Machines as Co-Designers: A Fiction on the Future of Human-Fabrication Machine Interaction

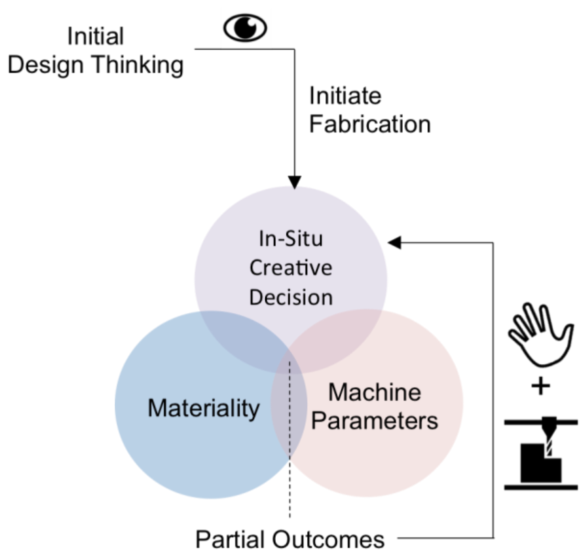

Figure1. Co-constitutes of an *Interactive, Concurrent,* and *Collaborative* fabrication pipeline between human and the fabMachine. Initial design thinking iteratively evolves throughout emerging design processes, gradually augmenting partial outcomes of human action, and the machine computation to adapt physical dynamics accordingly.

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Abstract
While current fabrication technologies have led to a wealth of techniques to create physical artifacts of virtual designs, they require unidirectional and constraining interaction workflows. Instead of acting as intelligent agents that support human's natural tendencies to iteratively refine ideas and experiment, today's fabrication machines function as output devices. In this work, we argue that fabrication machines and tools should be thought of as live collaborators to aid in-situ creativity, adapting physical dynamics come from unique materiality and/or machine specific parameters. Through a series of design narratives, we explore *Human-FabMachine Interaction* (HFI), a novel viewpoint from which to reflect on the importance of (i) interleaved design thinking and refinement during fabrication, (ii) enriched methods of interaction with fabrication machines regardless of skill level, and (iii) concurrent human and machine interaction.

Author Keywords
Human-fabMachine interaction; concurrent collaboration; creativity support; emerging design;

ACM Classification Keywords
H.5.m. Information interfaces and presentation

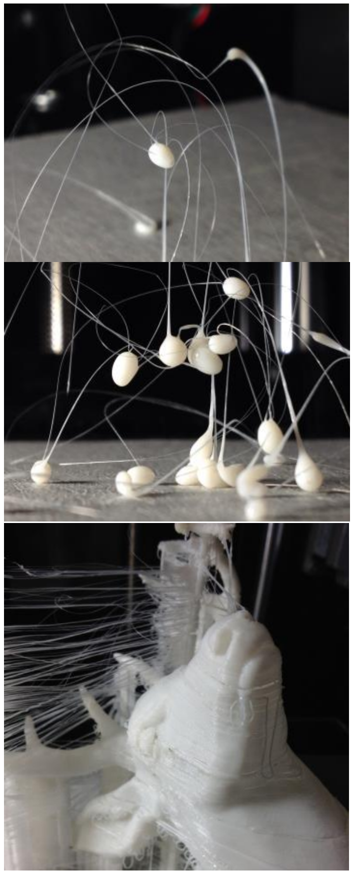

Figure 2. Through failed attempts working with his 3D printer, an artist discovered the "beautiful accident" printing technique. Such serendipitous 'accidents' could be exploited to inject aesthetics or enhance the textures of computationally fabricated artifacts.

*image retrieved from Flickr user clf cool

Introduction

Recent advances in computational fabrication have afforded the opportunity to use automated tools and machines to support personal creative endeavors. Due, however, to material costs, production time, and tool availability, users of such technology are often forced to design to the point of near perfection, then physically fabricate. If production fails, they must refine their design from GUI, and try to fabricate again. Yet, creativity and craft processes, rarely follow such a restrictive, linear process. They fuse ideation, prototyping, hands-on refinement, and iteration of all these processes, such that design decisions not only happen during ideation and design time, but throughout the entire lifetime of a creative work [42]. The immutable, unchangeable designs that are required by fabrication processes and tools place pressure and burden on the user to "get it right" the first time, and often prevent the user from partaking in additional activities involving other equipment or desires (*e.g.*, destruction, remixing, repair, or modification of existing artifacts). This prevents spontaneous and serendipitous in-the-wild design ideas from emerging and unintentionally hampers one's creative freedom during design and fabrication workflows.

