Modular Systems for Fabrication: Toward a Collaborative Partnership between Humans and Machines

by

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has been approved for the Department of Computer Science

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Modular Systems for Fabrication: Toward a Collaborative Partnership between Humans and Machines
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Abstract

In recent decades, considerable advances have allowed more people to use digital fabrication techniques such as 3D Printing to create personal artifacts. Instead of collaborating with humans to create a design, current fabrication machines, however, mostly follow humans' commands as one step input in order to output a physical object as a batch process. This way of working presents three big challenges: end-users without special knowledge can not fully appreciate advances of digital fabrication, machines cannot understand people's design activities during the creative process with improvisation, and fabrication machines are not designed to be collaborative to support individuals' creative processes with in-situ designs.

In this dissertation, I introduce the research to answer the overarching question: "How can humans and machines form a collaborative partnership in a creative process?" I investigate three elements and their influences at the intersections of HCI, digital fabrication, and collaborative systems to address these three main challenges. I present interactive design tools for end users to design complex moveable objects (Fabrication-HCI), empirical studies to understand individuals' design abilities and remaining challenges in developing collaborative fab machines (HCI-Collaborative Systems), and a collaborative 3D printer I built to enable close interactions between users and machines through multiple communication channels and various workflows (Fabrication-Collaborative Systems).

I conclude my dissertation with a vision of an *intelligent fabrication agent* towards the future of people and machines augmenting each other. I propose new research programs for developing an intelligent machine that detects and predicts human behaviors in creative processes, in order to provide various types of assistance depending on the context, such as guidance, recommendation, and teaching new skills.

Dedicated to Doyoung Park, my best friend, ex-boyfriend, and now prince husband.

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I thank NSF and Adobe for funding my research, and I owe my sincere gratitude to my family, friends, mentors, and colleagues.

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To my family, my parents, the reason for my life, my brother, my sister in law, my niece, and lovely cat. To my family-in-law, supported the agonizing time of graduate studies with their full empathy.

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The final word is reserved for my dearest mentor and advisor, Tom Yeh. All my motivations, trials, errors, being brave to try new things and inspired by failure, and keeping warmhearted came from him. He has believed in me more than I did leading me to become an independent researcher with courage—ready to speak out loud. Until very last moment, I was not sure if I can keep being academic, but as he believes that I will be successful in my career, I trust that it is not just a naive encouragement but his sincere trust in me. It is my job to turn it be true. Sometimes his groundless optimism made me nervous, however, he has never been wrong. I cannot thank enough, without his true patience, empathy, and a strong belief in me, all my success to this point would have never been possible. Since now, I will do what I had done so far– following his confidence. I will take every single word choice he put on me as an energizer, every single attitude he showed me as a benchmark. Whenever I feel clueless, I will recall what he would do in the same situation and try to be a person like him, with the confidence that there will always be a person who wishes the best of his luck.

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Chapter 1

Introduction

1.1 Motivation

Digital fabrication is on the verge of entering the mass market. Driven by technological advances in open-source hardware and software platforms, people's growing enthusiasm has yielded remarkable attention towards personal digital fabrication.

Advocates of digital fabrication note its increasing ubiquity. Market analysts have pointed out the increased ability to provide customized products using this emerging technology as one of the primary factors for this interest, propelled by continuous success[1] and growth of the 3D printing market [73, 95]. As 3D printing expedites the creation of prototypes and models within a production loop, many companies will be able to produce cost-efficient prototypes based on individual customer requirements, leading to their continued success in the market.

In addition to the growing use of 3D printing in the industry, many fabrication machines, particularly consumer-level 3D printers, have become available for a wide range of users. Advances in technologies and decreasing prices now allow the public to own a 3D printer for personal use; this trend of increas-

[1] As of 2019, when this dissertation is written, the global 3D printing market was valued at about $4 billion in 2014 and is expected to reach $44 billion by 2025, according to Allied Market Research.

ing accessibility has lowered the barriers for end-users to 3D print nearly anything. Akin to personal computers in the early 90s that became handy for individuals, 3D printers have also become increasingly inclusive of non-technical users, departing from being reserved for domain experts. However, compared to the economical price of hardware systems, very few end users actually *create* 3D models using an easy-to-use software. Many of them only take advantage of the increasing number of online repositories, full of free 3D models created by advanced designers. Partly due to limited opportunity to make models using current modeling tools, people often spend several weeks learning those tools until the goal of *making highly-custom items* can be achieved. This barrier hinders non-technical users from jumping directly into making, resulting in losing their interest in 3D printing—in contrast with craft experiences to quickly prototype and physically sketch the idea to visually validate and *design-by-doing*.

To transfer this scenario into 3D printing, which users closely interact with machines and materials for creative exploration, it is critical to understand end-users' barriers that they face during fabrication and to develop machines for *collaborative design*. Herein, I aim to uncover systems for end-users to support creative exploration through collaboration with machines. This suggests several requirements:

1. **Easy Access:** the means of enabling end-users to fabricate complex real-world objects should not impose any expertise in specific domain area (e.g., mechanical engineering)

2. **Support Creative Exploration:** the means for end-users should open creative exploration for open-ended experiments via *design-by-doing*

3. **Modular:** the solution should support free composition of each components by end-users to reuse, expand, and integrate with existing resources and future technologies.

1.2 Contributions

I have been exploring three elements that constitute my research towards an ultimate goal of building the future of collaborative fabrication machines: Human Computer Interaction (HCI), digital fabrication, and collaborative systems, as shown in Figure 1.2.1.

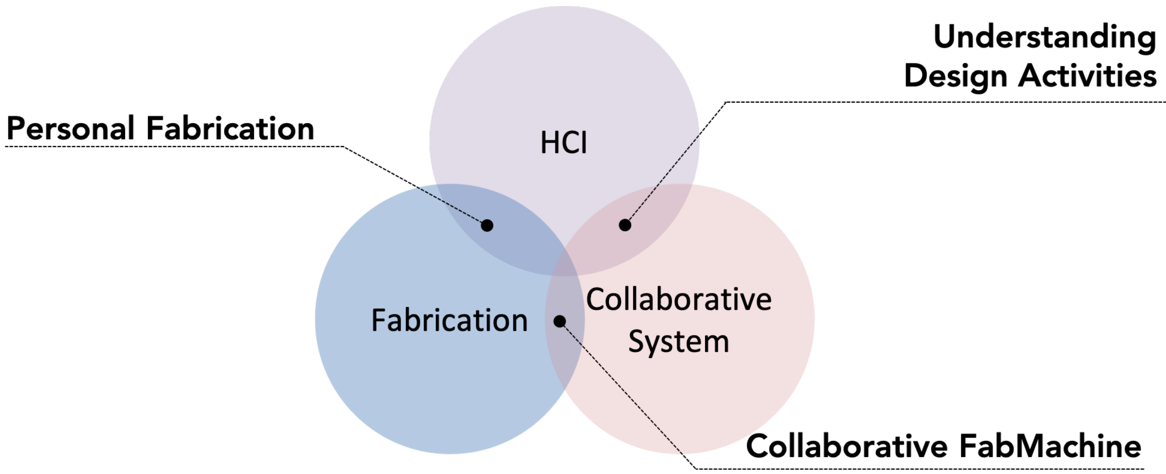


Figure 1.2.1: Three key elements of this research: HCI, digital fabrication, and collaborative systems collectively form my future vision towards collaborative partnerships between humans and machines

At each of the intersections, I asked three research questions to investigate how these elements collectively contribute to forming a collaborative partnership between humans and machines, particularly in a creative process.

