, expressing frustration when the pipe cleaners he used made it difficult to replicate the outline exactly. He was willing to give the system control over his actions but started ignoring the system when challenges appeared. He said, "It's hard to mimic or build something from scratch if you don't understand the materials very well…if the thing could assist you with new materials, that would be cool."

Anna had a similar experience. She also gave the machine a great deal of control over her actions and used a pencil to mark the paths so she could get them exactly right. For Anna, the "right" way to build something was the way that best fit her own personal tastes. She did not like the fact that she had to build along paths and that she had to move the laser point back and forth to see if her path was correct, saying, "I don't want to do that. And then if I don't do that I'm out of alignment. But then still I don't want to do it, so it's difficult." Like Jack, she ignored the laser once it became difficult to follow the pointer with her materials.

Like many of our participants, Jack (a programmer, gardener, 3D print enthusiast, and painter) and Anna (knitter) liked to make things by hand and described the value they found in the time consuming repetition that handwork often required. They saw technology as something that should be introduced to teach them new tricks or techniques, not to present new challenges to overcome. In relation to our system, their interest in corresponding with materials was fairly low. Anna chose her materials because she "thought they would do what I wanted" and would have preferred a design that cut out layers "like a cookie-cutter" to be stacked in order to create interesting shapes. For both participants, focus was placed on what new shapes they could make and not on getting to know the materials and how they could be molded and synthesized into variations of those shapes.

Machine as a Collaborator with Unique Talents

Participants who saw our machine as a collaborator with unique talents sought a symbiotic relationship with our system. These participants expect the machine to be good at things computers do well (e.g., visualize models, make calculations), while the human was in charge of things that humans do well (e.g., working with materials, responding to unexpected events). Participants in this category did not identify themselves as artists. Nina liked making various wearable things for fun, Katie liked scrapbooking, and Clare generally enjoyed working with her hands on DIY projects. Vanessa identified as a programmer and educator who liked helping other people make things, but did not do much making herself.

These participants saw the system as an opportunity to work with their hands and did not necessarily want or expect perfection from their resulting model. Clare put it elegantly when she said: "I guess I like that the machine is the expert on the abstract shape and I'm the expert on the material. I feel like we have a nice division of roles and the machine isn't making me feel stupid. The machine is only making the suggestion, I'm the one realizing it."

Vanessa felt similarly, expecting the machine to help her with the model but not expecting it to be particularly knowledgeable of her construction technique: "I'm not obsessed with every single point. A. Because it's bread [the material she is working with] and B. because I have an Exacto knife and a peanut butter paintbrush [her joinery material and cutting tool] so there's only so much you can do. That being said, even if this laser was so accurate it could fire a missile, I don't think I'd choose to use my time by tracing each dot so it's perfect…my goal is to make something that's roughly like a squirrel."

Both Vanessa and Clare were pleased with their experience and results, even though they did not conform exactly to their computer model. Vanessa fed the squirrel she made to her dogs and Clare put her Ivy goat head on the living room table, saying that it felt "like a house plant."

Nina and Clare's patterns of use illustrate the concept of correspondence. The ability to enter into close material engagements while building from a 3D model was one of the primary reasons they enjoyed Being the Machine. This was evident in their styles of working. When Nina used Magnolia leaves to create a pair of glasses to wear she took care to cut her leaves along the veins to preserve the natural curves and "poetry" of the leaves. She used the strong spine of the leaves as something that could add structural integrity to her model. When she was searching for building materials, she noticed that dead leaves take on a suede like color and texture. The idea that her glasses would eventually decay and transition into a new texture was interesting to Nina.

Clare built a model of a goat's head from ivy gathered in her back yard. She avoided cutting the ivy with scissors and instead, bent the ivy along the paths and glued them into place. She wanted her materials to help her reveal an interesting or surprising form, saying, "I did not want it to conform to the shape exactly because then I would just use a 3D printer, I wanted the materials to influence what the shape would be."