Unlike the limitless range of interaction techniques available to interface with smart watches [22], wearables [20], drones [2], and robots [19], interaction with fabrication machines, such as laser cutters, CNC mills, or 3D printers, is largely constrained to CAD software. The reliance such software has on point-and-click metaphors prevent a user from being able to interact and experiment with raw materials directly. Once the virtual model designed in CAD is moved to the physical production phase, the human as a designer is in charge of all unexpected issues at the design time, physical dynamics, and potential failures. This pushes a user to validate their virtual design before it is sent to a machine, rather than allowing a human to ***trust*** the machine as an assistant, which is doing own task ***right***.

Unfortunately, as the processes that occur within a 3D printer or laser cutter are largely hidden behind "black boxes", most novice makers and enthusiasts do not have the skills to start, operate, troubleshoot, or experiment with such machinery [16]. It can also result in failed prints and incomplete designs. Nonetheless, in some instances it could help inspire creativity and expression (See Figure 2). More often, the closed nature of machines limits their ability to spontaneously discover and experiment with the intricacies of tools and machines to enhance one's design (*e.g.*, change the flow rate and travel speed in 3D printing, or power, speed, and frequency while laser cutting, akin to changing the pressure one exerts on a paintbrush or force on a block plane). If machine-specific parameters could be modified during fabrication or destruction processes, details could be (un)intentionally added by both user and machine and real-time design decisions could be reintroduced into the digital fabrication process (*e.g.*, Figure 3). Today's fabrication workflows unfortunately do not support the adaptation or exploration of such variables, real time action, or augmentation of accidents to fabrication processes.

Although fabrication machines provides great precision and accuracy to generate physical representations of digital designs, designers who make use of hand tools hold a much deeper understanding about of their design, and place a greater emphasis on the role of tools and materiality in creativity and the creative

Figure 3. An intricately engraved laser cut wood sign (top) and metal etched laptop cover (bottom) that were the result of experts delicately controlling laser cutter parameters, applied to segmentation of imgages

*Images retrieved from tomsky.co.uk (top), and Flickr user Kevin Ng (bottom).

process. They do not simply view the equipment and tools they employ as technical devices that are means to an end. Rather, they believe and desire for them to guide and shape the eventual artifact they are creating [12]. In some sense, equipment acts as a collaborator and colleague, helping designers unlock new directions and artistic insights facilitating real-time intervention.

We observe that the essence and importance of tools, materials, and machinery has been lost during the digital fabrication process. To reintroduce materiality, mutable design decisions, and immersed improvisation due to effects of machine specific parameters into digital fabrication, we need to eliminate, at least reformulate the perceptions that fabrication machines are purely mechanical devices, restrained in an outdated industrial form factor. Designers should be free to leverage the precision and benefits of digital tools, while also being given the freedom to respond to the feedback, properties, insights the machinery can provide about their design in real time.

In this work, we seek to reframe how fabrication machines (we refer fabMachine here) can be viewed, designed, and utilized for personal and computational fabrication. This work aims to view such devices through a lens unbounded by the traditional GUIs that we as a community naturally gravitate towards today. We thus put forth the notion of ***Human-FabMachine Interaction (HFI)***, an interactive, concurrent, and creative collaboration between human and fabrication machines to harness the precision of digital fabrication and leverage the beauty and serendipity of handcraft and material manipulation on-the-fly. We envision fabrication machines as *colleagues* that strive to not only produce a physical artifact, but also aid human in creative work. By using design fictions and reporting on early prototypes, we explore how such technology could be exploited for collaborative and collegial efforts.

Towards Human-FabMachine Interaction

Many research that focused on computational tools, fabrication, and human interaction towards interactive fabrication technique, have explored novel methodologies to scaffold new user experiences to prototype and cultivate creating artifacts. We drew inspiration from this work to inform HFI.