To address these questions, I have (1) developed two novel design tools to lower the barrier for end users in making custom objects (Chapter 3, personal fabrication), (2) conducted empirical user studies to understand their challenges in design (Chapter 4, understanding users and their design activities), and (3) developed a collaborative digital fabrication that recasts 3D printing as a compositional process (Chapter 5, collaborative fabrication machines). Thus, this thesis makes the following contributions.

1.2.1 The intersection of HCI and Digital Fabrication:

I develop modular approaches for design tools in creating custom 3D objects, as solution to lower the barrier for end users in making. MoveableMaker and KineMaker are example systems, that welcome novice users to fabricate adaptive artifacts with off-the-shelf 3D objects, using modular libraries. These provide users libraries of 3D moveable templates and mechanical gearboxes, that can be assembled and embedded into existing 3D objects using an easy-to-use design language CraftML.

1.2.2 The intersection of HCI and collaborative systems:

I identify hidden real challenges that users face—resulting in design principles that embrace users' lacking modeling ability—then implemented a modular system for reducing errors from measurements. I characterized end users and their abilities in 3D model design and printing, and introduce FitMaker, a modular system to accommodate the impact of uncertain measurements in 3D printing of augmentations.

1.2.3 The intersection of collaborative systems and Digital Fabrication:

I develop Compositional 3D Printing, implementation of the concept and novel design workflows that showcase expanding capabilities of users and 3D printers in 3D Printing by collaborating with each other. Compositional 3D printing recasts 3D printing as an improvisational process of creating a final artifact through *design in printing*. Six novel workflows demonstrate that modular libraries enable various mapping between users' interventions as input during 3D printing (e.g., gesture recognition, sketching, etc.,) and printer's responses (e.g., adding textures, defining patterns and repeat, etc.,), demonstrating potential for much diversified workflows. Compositional 3D printing open-source framework also offers advanced users to further expand the options for collaboration.

1.3 Outline of Dissertation

My approach uses an iterative research methodology, as depicted in Figure 1.3.1, to develop collaborative 3D printing with modular systems that help end users fabricate a variety of artifacts through creative exploration, with different goals at different stages of making. This methodology thus drives the organization of the rest of this document.

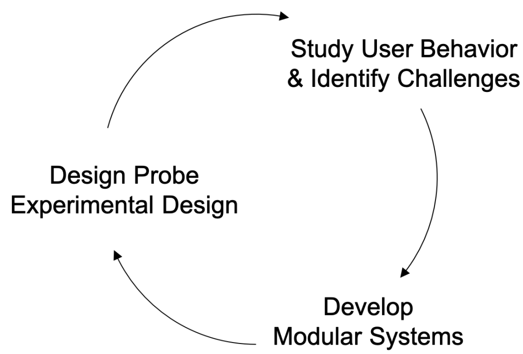


Figure 1.3.1: Iterative research methodology

Chapter 1, the current chapter, introduces the motivation of this research, the fundamental research question, key contributions, the outline of this document, and key terminologies that are frequently used in this dissertation. Further, I introduce a long-term vision yet to achieve through this research.

Chapter 2 provides an extensive overview of the foundational research, the previous and late-breaking efforts to address unresolved questions in each intersection of HCI, digital fabrication, and collaborative systems. This chapter also serves as a guide for thinking about the unexplored challenges pertaining to better approaches for addressing such issues in my dissertation and in the near future. A more through overview of recent works that is tightly related to each subquestion will be introduced in each chapter respectively.

Chapter 3 introduces two works that I conducted at the intersection of HCI and digital fabrication. Tactile Picture Books and Kinemaker projects address the research question of "How can end users fabricate custom complex artifacts using existing resources without requiring expertise?" by novel interactive design tools that help individuals design adaptive 3D objects using off-the-shelf models.

Chapter 4 introduces empirical studies to understand users in 3D design and printing, conducted at the intersection of HCI and collaborative systems. *Understanding Uncertainties in 3D Printing* strives to answer the question: "What are hidden challenges for end users in 3D design and printing, and what is the state of their capabilities to address them?" Then I introduce a tool as a solution to the question, "How can a modular approach accommodate errors resulting from design activities?".

Chapter 5 introduces a work at the intersection of digital fabrication and collaborative systems. Compositional 3D Printing, an effort to turn a 3D printer from a passive command executor into a responsive event-driven machine, addresses the research question "How can digital fabrication become a collaborative process of humans and machines?"

Chapter 6 summarizes the dissertation and outlines topics for a future research program: "What should intelligent systems do in a collaboration with humans for creative exploration?" at the core intersection of HCI, fabrication, and collaborative systems (See Figure 1.2.1). In this chapter, I propose several new research questions for future work, under the high-level goal of forming collaborative partnerships. First, "How can a fabrication machine detect and predict humans' design activities to provide in-time assistance?" from a technical standpoint. Second, "How does a machine's assistance affect group creativity?" from a theoretical standpoint. I expect these two research directions will open a new door towards future research program and applications in broader domains, including social creativity support robots in various contexts.

1.4 Key Terminology & Definition

In this section, I describe terms used in this dissertation. My definition refers to terminologies used in human computer interaction and digital fabrication, but also include how terms are used uniquely in this dissertation.

- **Digital Fabrication:** Digital Fabrication is a multidisciplinary sub-field of implementing software and hardware systems to innovate manufacturing/rapid prototyping machines, designing interactive systems to support users of 3D printers, laser cutters, CNC millers, and more. It also includes research regarding the development of new applications and where and how these technologies will be used, making a real world impact. Researchers and practitioners have not reached a consensus on the scope of digital fabrication. Currently, it has mainly been used for mass manufacturing, especially in industrial engineering and mechanical engineering. In contrast, my research aims at innovating technologies in the realm of 'personal' digital fabrication. In many instances in this dissertation, 'digital fabrication' indicates fabrication for individual users rather than mass manufacturing (unless otherwise specified).

  (Personal) Digital fabrication includes efforts to support end users for designing a custom artifact, a novel approach to support design activities and processes that use digital fabrication technology, and resources towards certain goals that users want to achieve. Digital fabrication technology specifically refers to recent technical advances and innovations in software and hardware systems.

- **Collaborative Systems:** *Java Distributed Computing* [29] defines collaborative systems as follows: *"A collaborative system is one where multiple users or agents engage in a shared activity. ... Collaborative systems are distinguished by the fact that the* ***agents in the system are working together towards a common goal*** *and have a critical need to interact closely with each other: sharing information, exchanging requests with each other, and checking in with each other on their status."*

I use the term 'collaborative system' in the same manner, a (fabrication) system/machine that works together with a user to achieve a common goal, closely interacting with each other.

- **Design/Designer:** In this dissertation, I represent design/designers at all levels with different skills and goals: from average craftsmen with limited experiences in making to skilled professionals who improvise all processes using commodity craft materials and tools through creative design activities. As far as their objective is creating a new artifact, I encompass both personal DIYers who want a unique object and expert/industrial designers who have sufficient knowledge to try out various design options. There have been debates on whether crafting is design, because traditional definitions of design necessarily involve planning, while crafting means every unique creation process results in a unique artifact every trial. I believe craft is also one type of creative design processes, as well as conventional design done by a professional.

  In Chapter 4, specifically, I propose two different goals of my research, to support both craft AND design by fluid, bidirectional, and iterative 3D printing; however, unless a distinction is mentioned explicitly, I use the words craft(smen) and designer interchangeably.