These participants also began to engage with the semiotic aspects of their project. Clare liked the idea of her goat, "being composed of the things that it eats." As she was building, she made another observation, "…ivy and goats, they are both pests to some degree." Nina had a different encounter with the symbolism in her model. In a follow up email, she talked about a moment when her friends' interpretations of the glasses differed form her own interpretation. Her friends thought her glasses were "weird." As she explained how she made them, her friends suggested that it could be an interesting way for girls to learn about technology like 3D printing, she wrote, "I thought this is interesting feedback, I never thought about gender in relation to this system." In this example, encounters with the objects after it was made provoked new insights and reflections about what objects represent and what the combination of handcraft and 3D printing brings to mind in different audiences. This suggests that opportunities for reflection on "making" and its cultural relevance are not confined to making activities. The objects, especially "weird" ones, and the way in which audiences encounter them in daily life can also act as an important site for semiotic reflection to take place.

Participants who worked in this mode liked the idea of working with their hands to "enter a creative state of mind," "relinquish control," or simply take time to look at something other than a computer. They liked that the system was specific enough to help them build interesting items from computer models but also open enough for them to come up with their own strategies for building.

Machine as a Generative Constraint

Participants who saw the machine as a generative constraint were curious how this particular process could help them experience their existing art or craft practices in new ways. The relationship between human and machine was one of intrigue. The machine was encountered as an entity that had an interesting and culturally important way of transforming data into 3D forms. The participant's approaches were characterized by curiosity as they attempted to find out how interesting this machine could be when put into "dialogue" with their existing practice.

Most of the participants who interacted with the machine in this mode had backgrounds in the arts. Josh was a composer who received his PhD in Music, Ellen was in school for her Masters in Fine Arts, Zach was an industrial designer, Arlo was an exhibiting artist who frequently used fabrication machines, like 3D printers, in his work, and Matt was a ceramics professor and exhibiting artist. The ability for our study to attract the attention of artists was interesting in and of itself, suggesting a potential match between the artistic values we used to inform the design and what these artists really did value. It also indicates that artists have an interest in exploring the liminal space between human and mechanical making practices.

Participants in this mode spent the most time with the system, displayed patience, and gave the machine a large degree of control over their actions. They felt comfortable with the idea of working through difficulties to reveal new possibilities, in the words of Matt, "I'm fine with struggling, I'm a good struggler."

For Matt, giving control to the machine was a way to make the machine visible as a symbol in the work he created.

Matt chose to make a spiral staircase out of clay. The G-Code file for Matt's staircase model has some unusual features. Each stair has a bit of internal scaffolding, which looked like a "squiggle" in the middle of the outline of the stair. Matt remarked, "I want to represent that squiggle" and when we asked him why, he said, "the red dot (laser) is telling me to, I want to follow the red dot no matter what." He used various tools and techniques to adapt to the dot. When the wet clay of the staircase model succumbed to the force of gravity, he decided to try a new dot-friendly strategy of coiling the clay in order to create a model of a cone. Adapting to the dot seemed to be a way to represent the "hand" of the machine in the products created. Matt thought the idea of using clay to create mechanical scaffolding patterns in simple structures, which "could have been beautiful." In this case, the idiosyncrasies of 3D printer paths were seen to have aesthetic potential and the ability to add new visual textures to his work.

For Josh, a composer, the machine offered an opportunity to translate 3D forms into music. He followed the laser point, placing a note at every position where the laser stopped. After creating his composition from a 3D model of a gun, he came up with more ideas about how 3D printing process could be interesting in the context of composition: "The idea of layers is extremely rich…I could decide that the points from the first layer are going to be pitches, the second layer is going to be rhythms, the third level is going to be dynamics, the fourth level is going to be articulation, the fifth is going to be…something else. It could start very basic and getting very specific as the gun, or other object, comes into focus."

The ability to work in a hybrid space was appealing to Josh because it offered him access to digital information through a familiar medium. Josh mentioned that he could also translate 3D models to music through programming but he felt most comfortable working by hand. He described how the constraints imposed by software, even if he programed them, might make him feel "alienated" from his own work. Because our system delegated action to Josh, and not the computer or machine, Josh found his experience with Being the Machine to be more personal than working on a computer alone.