Embodied Fabrication Techniques

Many of alternative ways to allow for more natural, and humanistic methods have been explored, to design and fabricate objects. Tactum facilitates on-body design, allowing for personalized design of artifacts that are one-off, and unique for everyone [14]. In a similar vein, Protopiper [3], D-Coil [29], Mobile Fabrication [33], in addition to a common portable 3D printing device, 3D Doodler, allow users to extrude materials from a hand-held portable device to allow for real-time sketching on-the-go, sometimes in scale. Interactive Fabrication [41] introduces users' embodied interaction for input to a direct production, demonstrating how personalized, artifacts could be created by not losing designer's original intention Being the Machine [10] explored using human body as the mechanically controlled tool, trading precision and control with the ability to realize surprising and unexpected forms of artifact. Each of these projects enabled new modalities and methods of a design, however, they largely assume that there is no delineation between design and fabrication time and that the interaction is unidirectional (from human to machine) in that each fabrication machine was simply an output device.

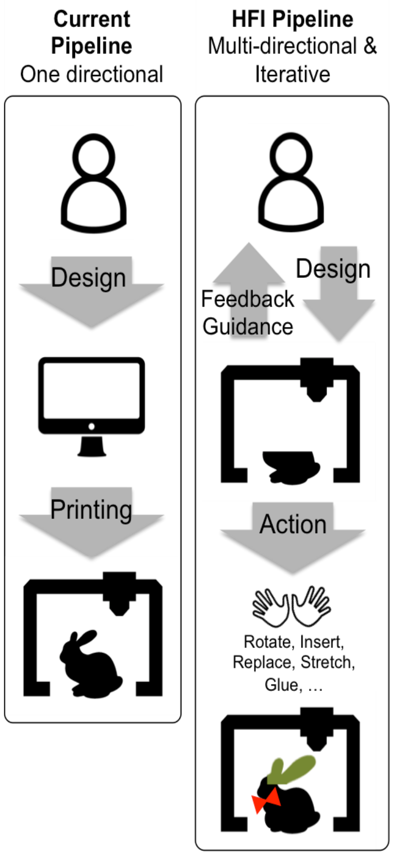

Figure 4. A re-imgination of a 3D printing workflow from the vantage of HFM Interaction. This proposed multi-directional process allows the user to modify their design during production, allowing for spontaneous decisions and ideas to be incorporated without needing to begin production from the beginning.

Flexible Fabrication Pipelines

In addition to enabling digital fabrication machines to support new materials [17, 18, 27, 40] and decrease fabrication time [25], much attention has been devoted to augmenting fabrication workflows to allow for modifications outside design and ideation time. With Constructables [24], a user could point different laser pointers towards the bed of a laser cutter to interactively draw and design artifacts on a “drafting table” in real-time. Encore and Patching developed new pipelines to affix existing 3D-printed objects with alternative geometries [7, 38]. Reprise [8] empowered users to design augmentations and adaptations to existing real world objects. Recently, On-the-Fly Print allowed users to slice a model in the middle of the extruding and add ad-hoc details [28]. Each of these projects accommodates “afterthought” design decision. Nevertheless, they assume that users would send a perfectly planned mesh for extrusion, and that the printer would ‘execute’ commands in a straightforward manner [9, 10]. They also do not allow machine specific parameters to be manipulated to influence the final details of an outcome (similar to Figure 3).

In-Situ Guidance from FabMachines

Many have begun to explore how fabrication tools can provide richer feedback to teach, or assist, the user throughout their process. Drill Sargent [34] and Zoran et al.’s Hybrid Craft [45] and augmented airbrush [35], made use of hand tools (*i.e.*, an intelligent drill/saw and chisel, respectively) to guide users towards a representation of a pre-designed form. Proxy Print also explores this idea, by using 3D printers as a tool that would print a proxy to assist novice jewelry designers throughout their replication process, rather than 3D printing the final product for them. In a sense, computational tools subsidized designers, but did not rely on perfect computation and fabrication– owing to uncertain design elements such as materials [39]. These partly supported designers’ creative freedom, as they reaped the benefits of working through a material (*i.e.*, risk, uncertainty, and serendipitous discovery) while being supported in expressing their insights along the way to arriving at the target form.

Inspired by this work, we propose that the future of fabrication will be a fusion of the ideas. Human-FabMachine Interaction should support enriched, novel methods of interaction, leverage craft practice (which supports design decisions throughout the fabrication workflow), and enable users to learn, be inspired by, and work alongside the tools and machinery that analyze dynamics, inform, and instruct designers, that are required to complete their desired artifact.