- **Creative Making/Process:** In this dissertation, 'making' refers to all activities involved in crafting and designing an artifact using craft materials, tools, and digital fabrication utilities. Similar to creative writing, creative making is a making that does not follow predefined instructions. Thus, what to use and what to do are decided by the "makers" themselves in-situ, according to the initial goal. I hold design and craft as similar processes in that a user takes their familiar means of making while improvising design decisions.

1.5 Envisioning Future Through this Research

I envision the future, fabrication machines that aid people to diversify their thinking[2]. Those robots and AI systems provide a variety of assistance from recommendation to guidance to teaching new skills—through collaborative processes of sharing information, checking-in, and interacting closely toward a common goal, similar to the definition of *collaborative systems*. For example, as the simplest robot with a 3-DOF arm, a 3D printer can help humans navigate a complex fabrication process. Users can design sophisticated artifacts by thinking-by-making. Now is the time to consider how human factors could be taken into account to innovate the future of digital fabrication systems, which will be driven by AI. The goal is to advance digital fabrication with such intelligent systems so that an intelligent fabrication machine helps people diversify their way of thinking in creative processes. The critical question here is: *"what can the technology do to enable people to improve tasks that they already do well, such as being creative in their designs, while enabling us to delegate to the machines tasks that they can inherently perform better, such as tasks that need high levels of precision and speed?"*

My ultimate goal in developing collaborative digital fabrication machines is to support a creative improvisation in making to diversify people's way of thinking. This can be followed by a collaborative fab machine that closely interacts with users via seamless communication. In doing so, technology will help machines better inform and guide people's work, while completing the most tiresome tasks. Akin to creative writing, physical making is a way of expressing ideas by gradually applying emerging and on-the-fly decisions of creators. People have more opportunities to improvise expressions using the different materials and tools involved in the process when they can see and validate intermediate artifacts on hand step-by-step. Meanwhile, they can progressively physicalize a vague idea into the tangible form of a desired artifact. People can observe and evaluate the quality of the product directly, how much it matches their expectations to make the next step of in-situ design decisions based on this multimodal

[2] Ken Goldberg, a robot/AI pioneer, once stated "Artificial intelligence and robots will help to diversify human thinking. And rather than worry about a robot apocalypse, I urge a focus on Multiplicity, in which diverse combinations of people and machines work together to solve problems and innovate"

validation. A machine's role here is to help people express untold or ambiguously-stated ideas and using their familiar way of expression. Then it can provide guidance to elaborate those expressions until they finish their creation. This dissertation describes the journey of identifying the needs of innovating digital fabrication to aid individual design activities, towards the future of Human-AI collaboration in digital fabrication. Ultimately envisioning the future in which people *live* with machines (AI), these machines will closely exchange information with human designers towards a common goal, helping us complement each other.

In addition to my efforts to develop a base system for an event-driven 3D printer, remaining areas to explorer and what to achieve towards the future will be detailed in Chapter 6, Future Outlook.

1.6 Statement of Multiple Authorship and Prior Publication

This research is undertaken not by me alone, but by many collaborations with my talented colleagues and friends (see Author List). This dissertation is partially based on papers previously published in ACM conference proceedings. I am the primary author on all publications and led the projects, collected and analyzed data, and implemented the systems.

1.6.1 List of Authors

While I initiated the idea, implemented systems, developed uses cases, scenarios & examples of all projects described herein, I must acknowledge contributions of my colleagues who provided with invaluable help and insights.

In particular, the following author(s) contributed to Chapter 4.2.: Designing and running user studies on the Amazon Mechanical Turk were done by the collaboration with Anhong Guo. The writing has been reviewed and polished by Jennifer Mankoff and Scott E Hudson.

The following author(s) contributed to Chapter 5.2.: The gcode templates for the expressive 3D printing (e.g., printing hairs by user's finger movements) were manually created by Haruki Takahashi. The idea of developing "expandable" design literacy and free mapping to output movements of 3D printer was enhanced by the discussion with Clement Zheng. Illustrations were sketched by Clement Zheng using Adobe Illustrator, some figures that depict the details of input detection (Figure 5.2.11 and 5.2.12) and output expression (Figure 5.2.16) were created by Haruki Takahashi. The writing has been reviewed and polished by Michelle Annett, Daniel Ashbrook, and Mark D Gross.

My thesis advisor, Tom Yeh, provided priceless advice on the direction of all projects in line with this research, detailed in this document.

1.6.2 Prior Publications

Following chapters are partly published in ACM Conference Proceedings.

Chapter 3:

[57] Jeeeun Kim & Tom Yeh. Toward 3D-Printed Movable Tactile Pictures for Children with Visual Impairments, In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*

[119] Jeeeun Kim & Tom Yeh. CraftML: 3D Modeling is Web Programming. In *Proceedings of the 36th Annual ACM Conference on Human Factors in Computing Systems*

Chapter 4:

[59] Jeeeun Kim, Anhong Guo, Tom Yeh, Scott E Hudson, & Jennifer Mankoff. Understanding Uncertainty in Measurement and Accommodating its Impact in 3D Modeling and Printing, In *Proceedings of ACM Conference on Designing Interactive Systems*

Chapter 5:

[60] Jeeeun Kim, Haruki Takahashi, Homey Miyashita, Michelle Annet, & Tom Yeh. Machines as Co-Designers: A Fiction on the Future of Human-Fabrication Machine Interaction, (alt.chi) In *Proceedings of Extended Abstracts of the 35th Annual ACM Conference on Human Factors in Computing Systems*

[61] Jeeeun Kim, Clement Zheng, Haruki Takahashi, Mark D Gross, Daniel Ashbrook, & Tom Yeh. Expanding & Supporting Workflows Towards Compositional 3D Printing. In *Proceedings of 2nd ACM Symposium On Computational Fabrication*

Intelligence augmentation, or IA, aims to use similar machine learning technologies to assist — rather than replace — humans.

Murali Doraiswamy

Chapter 2

Related Work

Towards the overarching research question of "How can humans and fabrication machines form a collaborative partnership?", my work builds upon three intersecting fields of research in HCI, digital fabrication, and collaborative systems. Firstly, at the intersection of HCI and digital fabrication, I review existing research and the ramifications of (1) design tools for personal fabrication. Secondly, at the intersection of HCI and collaborative systems, I examined extensive prior research in (2) machines for on-the-fly design. Lastly, at the intersection of collaborative systems and digital fabrication, I studied the existing landscape on (3) collaborative machines and social robots, to understand what to learn, to build a digital fabrication system that operates as a design partner in human-robot(machine) teaming.

2.1 Design Tools for Personal Fabrication

There exist a great number of computational tools for end users to design things for 3D printing, from general purpose CAD tools to advanced software systems that address emerging challenges in modern 3D design. I review these works to understand the current state of design tools that have been developed to support *personal fabrication* for individual users, and what are remaining challenges for end-users that I target in this dissertation.

2.1.1 General Purpose CAD tools

A plethora of commercial tools are available with easy access for end users, such as AutoDesk's design tools (e.g., 3DS Max[4], Fusion 360[5], Maya[6]) as well as Rhino[97] and SolidWorks[105], have updated their functions to better support individuals' design activities. Despite easy access and many written and video-based tutorials, however, novice users tend to spend several weeks fully familiarizing themselves with the interfaces [42]. To navigate functions in order to successfully interpret their design intentions into a virtual 3D model, non-technical users must climb steep learning curves. Many of these tools are developed for general use and do not embrace any constraints. As such, these also do not assist users in performing specific design tasks, such as assistive device design and/or wearable designs. Moreover, such tools do not ensure printability, especially when end users choose a low-cost FDM 3D printer for physical fabrication. For example, regardless of a number of free models in 3D warehouses enabling non-expert users to obtain a 3D model, SketchUp [104] users who want to print those models may become frustrated with non-manifold meshes that hinders users from 3D printing.