Machine as a Symbol of Perfection

Participants who saw the machine as a symbol of perfection used it as a way to confront and cope with personal feelings of imperfection.

Brynn, an art curator and game designer, saw 3D printing as a representation of perfection and control. She wanted to build a grandiose model like the Titanic or the Eiffel tower with Easy Cheese (a spreadable cheese that squirts out of a can). When asked why she wanted to use Easy Cheese, she said: "I knew that it would be impossible to do something perfect with Easy Cheese, so I felt more comfortable being more up front and candid about the fact that this is not going to be a beautiful object. Also, the absurdity. I really appreciate how 3D printing is a very formal, mechanized, precise process and we're kind of breaking that – we're using very sophisticated tools to do something very unsophisticated, which I appreciate a lot."

Failure was a theme in Brynn's session and she said, "I feel that failure and messiness is a really important component if you want to be good at anything." Brynn wanted to become more comfortable with the idea of failing and saw Being the Machine as an opportunity to work through some of her anxieties. She said, "I'm definitely a recovering over-achiever and I work really hard to not be super hard on myself, so this [points to her model] is an achievement." While she followed the machine paths in building, she was not concerned with being exact. At one point, her model was bumped out of alignment and she carried on without a worry. Her goal of failing seemed linked to not caring about getting things "right." Yet, the ability for the system to provide some point of guidance, the laser dot, that stood for "3D printing" and all the perfection it entailed seemed to imply that it could be perfect, thus making failure a viable alternative experience.

Gail felt that "creativity begets creativity" and described how her interaction with Being the Machine could cause her to see everyday things through a new "lens," which would make new creative uses of those things visible. She also used making as a way to confront uncomfortable feelings. She had recently taken up pottery and found it to be a positive exercise in her life. "What I learned in pottery was that I should try to do things not just because they were beautiful, perfect, or the best or something. It's still worthwhile to try things out, which sounds cliché, but I think it's good for me." She felt that breaking, in the context of making things, offered a valuable exercise in cultivating her own acceptance of imperfection.

3D printing, as a symbol of perfection, played an important role in these interactions as it prompted participants to look within themselves and confront uncomfortable feelings. A participant's ability to experience these feelings was tied to the system's potential for breaking and failure.

DISCUSSION

Four different roles for the machine were revealed in our study, each with a unique configuration of chance and control. The role of "omniscient helper" evoked a common expectation of machines as facilitators or teachers of new skills. The other three roles suggest new areas of interest for hybrid-fabrication design. The "collaborator with unique talents" represents a desire for people to work in close connection with diverse materials to create new forms from digital models. The role of "generative constraint" displays how mechanical processes can be enacted to push existing practices in new creative directions. And, the "symbol of perfection" represents a desire to use computation in making as a way to exercise personal acceptance.

Evoking 3D Printing as an Aesthetic and a Sign

We designed our system to support an artistic tactic of symbolic juxtaposition. Participants who identified as artists displayed the most attention to this tactic as they questioned the symbolism of performing 3D printer instructions by hand. In terms of correspondence, artistic interactions with our system were characterized by a simultaneous correspondence between materials, our machine, and the meanings that emerged from these combinations. This was reflected in the way artists used the system. While most participants saw Being the Machine as a way to make a particular kind of object, artists treated it as a method for *translating* an object across different representational domains. For instance, Josh described Being the Machine as a way to translate a 3D object into instructions ordered in time, to a spatial representation of notes in 2D space (a score), to music that would be performed and experienced in time. Framing the system as a process of translation allowed artists to understand the mechanics of 3D printing in terms that were familiar to their own practice. For instance, by seeing both G-Code and musical composition as instructions ordered in time, Josh was able to surface relationships between G-Code and composition that might push his practice in new directions.