Human-FabMachine Interaction

Current fabrication machines and techniques are unidirectional. With 3D printing, for example, users design 3D-models in GUI based screens, thus having little confidence (or immense doubt) that the model will be printed as desired (See Figure 4). They then send the design to a 3D printer and wait until the print is completed (or failed). Once completed (or failed), they inspect their artifact, integrate new ideas into their model or design, and begin the process again. This rigid workflow does not allow the user to interface with the printer in real time or modify their design or the physical artifact during print time. A user thus becomes a slave to their 3D printer, adapting their workflow to the processes of their machine.

We argue that this pattern of design and fabrication is detrimental to the designer and unintentionally forces them into a pattern of working that is contrary to how we naturally learn and grow: *learning by doing*. From expertise gleaned through 10,000 (or more) trials [10] to the satisfaction and joy that results from using hand tools [3], our ability and desire to try, fail, learn from our failures, and try again, shapes our creativity and insights about what is possible, and enables us to develop new solutions to complex design challenges.

We thus need to refocus our views of digital fabrication such that the *user* and their *workflows* are at the forefront of fabrication processes. The crux of human-fabMachine interaction is thus that our interactions with fabrication techniques and processes need to a multi-directional interchange of task leadership and control with human operators. Users should be able to make the incremental and impulsive design decisions using movements, interactions, and behavioral patterns that convey precise, delicate details, and larger, complex operations. They should be supported in making modifications to digital representations of their artifacts in addition to the physical artifacts that already exist, are being remixed, or are in progress. Such modify-cations should be captured and reflected in the digital software and tools, and the equipment they use. The role of the fabrication machine needs to be such that is a cooperative collaborator who works intelligently with the user, rather than a fabrication appliance that follows orders. Equipment and machinery needs to be able to anticipate forthcoming errors, advise the user about potential design opportunities or alternative tasks, and disentangle the multitude of operations, equipment, and tasks required to create a close facsimile of a user's vision by computation.

The human and machine should be supported in doing what they do best when the task leadership is at one side. For the human, this is handling and exploring materials to understand their intricacies, integrating personality and aesthetics, and understanding the vision of the desired artifact. For the machine this is employing precise movement and repeatability, modulating temperature, speed, and control, and so on. By reemphasizing the relationship that exists between users, fabrication machines and tools, the processes and tasks to be undertaken, and the larger vision that the user has, personal fabrication can begin to recapture the true essence of craft and handiwork missing from digital fabrication pipeline recently.

Three facets thus appear essential to the realization of the human-fabMachine Interaction:

Accessibility (A)

Designers and novice users' hybrid handcrafted design processes should be supported from beginning to end. Employed techniques should capitalize on the joy of discovery and lessons from failure, and wonder of exploration. They should enable a range of opportuni-ties to explore and interact with equipment and tools, whilst ensuring fewer chances for user frustration and machine failure. Tangible and embodied interaction in mixed craft practice should be supported regardless of the level of domain knowledge [5].

Fluidity (F)

Interaction should be flexible enough to support design decisions that occur throughout the design process. At a minimum, users should be able to easily pause the process, have time to think of the next or ad-hoc design decision rather than planning the entire artifact from the beginning of a design, add new materials or techniques, and resume the initial process at any time.

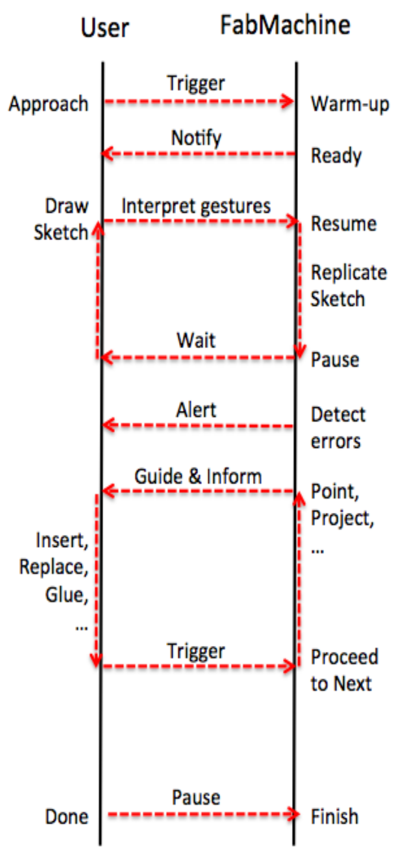

Figure 5. A possible exchange of task leadership, where the human has control and leadership at each stage of co-design process. From the preparation of the virtual model to holding the final physcial artifact in hand, the user and a fabrication machine collaborate, dealing with problems, materials, and partial representation of outcomes.