Recent work, such as CraftML, tries to lower the cognitive barrier for learning 3D modeling by introducing XHTML-style construction of solids. Also, modeling in CraftML results in 3D models that are watertight for guaranteed success in actual 3D printing [119]. Still, efforts to help end users easily design 3D models have not transferred their advantages to the creation of those models. Challenges associated with the physical fabrication process still remain, as detailed in the next section.

2.1.2 Interactive Tools for Fabrication

Interactive computing inspired the computational tools to support crafting and design, aligned with the concept of *continuous interaction* between user and computer [47]. For example, Plushie and Beady construct a 3D simulation model in digital space, based on a user's 2D sketch input [50, 78]. A user draws a crude shape of a stuffed toy using a pen, then the computer generates a 3D model. Similar to a physical crafting process, the system enables a user to think about one feature at a time, seeing the instant outcome generated by the computer.

However, the design space of these practices is limited to the screen, via a 2D representation of a 3D model. It disconnects machine parameters from the process, to be used as design sources.

2.1.3 Design Tools to Speed up Iteration

Ultimately, it is reasonable to assume that unless the design space is *highly* constrained, iteration will be a fruitful and necessary part of the design process. However, consumer-grade 3D printers are mostly very slow, lengthening the iteration cycle. Novice users have encountered a major obstacle: the long process time to create a prototype and the iteration, resulting in their losing interest in continued use of 3D printers.

In contrast with hand sketches and cardboard prototyping to express and improvise design ideas, the physical process of 3D printing prototyping can easily take overnight to get the initial outcome, which blocks all other decisions that would be made based on the outcome. The use of laser cutting as an alternative prototyping method is suggested to address this issue [80], as well as replacing 3D volume with quickly assembled parts using LEGO blocks [82], post-deformed acrylic plates in 3D [11], and thermoplastics [1]. WirePrint is a step-forward approach that reduces construction time by low-fidelity fabrication, printing only open wireframe structures of a 3D model, instead of solid geometries with all closed surfaces. Compared to traditional 3D printing, these alternative means of fabrication can reduce print time by a factor of six [81]. Printing with multiple extrusion heads [35], printing with voxels in parallel in the same layer [39], or using entirely new technologies, such as Continuous Liquid Interface Production (CLIP [19]) are further examples. Alternatively, a previous print may be patched without a full reprint [108], or reshaped after printing [31].

These tools help users get tangible artifacts in a shorter amount of time to validate features for the next iteration. This work has tried to reduce the need for iteration via better design tools, or to speed up the iteration process. However, for the most part, such advances are not based on empirical studies of the problems end designers face, nor do they address challenges such as measurement that arise outside of the design and printing process. For example, if users do not possess sufficient design skills and their constraints are not well understood by system designers, users cannot take advantage of this fast iteration.

2.1.4 Design Tools for Domain-specific Design

Taking into account the limited capabilities of average users, narrowing down design tasks has been considered to change end-user design experiences. In support of very specific types of tasks, new design tools abstract away low-level technical knowledge for novices, rather than expanding functionalities to assist every design task across all applications. Researchers who share interests in computational fabrication and graphics have been pushing efforts to encapsulate secondary information.

Reprise is an exemplary work that supports assistive 3D model designs to adapt real world objects without domain specific knowledge [23]. Inspired by an intensive survey on existing practices of making adaptations—how people make augmented design using crafts, in order for altering the type of movements required to repurpose existing things—Reprise requires a user to choose the movement type he can perform using a natural language (e.g., rotate, squeeze, etc.) to automatically generate the desired mechanisms. The system then helps end users create 3D models that reshape the real world object. For example, Reprise could help redesign a protracted squeezer for a spray bottle handle or a larger pull for a hoodie zipper, for people with fine motor impairments and situational disabilities.

Designing objects in life-scale for personalized environments (e.g., furniture, garments) has been on the rise, as another promising application area of digital fabrication. Sketch-Chair is a tool that allows end users to create a comfortable chair, designed for an idiosyncratic individual's posture [99]. Similarly, using various types of digital fabrication methods, researchers have tried to help end users design *large* objects such as furniture [64, 118]. Following this research for fabrication at scale, plenty of interesting works have been proposed, for users without industrial/civil engineering expertise to 3D print modular parts for the construction of buildings [62, 69]. Users do not need to pay attention to physics or forces that will be applied to objects when these are fabricated and deployed; they only need to consider shapes and aesthetics which is not an ideal direction to support designers for a longer term. Igarashi et al.'s design tools help users design 3D objects, such as fabric covers for real-world objects through free-form step-by-step sketching [48, 49, 83]. The user's work is only confined to specifying the input object and where the opening should be located.

Since commercial machines for extruding sauce and chocolate drizzles have been introduced into the market [2], customized food designs for programmable tastes and controlled aesthetics became another interesting domain of research among digital fabrication communities. Design tools are available for personal cook to manage standard taste, envisioning the future of a digitized kitchen [77, 123]. Additionally, shape-changing ingredients may suggest interesting food production and consumption experiences [111]. For example, for end-users with inexpensive 3D printers, Ori-mandu provides opportunities to combine digital fabrication and cooking [65]. These works help users aim specific goals in a particular domain of cooking, controlling taste or providing food consuming experiences, rather than transferring all knowledge related to generic digital fabrication.

In summary, these works contributed to change the accessibility of users. What we can learn from these works is that, for novice users with insufficient design skills, those systems help them focus a specific design goal by abstracting away low-level technical knowledge (e.g., constructive solid geometry processing). However, there still exists an area to be explored. How can those tools help end users have opportunities for creative exploration towards *fabricating anything*? Narrowed design tasks may also limit the type of application a designer can work for. For example, though Facade can support fabricating tactile overlays on physical flat panels of home/office appliances, it is hard to imagine that the same user groups can extend their designs for non-flat objects [34].

2.2 Machines to Support On-the-Fly Design

Another big challenge for end users remains around their design goal and gradual process to achieve it. In fact, it is common that users do not have a clear picture of the target at the beginning. In that case, users can benefit from a creative exploration with many options until they discover their needs. To fully empower a creative experimentation, innovating fabrication for on-the-fly design through seamless communication with computers has become a crucial assignment for HCI researchers. Since the interactive fabrication concept was introduced [115], researchers proposed a vast range of topics that address a number of challenges towards collaborative design. I review works under this topic, to learn what to reflect to the future development of fab machine by identifying limitations in supporting (1) direct manipulation, (2) seamless conversation with the machine and material, and (3) recognizing design context.

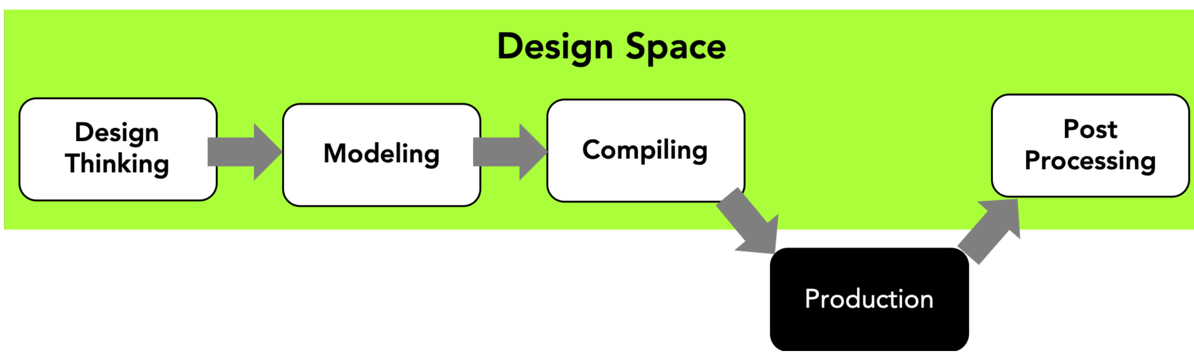


Figure 2.2.1: Current digital fabrication is a linear, batch process. It prevents users from participating in design under the machine's operation, limiting user's design opportunity.