Artists were interested in exploring both the symbolic meaning and aesthetic potential of the translation offered by Being the Machine. For Ellen, who created a to-go cup from discarded plastics, human labor became a prominent theme in juxtaposition with mechanical processes. She felt that doing her work entirely by hand or by machine would not have allowed for this meaning to come across in the same way. After completing her model of a cup, she crushed it in her hands and watched it spring back into form and then mentioned photographing it on her light-table to see if it cast interesting patterns. Ellen and the other artists did not see their objects as finished but as one possible state within an ongoing series of translations. Their interactions were oriented towards creative growth rather than the production of a particular kind of object.

Artists felt that the opportunity to interpret machine instructions by hand could produce interesting visual textures as well as commentaries on human-machine relationships. Yet, they felt that they needed more time to explore Being the Machine in order to understand its relevance to their own practices. They did not expect the machine to do the hard work for them or to make things look beautiful; rather, they wanted to enter into dialogue with the machine and play with its unique and symbolic way of constructing objects.

Participants other than artists, specifically those who saw the machine as a "symbol of perfection," also explored the significance of juxtaposing human and machine actions, but in a more personal way. For them, becoming the machine was encountered as becoming perfect and allowed them to juxtapose their imperfect actions with the concept of the perfect machine. By facing the chance of failure, a valuable opportunity for personal growth, in terms of both confidence and creativity, unfolds. While interfaces that produce beautiful results with little effort may be initially exciting and motivating, our results suggest that people also value experiences with technology that require initial struggle but reveal paths towards virtuosity, much like learning to play musical instruments.

Reflecting on Control and Human Experience

Participants valued Being the Machine and making-by-hand for similar reasons: it allowed them to slow down, focus, spend time with themselves, meditate, reflect, and engage with materials for the sake of engaging with materials. Many felt the attention required to follow a single laser point supported playful and immersive experiences that engaged body, mind, context, and materials. Participants were willing to "relinquish control" in order to open a space for these kinds of experiences. Such experiences could be described as aesthetic [5] and suggest that aesthetic interaction [15] and experience-centered design [25] could be useful frameworks for guiding the design of digital fabrication systems that foster reflective modes of making.

We found trust and control to be primary factors that shape experiences of hybrid making. By designing our machine to act on the user rather than materials directly, Being the Machine set up a space of possible actions for the user to traverse. The user's interpretation of the machine's instructions delegated differing levels of agency to the materials, machine, and the user, allowing them to cater our system to fit their desired experience of making. The willingness of many of our participants to enter into partnerships with the machine at the expense of predictable outcomes reflects the primary role personal growth plays in Ingold's non-hylomorphic view of making. This also suggests new opportunities for hybrid-systems research that explores ways in which humans, machines, and materials can operate as more equal partners in making.

FUTURE WORK

We plan on using the insights gleaned from this study to update our design and conduct longer-term investigations of our system. We are interested in how patterns of use change over time and new opportunities for design that may be revealed from these patterns. We plan on updating the system to make the aspect of portability more evident in order to study the way in which *place* factors into correspondence along with materials and meanings. We also observed that the lack of ability to display information in any form other than a single laser point made the system feel over constrained for some users. We plan to offer additional controls to vary the display, such as an outline of the entire layer, based on user desires.

By taking more advantage of our hands as sophisticated tools with machine guidance, it is possible to build objects and models at scales that are still difficult for 3D printers.

For example, making the machines "smart" enough to network with others could also offer interesting opportunities for collaborative building at large scales. We intend to conduct further studies that explore the potential of collaborative fabrication.

CONCLUSION

We designed and evaluated a portable hybrid fabrication system that invites people to build 3D objects with materials from their personal environment, while in the same process, encouraging them to explore the tension between mechanical and human modes of production. We found that a balance of trust and control was critical in allowing people to enter into their own aesthetic experiences with fabrication. By using a minimal interface to delegate machine instructions to users, our system allowed users to interpret machine commands to fit their desired experience of making. The way in which users interpreted the machine commands revealed four kinds of relationships to fabrication technologies and demonstrated the potential of reflective, experimental, and collaborative engagements with digital fabrication systems. The values of art we used to inform our design were successful in supporting open-ended and semiotic forms of making, which participants found to be valuable in their daily lives.

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