To support fluidity, designers must be able to interact not only with the final artifact, but also incremental representations of the artifact, which may lead them to discover new forms, textures, shapes, and dynamics that were not intended during initial ideation.

Concurrency (C)

To catalyze the two requirements above, concurrent multi-directional interaction needs to be established as the ground truth. Allowing for simultaneous, real-time collaboration with fabrication tools/machines will enable in-situ design decisions and actions by the human, and function by the fabrication machine to co-exist and create with each other harmoniously, in both directions. Machines need to be intelligent enough to analyze the situation, provide feedback and notification about its status and suggested design options, and guide the human towards their intended design. By doing so, it will actively add creative freedom to the process, rather than remaining in a passive appliance.

Figure 5 illustrates the fluid timeline of co-design with a new type of perceptive, analytic, descriptive, and informative fabMachine-- which is concurrently reactive through the process, showing example interactions to collaborate each other.

Fictions on Human-FabMachine Interaction

To illustrate the power of human-fabMachine interaction, we present a series of design concepts, written as short narratives. As identified by Blythe and Zimmerman et al. [6, 44], the creation of fictional stories can help reveal challenges and opportunities for prospective interaction design research, or in our case, digital fabrication. Such speculative narratives not only provoke futuristic design thinking, but also allude to the future challenges fabrication needs to consider [26]. Each concept is driven by an idealized vision of humans and machines working harmoniously, using fabrication enthusiasts Martin, motivating future research. We denote where the three facets of Accessibility **(A)**, Fluidity **(F)**, and Concurrency **(C)** are explored.

Chapter 1: Fabrication Lenses

Given the assumption that users have control and freedom over a fabrication machine to reflect their craft practice, if one wants to modify an existing artifact or a model in the middle of production, how do they determine required action, or be aware the effects on the rest of a design? How can the user obtain real-time, in situ, spatially-aware feedback about their designs and the effects of their physical actions?

Martin is repurposing some 3D printed vase to a flower to adorn the walls of his office. He is unsure about how to change their appearance to make them more realistic, so he pulls out his smartphone and opens his Fabrication Lenses. Using AR, Martin can access different lenses that correspond to different analytics and views of his digital design **(A)**. By pointing his smartphone towards a flower that is being de-printed and switching to the 'Simulate Lens', Martin can view a simulation of what would be happen to the leaves on the stem if he wanted to re-print them using a transparent material, based on the current printer parameters and what is left to remove from each petal. Such a lens allows Martin to see the results of his potential actions [22] without stopping his job to change his model **(C)**. Martin decides that he does not want to change the shape of the petals so he leaves the original model as is, instructs the printer to start printing, and goes for lunch.

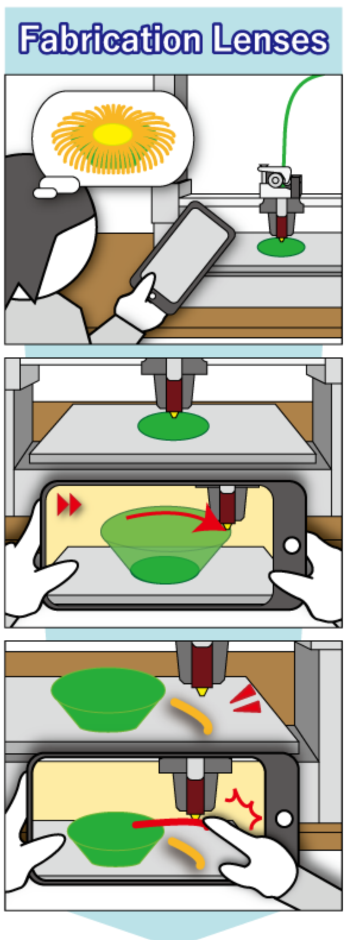

Figure 6. With a set of Fabrication Lenses, users can preview, simulate, map, or rewind the process and assign function to a machine to reflect the on-the-fly design decisions

After lunch, Martin notices that one of the flower's petals fell off while he was away. Using, the 'Status Lens', Martin is able to view timing and layer information when it starts failing like a mirage [43], so he can go back in time to examine the reason. This information helps him to figure out that he can salvage his flower print **(F)**. He switches to the 'Mapping Lens' and is guided to the position where he can place a penny near the next-to-be printed petal stem rather than in the next iteration of the print **(C)**. (Figure 6)

Chapter 2: Adroit Slaves

Just as a painter experiments with, and learns from the visual feedback of paint brushes, there are several machine-specific parameters that can be modified to reflect materiality, and influence the fine details of a design (e.g., printing speeds, flow rate and thickness of walls, etc., to control thickness and texture pattern of the surface [37]). How can a user indicate to a machine that such modifications are desired?