Current 3D printing is a linear batch process (see Figure 2.2.1. This only allows users to enter one input into the machine in one form, as a 3D model (likely as an STL file) at the beginning of the 3D printing. Production is encapsulated inside a blackbox, while a 3D printer is operating. Thus, compared to a vast range of input options available in Computer-Aided-Design (CAD) software, options for modifying objects in the physical production activities are limited. If a user desires to alter a design mid-print, either if a flaw is noticed or user has an interesting new idea to apply to the current design, her only options are to wait until the machine finishes or to halt the operation. In comparison to traditional crafts that users can add or remove materials at any time using various tools, such limited design opportunities in physical digital fabrication introduce big challenges that we need to address, as described in detail below.

2.2.1 Challenge 1: Direct Manipulation

Enabling end users to directly manipulate the workpiece at hand is a key interest. Researchers seek to transfer activities from traditional crafts into the digital fabrication world. In the example of measurements, SPATA calipers and protractors help users bring physical values directly into the digital design space [113]. This is particularly beneficial for 3D adaptation designs that augment existing real world objects. Conversely, Constructables brings users' design space from the digital level to the physical level [79]. A user is allowed to handle physical features directly. Unlike current 3D printing practice, this work enables users to visually validate every piece of the fabrication process step-by-step and make the subsequent decisions depending on that validation. For example, working with the Constructables toolset enables a user to first cut a large piece of material into the right size (e.g., a large wood plank into a book cover size), then to add features (e.g., adding a foldable hinge structure at the middle of book cover), and finally to add details such as filleting corners. These *on-object* interactions [8] are essential for a fluid physical fabrication. As D-coil and Hybrid Artisans introduced, on-time feedback is provided for users to gradually build up an intended model [90, 124].

These work teach what factors should be kept in implementing a collaborative machine. Enabling end-users to work on a current workpiece, in line with tight feedback from materials and machines is one of a kind. Though, communication between users and machines is still via numerical values, using a traditional interface. Facilitating direct communication with existing real-world objects and materials using various modalities that users feel comfortable remains uncovered.

2.2.2 Challenge 2: Seamless Conversation with Objects in the Loop

Stepping further forward to the concept of direct manipulation, research in this domain has expanded the idea of the *on-object* interaction. On-the-fly printing syncs-up 3D modeling in software systems and 3D printing in the physical world. Similar to a LEGO assembly, for instance, a user first creates a brief work piece of a plane body, then gradually adds details of wings and a cockpit, while a printer is printing the body. Once a user makes a decision based on the current work piece, the printer follows the user's step-by-step design action to apply the decision onto the object in the right order. Thus, the user can validate features based on a physical model, not based on a digital model that can be viewed and validated only via a screen [91].

However, the interaction of users with the physical model is still limited to the on-screen design space, resulting in a separation between the digital *design* of the model and the physical *outcome* of the model. Recently, RoMA brings a user's interactions out to the physical world. While the user can interact with the physical work piece, he can also see the preview of the model projected onto this work piece by a virtual reality (VR) device. Design actions of adding on and cutting some parts from an original model are queued into the system, then 5-DOF armed extruder follows a user's step-by-step design decisions to progressively build up a final 3D artifact [92].

To summarize, recent work has begun to tackle a solution for seamless communication that stands in the way of uptake of personal fabrication. While AR/VR could be a next-generation interaction modality, however, it is not ideal for end designers to work with this expensive hardware. Also, the information flow over the AR preview is one-directional; computers can show what to be achieved, but users always need an extra interaction medium to express their design intentions over time.

2.2.3 Challenge 3: Recognizing Design Context

One reason why the needs of *seamless conversation* between users and machines has been underestimated is that there is no action required from users other than entering a digital 3D model from the current digital fabrication pipeline. Although users find the model does not meet their original idea in mid-print, nothing really they can do at this moment other than halting. Additional design context recognition is not an essential function of a 3D printer because it only needs to output a physical model as a result of submitting printing job. Ideally, if a user can take another design activities, adding materials or removing some details in mid-print, this new *intention* must to be understood by the machine, recognizing changed design mind of the user. For instance, if a user's design input is changing, the machine needs to first detect some constraints and precondition, what constraints exist to anticipate ramifications of additional input associated in that, then finally pause current production and safely resume later.

Encore first demonstrated the case of design context recognition. This interactive design tool invites end users to reproduce an advanced artifact based on the features of an existing 3D model. For example, if a user with a 3D printed teddy bear wants to repurpose it from a decorative figurine to a refrigerator magnet, he can place it into the system to generate additional parts for magnet attachment by *printing-over*. Then, the system finds the most viable place to print an attachment via surface normal analysis. The system next generates mechanisms to attach those parts in place, printing add-ons onto the existing object [22].

Patching 3D objects adds the value of a subtractive system beyond the scope of the additive system proposed in Encore. The system allows users to carve excessive parts of an existing 3D model with previous mistakes [108], as well as allowing attachments of additional design details. As an example, user wants to print a smartphone stand that will fit in a car's cup holder. However, the user forgets to leave space for the home button, resulting in a 3D model that hinders the physical button from being pressed. Until a 3D printed object physically interfaces with the phone, it is hard for the user to know

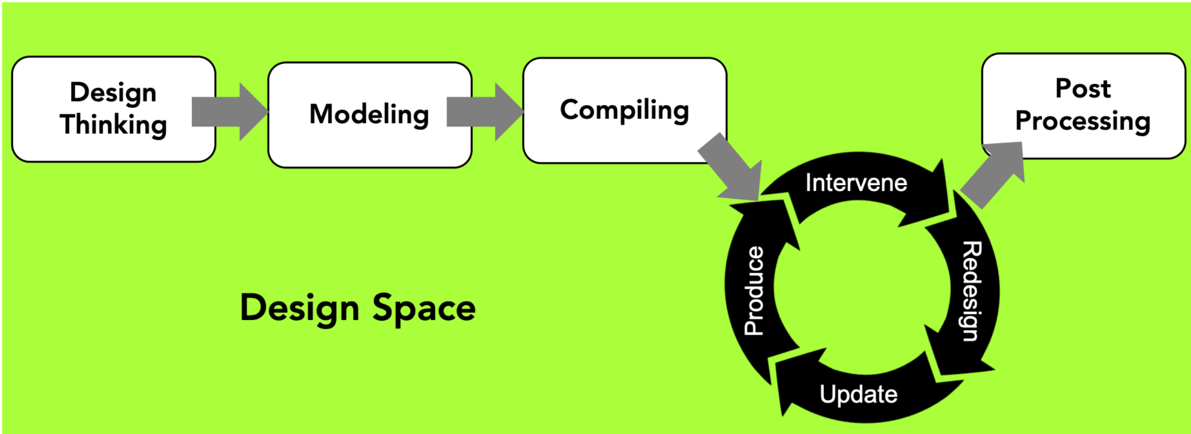


Figure 2.2.2: In comparison with the current linear process of digital fabrication, the future digital fabrication allows the user to participate in physical modeling, intervening to redesign and update design decisions, as well as virtual (digital) modeling

what decision has been made incorrectly. In that case, instead of redesigning and reprinting for another couple of hours, the user can locate the printed model back into the system and create the additional feature: a hole. Now, the system recognizes that the design context, a new model does not necessarily requires to fully generate an artifact from scratch, but can be achieved by carving a feature out from the current input (a physical 3D model), resulting in significantly saved time and materials for the iteration.