Martin is designing a large Peltogyne wood façade to cover the ugly bezel and of his recently purchased TV and cables underneath. He does not simply want to design a pattern in an SVG tool and let the laser cutter engrave all the way through. He has worked with this laser cutter in the past and knows the personalized visual effects he can coax out of the raster engraving using different power levels and laser frequencies. But, has never done so with this specific wood. He thus asks the machine to capture and analyze the properties and thickness of the hardwood **(A)**. With the knowledge the laser cutter has amassed from his hours of experimentation with acrylic and plastics, his laser cutter suggests five combinations of frequencies that could create unique layered effect and engraving patterns that are similar to what he has done in the past, and newer that he has never tested **(F)**.

After viewing a visualization of the thickness of the wood, which was generated from the status of his laser cutter, one interesting thought came to his mind, so decides to change his initial design to incorporate more of the knots that naturally occur in the wood. While engraving, the laser cutter pauses at certain points, inviting Martin to gesture above semantic areas of the target pattern (stems of bamboo wood through entire drawing), where he wants this effect to appear **(A)**. As the machine automatically picks up where it left off, Martin dynamically takes control of the laser power whenever the laser is near the area he gestured **(F)**. The laser cutter adaptively changes the engraving speed that were originally computed for the wood, to accommodate Martin's laser control to ensure that he does not burn a hole in his material. This process seamlessly executes, so as not to disrupt Martin's focus and ensures he doesn't have to start the entire process from the scratch **(C)**.

Chapter 3: The Sensing Machine

Current fabrication machines cannot respond to any user input that is not provided via a 3D printing program (e.g. CuraEngine). If fabrication machines could perceive and interpret delicate gestures or natural movements and anticipate design intentions from them, what would the resulting operations be?

Martin wants to make a pop-up birthday card for his son using a sketch of his son's face as the popping element. As Martin approaches to his 3D printer, it automatically begins warming up, anticipating that it will be needed **(A)**. Martin begins to sketch his son's

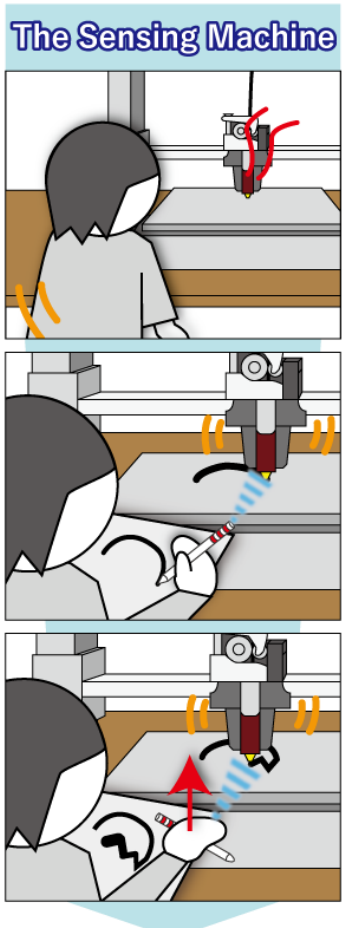

Figure 7. A Sensing Machine that captures ambient data, including human gestures and actions with tangible medium, to read, interpret, and generate artifacts as they are fabricated, by automatically warming up, being transmitted remote data

face on a nearby piece of paper using a marker The printer uses its' gesture sensing capability to observe and interpret its movements, converting them into machine code, also considering the materiality of the paper substrate he is using and the machine specific parameters needed to print fur **(C)** (Figure 7).