As opposed to past linear process of executing fixed commands, the future of digital fabrication needs to be an iterative process in which a user can always update the model with their changing design decisions, as shown in Figure 2.2.2. In doing so, the 3D printer's operation is not hidden in the blackbox anymore, it becomes an iterative process of a fluid conversation with machines for *design-by-doing*.

2.3 Collaborative Machines & Social Robots

Towards a vision of collaborative machines as a design partner for an end-user, human-robot teams often cooperate to achieve a common design goal in creative making. Gradual innovations in digital fabrication, from general-purpose design tools to machines that support on-the-fly design processes, shed light on the potential of *collaborative machines*. Integrating lessons learned from prior research, 3D printers are ready to evolve from a passive, dumb command executor into an active, intelligent design agent. The collaborative digital fabrication machine I envision is distinctive with interactive fabrication in that the machine is working together with users, with a critical need of much more closely interacting with users: sharing status (recognizing human behaviors), exchanging information concurrently with each other (dynamic interaction supporting improvisation).

If we look in and outside of the digital fabrication domain, there has been a great amount of research on designing social robots collaborating with human workers. I review this research as it proposes what to be achieved in the future, and what to be *prepared* (in this dissertation) to step further towards this direction. Note that I have not applied all lessons and provided solutions for the limitations of these works. Yet, the solution I introduce (an event-driven 3D printer and an opensource platform to expand its capabilities) is implemented to incorporate these requirements as key features; (1) recognizing human behaviors (design activities), (2) supporting dynamic interactions and (3) improvisation during modeling and fabricating.

2.3.1 Feature 1: Recognizing Human Behaviors

Most research in developing advanced robots is rooted in planning, because robots' actions were mainly observed as trained operations [14]. In the field of human-robot interactions, human-robot teaming has been a long-standing research topics. Potential solutions have been suggested to improve many AI techniques that can power a robot collaborator, such as reinforcement learning [36] and action selection based on anticipation [40]. This research presumes, though, shared expectations and mutual understanding [37], with robots that are able to *learn* from common human behavior. In a mass manufacturing where human behaviors are limited to certain actions (e.g., pick-up, categorize, hand-over), robots can easily predict human actions. However, creative processes are tasks where individual's design choices are less easily predicted. Their step-by-step design decisions can branch to many directions from these simple choices of conventional behavioral patterns. Hence, it is challenging to develop a supportive algorithm to *plan* a robot's responses that supports all human behaviors—to design activities in a variety of contexts.

2.3.2 Feature 2: Dynamic Interaction

Despite a wealth of advancements in algorithms for planning, it is still challenging to respond to the wide range of possible human behavior. Every individual is unique and implementing personal robot responses inevitably requires proactively engaging with a particular person and different contexts. Hoffman and Ju proposed a series of dynamic robots in various situations that operate (1) around, (2) in front of, and (3) with people. These robots respond to people's behaviors with their own *purpose, intent, state, mood, intelligence, and capabilities* [41]. As examples, the authors introduced an office lamp-bot at a desk that mechanically reacts according to the user's movement; and a musical robot that improvises play on a instrument, mimicking but also adding variations to a human player's music play. Jung et al. sees further potential of forming a human-robot team by investigating robots' effects in various forms of collaborations [54].

2.3.3 Feature 3: Supporting Improvisation

In the field of digital fabrication, the concept of a 3D printer that performs tasks that it can inherently do better has been proposed, while it still leaves a space for people to perform creative improvisation [114]. Supporting the fluid exchange of design intentions between designers and machines, the system encourages users not only to design things using digital CAD systems, but also to physically mark the position of additional elements such as a button or to carve out excessive parts by hand. The system enables users to improvise design actions using existing materials and tools available now, applying those step-by-step design actions using a variety of interaction modalities such as scanning physical objects and hand gestures to cut and paste, etc.

Examining the nature of prior works that aim to support the dynamic interaction between humans and machines, my goal is to implement a collaborative fabrication machine. Ultimately, a collaborative fabrication machine is to nurture creativity through exploration, cooperating with this machine as an active design partner. I envision that this future machine offers versatile opportunities for designers across any stage of digital fabrication; from ideation to planning to execution.

User-centered design means understanding what your users need, how they think, and how they behave – and incorporating that understanding into every aspect of your process.

Jesse James Garrett

Chapter 3

Digital Fabrication-HCI: Personal Fabrication

3.1 Preamble

At the intersection of HCI and digital fabrication, I ask: "How can end users fabricate custom complex artifacts using existing resources without requiring expertise?". Previously, 3D printing has been mainly used for expert designers or limited group of people. Creating a unique item for particular purpose has been reserved for experienced designers, who are skilled at manipulating sophisticated 3D modeling tools. Average users, however, who lack the skills to use those computational tools, are faced with steep learning curves [70]. Although a number of free online repositories exist, if users do not possess relevant skills sets in specific design tasks, such as transcribing 2D visuals into 3D interactive educational materials, there is no easy way to accommodate individuality. For those users, it is critical to provide right design tools that are easy to use and help them achieve their goals of creating custom objects with minimum amount of efforts.

In this chapter, I introduce two modular approaches for end users in creating complex objects, in special education and mechanical design. These domains are chosen because, while these topics may bring about many users' attention and interest into 3D printing, creating adaptive education materials and custom movement design are especially hard for users without expertise.

I first introduce Tactile Picture Books, the world's first 3D printed books for young children with visual impairments, and a design platform for caregivers– teachers and parents– to create, customize, replicate, and distribute educational materials for developing emergent literacy skills. The platform helps these stakeholders leverage their prior experiences of remixing craft materials and existing objects, to transcribe visual features in children's picture books into tactile form. Such tactile pictures help children with visual impairments maximize multi-modal experiences. I add that 3D printing and the artifacts created using this system have a great potential for a broader impact, by providing open access to a wide variety of audiences and by being used by hundreds of people around the world.

Then, I introduce Kinemaker, a design toolkit to enhance interactivity on passive 3D objects by supporting the composition of mechanical components into off-the-shelf models via creative exploration. Going beyond previous efforts that reduce end-users' engagements with computational optimization and simulation, Kinemaker users assemble mechanical blocks to create a variety of movements by free explorations of assembly of such blocks.

I discuss remaining debates among researchers, to emphasize my design choice to advance beginners' abilities by engaging them more actively in design tasks.

3.2 MoveableMaker: Design Tool for Supporting Adaptive Tactile Picture Books Design for Visually Impaired Children

Many children's books contain movable pictures with elements that can be physically opened, closed, pushed, pulled, spun, flipped, or swung. They are beneficial for the development of emergent literacy in young children. But these tangible, interactive reading experiences are inaccessible to children with visual impairments because these are too closely tied to literacy and texts.

Meanwhile, 3D printing has been shown to be a promising method for transcribing pictures in regular children's books to be accessible to visually impaired (VI) children [106]. A picture can be 3D modeled and printed to be touched, felt, and understood by a VI child.

MoveableMaker is a tool for designing highly custom 3D tactile picture books for children with visual impairments. Using a set of 3D-printable models designed as building blocks for creating movable tactile pictures, these components can be touched, moved, and understood, empowering live interactions with caregivers—parents and teachers. With templates that can be integrated with 3D objects, I propose CraftML, a design language based on XML and CSS for specifying the content and structure of a movable tactile picture (analogous to Web design), empowering wider community members of 3D printing to participate in design of adaptive educational materials.

Figure 3.2.1: 3D printed multi-modal picture books, that help developing emergent literacy skills for young children, can facilitate more engagements into reading experience if enhanced with moveables

3.2.1 BACKGROUND

Creating adaptive materials has been identified as a critical factor to facilitate special education [55]. Among many efforts, practitioners and educators have focused on designing such materials to promote multi-modal experiences using tactile artifacts [116]. To date, many approaches to create tactile pictures for children's book have been supported by handcraft, mainly remixing already existing objects and craft materials to enhance multi-modal sensory experiences [33]. Since most creators of these books are caretakers of blind children, teachers and parents, and librarians, they still want to keep their conventional creation process of remixing familiar materials and resources. As 3D printing becomes popular, it has been used for tactile visualization for people who are visually limited [101]. 3D printing affords ease in replicating and customizing book images, which are key challenges in creating tactile graphics [68] while helping children with visual impairments develop emergent literacy [58].

For parents interested in creating tactile graphics, there are resources and guidelines [33, 52] that introduce essential elements of good tactile pictures. These guidelines emphasize the importance of interaction and mobility. Most tactile books have mobility features that guide children's interactions. However, if tangible interaction provides non-visual access to the pictures [20, 75], how can we incorporate interaction features into 3D-printed books? Books that incorporate tangible interactions encourage children's interest in the content, exercising perceptual motor skills that evolve to linguistic skills [38]. Holding children's attention is the key to developing emergent literacy in association with books [84]. Therefore, books combining tangible techniques with 3D printing can play a significant role in promoting children's active participation [74]. Because interaction engages disabled children in an inclusive learning process and encourages development of early narratives [16], tangible interaction would be an essential component of 3D-printed tactile books. Most parents and teachers of VI children lack a clear understanding of 3D printing, even though this emerging technology can help them create unique educational materials for their children [117]. Online 3D design warehouses (*e.g.,* 3D warehouse[1], Thingiverse[2], GrabCAD[3], etc.) have provided opportunities for them to print a premade 3D design. For example, it is not necessary to have a refined skillset to design a fine giraffe in 3D; even blind children can print a giraffe via voice command and then touch it to get a notion of what it looks like [52]. 3D warehouses also enable reuse of 3D tactile models for novice designers. But if parents want to customize a premade model by integrating mobility to create a tactile book, how the technology supports their needs is under disclosed.

3.2.2 Design with Moveable Tactile Pictures

MoveableMaker enables the creation of highly custom 3D-printed tactile picture books. Here, I present a suite of reusable 3D components I developed for the purpose of enabling creating customizable movable tactile pictures.

Design Considerations

Before implementing, I identified design requirements that influenced many of my design choices.

- **Easy to move and touch:** This supports the specific objective of the project, i.e., making tactile pictures movable and touchable for VI children.
- **Easy to print:** A model can look nice in a design environment yet not be easy to print with a low-cost 3D printer. The model may have invalid geometry. It may require support material. It may be necessary to break a model into parts that can be separately printed.
- **Easy to assemble:** When pieces are printed separately, assembly must be easy.
- **Easy to customize:** It should be possible to customize various aspects of a component.
- **Easy to reuse:** The parts should be easy for people to reuse to make new tactile pictures.
- **Hard to break:** Young children are often destructive. Parts should be sufficiently sturdy to allow repeated uses.

[1] `https://3dwarehouse.sketchup.com/`

[2] `http://thingiverse.com`

[3]

Elements of Moveable Tactile Picture Creation

Here I detail four elements to create moveable tactile pictures, (1) page and canvas, (2) tactile objects, (3) moveables templates, and (4) effects.

Element 1: Page and Canvas

The basic element of book composition is the page. I modeled a book as a series of tile-like pages. Each page is composed of three types of components: canvas(es), tactile object(s), and connector(s). A canvas acts as a container for one or more tactile objects placed onto them. Each tactile object is physically joined to a canvas by a connector. The most basic page has one canvas, one object, and a connector joining the two. A more complex page may have multiple canvases of different sizes and different heights, all joined together. A canvas is modeled as a flat, rectangular solid. Users can customize sizes and positions. A canvas can have a frame and rounded corners.

Element 2: Tactile Objects

I implemented two methods to create tactile objects, via a 2.5D relief form of 2D visuals and via off-the-shelf models that can be imported from repositories and modified accordingly.

Relief: Relief is the most common form of tactile graphics in today's children's books for VI children. A tactile artist creates a master mold using clay or equivalent materials. Then a specialized printer is used to press paper against the mold to re/produce the image in relief. Two methods can bring relief patterns into 3D. One way is using a 3D scanner. Another is to use computer vision to extract salient features and map them to different heights. Then a contour map type of structure can be generated as shown in Figure 3.2.2.

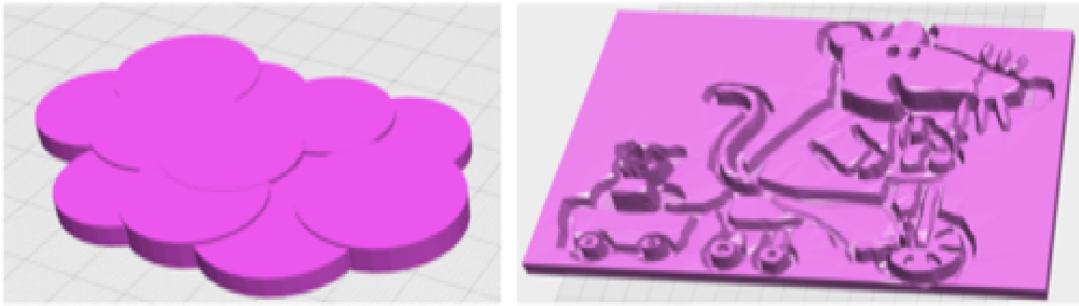


Figure 3.2.2: Relief patterns in 3D-printed tactile pictures. Additive method that brings volumes up (left), and subtractive method that line of areas put back from canvas base (right)

3D "Things": Many premade, ready-to-print objects are now available on sharing sites such as Thingiverse. I used two methods to incorporate premade 3D *things* into a model. The first method involves choosing a prominent side or viewing perspective, for example, the profile view of a cow or a top view of a bucket. This method is preferred when the story needs to emphasize a particular attribute of an object, for instance, how tall a cow is. Given an imported model, the process of obtaining a perspective 3D model is as follows: First, I define a plane cutting through the imported object, then, define a large cube on one side of the plane. Finally, I take the difference between the object and the cube to obtain a perspective representation of an object. This process results in cutting out part of the 3D object with a plane. The second method involves representing an object as a whole, for example, the entire cow or the entire bucket. This method is preferred when the story emphasizes free exploration of an object from multiple viewing perspectives; for instance, how does a cow look like?, and how thin its legs are? at a different page. Given an imported object, users may keep it as is, scale it to convey its relative size in comparison with another object, or flatten it a bit to reduce the overall thickness of the page, as shown in Figure 3.2.3.

Element 3: Movables

MoveableMaker consists of several types of moveable templates. As a set of components, templates can be added to or integrated with canvases and tactile objects to make these 3D objects movable.