The print head and his hand then become linked, such that his movements are replicated by the print head and the sketched lines are realized via the fur printer filament **(A)**. He soon realizes that, although the width of the fur matches the width of the marker, it is too wide. He continues to sketch, but then hovers his palm above his sheet of paper to dynamically change the thickness of the deposited fur **(C)**. For safety, the printer alerts Martin as soon as he exceeds the flow rate limitations of the machine **(F)**. After printing a copy of his son's face, Martin feeds the substrate to his automated paper cutter to cut out the popup pattern needed to make the card origami. As the substrate has a different topology throughout, the cutter occasionally prompts him that it will ruin some of the deposited fur at the current blade thickness **(A)**. Martin then gives the cutter permission to automatically adjust the blade depth as it sees fit. Once cut, Martin is able to follow the fold lines that have been scored on the paper and completes the creation of his birthday card.

Chapter 4: Come and Follow Me

Limited feedback from fabrication machines makes co-working difficult, especially when there are an unlimited number of ways to change a design, e.g., change the model in the middle of printing process, customize textures, insert foreign items [29, 32], or use multi-materials [31]). How should a printer notify the user when and where they can interact? Should it stop and await users' action, or perform alternative tasks in the meantime?

Martin is making an interactive tactile children's book for the visually impaired to donate to a local library. His book combines felt, 3D printed interactive movables [21], sensing elements, and heat-reactive materials to intrigue children's interests in emergent literacy. Martin begins to fabricate the first page of the book. Informed by the template Martin loaded into the embroidery machine's software, the machine uses it's projector guidance **(C)** system to show Martin where, and at what orientation, he should place each of the sensors and 3D-printed artifacts so that the conductive traces that connect each component will be optimized **(A)**. Once he has placed the components, the embroidery machine determines it will take 15 minutes for the traces to be sewn **(F)**. When the machine finishes sewing, it sends a notification to Martin's smartphone that it is ready to begin the next step in the template, sewing an embroidered, interactive cat onto the page, but waiting for his next action **(C)**.

The cat is to be made from a hybrid of acrylic and conductive yarn and fabric-based heat sensitive materials underneath its face. Martin squeezes the spools of thread attached to his embroidery machine to indicate the relative composition he would like the body of the cat to have so that there will be enough conductance to power the heat-sensitive panels **(A)**. The machine soon begins stitching the outline of the cat, but pays careful attention to Martin's hands, which are arranging heat-sensitive panels on the page in a decorative pattern **(F)**. As Martin's hands move, the embroidery machine slows down its stitching speed,

Figure 8. A flying 3D printer and a rolling mobile laser cutter printer that a user remotely control without any limitation of scale. We envision the eventual fabrication removes current limitations, scale, safety, and limited access control at a time.

determines which areas of the body still need to be sewn, and adaptively moves to other locations to avoid colliding with his hands **(F)**. Once he has placed all the heat-reactive panels, the machine ramps up to it's normal stitching speed to finish the cat outline. As part of the last step, *i.e.*, securing the heat resistive panels, the machine asks Martin to squeeze the spools again so that it can adapt the yarn composition to be stronger, and thus better able to hold the panels in place.

Chapter *N*: Within-the-Wild Fabrication

Much creativity comes from immersion within rich environments and spaces. Technologies such as mobile tools [1, 33] and swarm bots [15] will enable users to design and fabrication and collaborate with their cohort designers out of the design studio or maker place, at any time. When fabrication is not limited by the size of material beds or the number of contributors in the process, how will machines adapt to the ever-changing environments they are introduced to?

With their set of portable fabrication machines, Martin's wife, Emily, is looking to bring some holiday spirit to their garden. Martin, who is travelling abroad, sent her a photograph of a garden gnome carved like an angel. Unable to carve it herself, she shows a picture of the gnome to her stone-milling robot and asks it to create something that is similar in spirit and aesthetics to adorn as ornament. The robot rolls over to a group of nearby boulders and begins to etch gnome designs on them by modifying its carving speed and power to adapt to the hardness, size, and density of the stones **(C)**. As the power required is immensely high, the robot erects a safety perimeter around itself to shut itself off when her little son comes too close **(F)**.

While the roller laser bot is etching, Emily begins conducting the movements of her drone wrapper robot, which is decorating her spruce tree with festive ribbons and garland. As gestures towards different areas of the tree, the wrapper robot winds strips of ribbons into conical and curved computational patterns that look like ornaments **(A)**. Her junior 3D drones hover nearby, shooting a white flakey material on top of the ornaments to represent snow. To add some light and vibrancy to the tree, she snaps a picture of it's current state, and sends a notification to her tree-climbing agents that it needs more color. The swarmd each load up a series of wireless LED light modules, begin to climb the tree, and deposit the LED light modules in locations on the branches that will be the most visible and aesthetically pleasing **(F)**. Once finished, Emily video calls Martin to show him the results of her, and their robot's design efforts (Figure 8).

Realizing Human-FabMachine Interaction

Although the notion of Human-FabMachine Interaction and our ideations on them may seem far-fetched, they represent a variety of possible paths along which the gap between advanced interactions can be bridged.

Initial Explorations

As a starting point towards fully realized Human-FabMachine Interaction, we created two baseline prototypes of the *Sensing Machine*. First, we developed a responsive printer that perceives human gestures. The interaction medium consists of several sensors that detect user behaviors and ambient data, such as one approaches the printer, changes the luminosity of the room, or sketches with regular drawing tools or finger directly (Figure 9). When such behavior is detected, the 3D printer will adapt them into printing parameters, *i.e.*

Figure 9. An early prototype of the Sensing Machine that captures users' gesture path and replicate 'drawing' with plastic. A leap motion tracks the human gesture, being connected to an Arduino to communicate with a 3D printer.

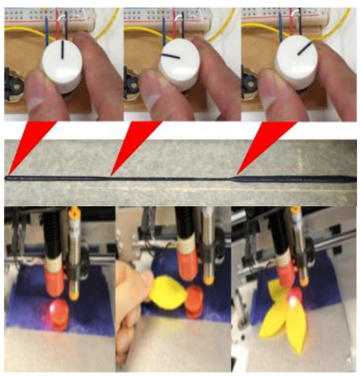

Figure 10. The connected a number of sensors enable the printer to control printing parameters, *i.e.* thickness of deposited lines real-time (Top). It can also guide human to enable inserting foreign items onto the object (bottom)

flow rates, movement speed, and extruder positions. This reactionary form of fabrication reduces the gap between design actions and the eventual outcome, removing the chasm between the workflow where designer, machine, and the artifact are involve.

We also explored manually modified G-Code to explore time and space required for embedding physical action into the printing process. RepRap 3D printers (Printrbot and NinjaPrinter in our case) are able to pause itself and guide the user to the precise location with laser pointer, where the cavity component could be inserted (Figure 10). Such guidance could have also been realized via projected images on top of the already printed layers of the artifact.

Implications for Future Fabrication Design

The Human-FabMachine Interaction fictions enabled several implications of fabrication interaction to come to light.

Adaptive, Real-Time Processes: Even if advances enable workflows to decrease by a tenth of the time, challenges with material availability and access to machines, for example, will still exist. As many design decisions are only made once one holds and manipulates their artifact, it is important to consider the implications of real-time feedback and processes that adapt to our every whim. Without fear of losing the control, with the confidence of taking the lead of production, human's employed action into the middle of fabrication process auspiciously achieves design goal.

Supporting Human-Problem Interaction: Fabrication machines use precision and optimization, whereas craft encourages imperfection, iteration, and imagination from them. Human-fabMachine interaction encourages these two disparate methods to become fused as one. This generates questions about who really is in charge, how (potentially irreversible) conflicts are mediated, and the metaphors we use to explore and design hybrid human-machine interaction. Collaborative fabrication across multiple users and machines adds more challenges into the process of fabrication.

Less Harmful Workflow: Chapter *N* briefly touched on the importance of safety within personal fabrication with the erection of a "safety fence". When users are working with portable machines out of safe lab configurations, it becomes easier for someone unconsciously to act in ways that override a system's safe guards, being distracted, forgetting that hot 3D printer nozzle or the laser is on, and pointed at the material, burning materials, *etc*. While changes to workflows or enhanced safety protocols could help mitigate some of these unsafe scenarios, determining how to support both safe and experimental practices will be a crucial challenge moving forward.

Conclusion

This work has hypothesized on the future of digital fabrication by arguing for the importance of bi-directional, collaborative interaction between users and the machines they employ. We proposed the next generation of fabrication technologies should be collaborative, as opposed to strictly technical machines. We envisioned this becoming a reality through the Human-FabMachine Interaction, a novel construct through which fabrication workflows should be reconsidered to leverage accessibility, fluidity, and concurrency. Through a series of design fictions and initial prototypes, we illustrated how the Human-Fabrication may come to fruition and speculated on possible futures for interaction and design processes.

Acknowledgements

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