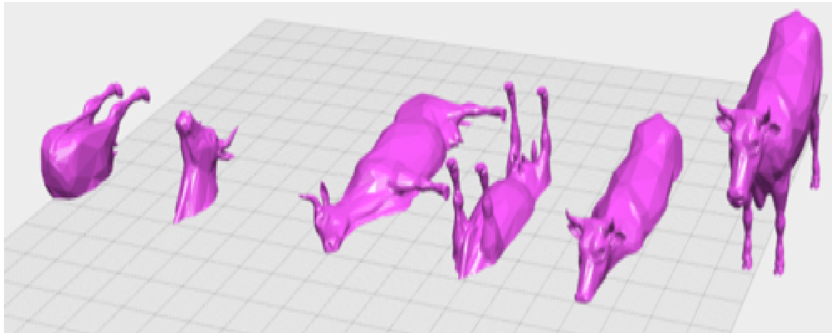


Figure 3.2.3: A premade cow model in various perspectives, split in half x-, y-, z-axes, so that a rear and tail, a head, side view, four legs, top view, and the entire appearance (from left to right) can be represented as a series.

Hinge: A hinge movable is designed to provide a tangible experience equivalent to that of opening a door or flipping a lid. Many hinge models can be found on Thingiverse. I tested several and decided to settle on one (Thingiverse Thing:436737), because (1) it is printable without scaffolding (2) it fits my canvas models well, (3) it does not need post-assembly (4) it is parametric in size, length, volume, etc. Several attributes, such as width and height, are adjustable. I enhanced the model to make a print-and-assemble design possible. First, I added a clamp-like structure to make it easy to attach an existing tactile picture page. Second, I created a trough-like component that can be glued to a canvas as a holder of the hinge.

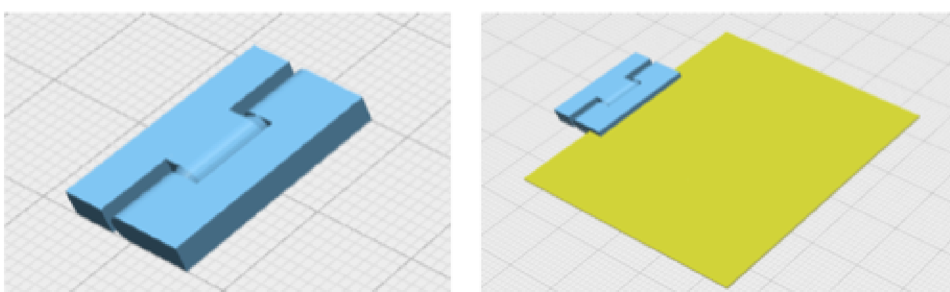


Figure 3.2.4: A hinge movable (left), added to a canvas (right).

Track: A track movable enables a tactile object to be moved by a child along the direction of the track, for instance, dragging a rocket from the bottom of a picture to the top. I model the track after a drapery track, which consists of a long horizontal track in an upside-down T shape. An arbitrary tactile object can be attached to a moving platform (Figure 3.2.5).

Spinner: A spinner movable enables a tactile object to be spun, turned, or rotated, for instance, turning a wheel of a vehicle. For VI children, there are plenty of physical examples to apply *spinning* to the real world, such as wheels of cars and trains. I model the spinner using two components, one is a base with a pin, and the other is a wheel with a flat top that connects to a tactile picture. The components can be printed separately and then assembled. A tactile object can be placed on top (Figure 3.2.5).

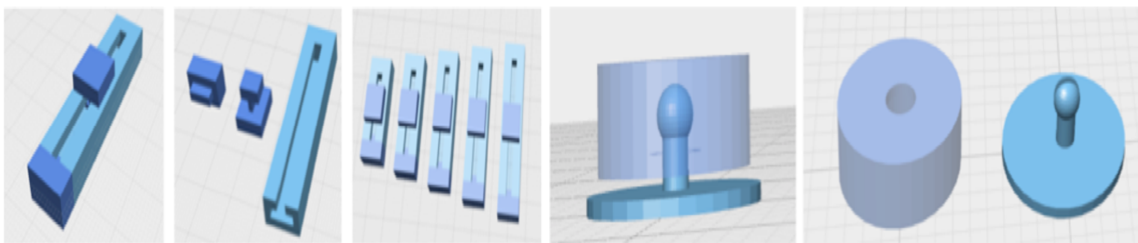


Figure 3.2.5: A track moveable, in parts, with varying heights and a spinner movable combined, in separated parts as axe and rolling disc (from left to right).

Slider: A slider movable enables a child to slide a canvas to the side, for instance, to reveal the content underneath the canvas. In comparison, a track movable is mainly used for moving a single object. The physical analogy would be a French door. A slider has two tracks along the two sides parallel to the direction of movement (Figure 3.2.6).

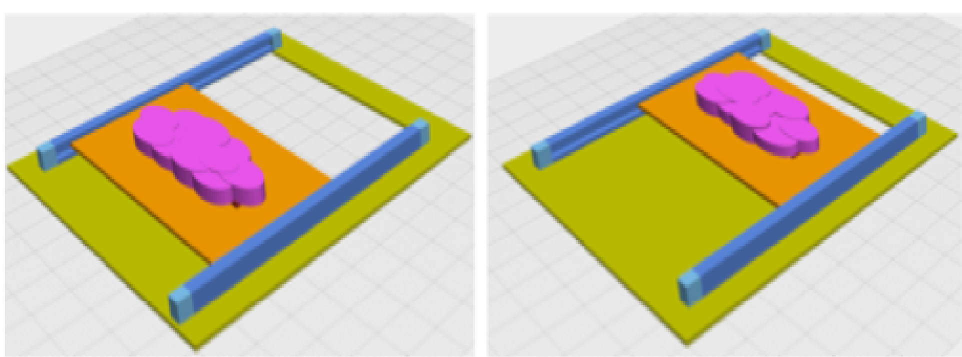


Figure 3.2.6: A slider movable carrying a cloud. A tactile cloud picture is placed on top of base that slides through side path.

Lift: A lift movable enables a child to raise or lower a tactile object. It is modeled as a vertical stack with a number of tracks on each side. The number of steps can be changed by varying numeric parameters (Figure 3.2.7).

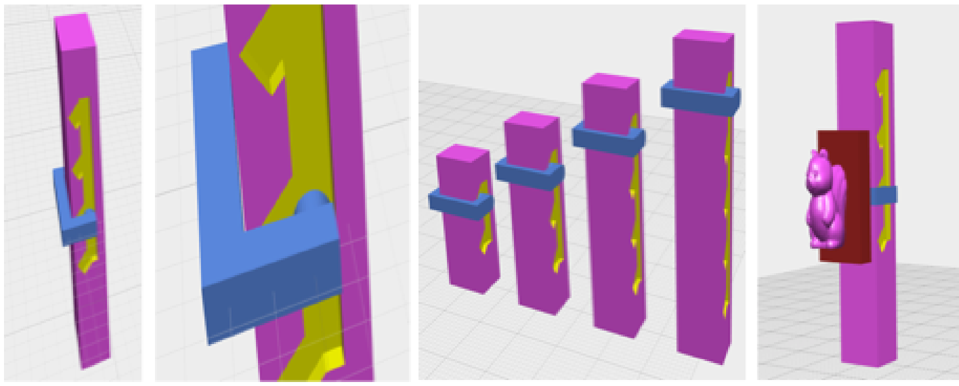


Figure 3.2.7: A lift movable to raise or lower an object. According to the number of slots, a squirrel tactile picture is carried to different height

Element 4: Effects

My objective to promote emergent literacy is to enable the creation of a new class of tactile pictures that are movable so that generated objects can convey concepts that would be hard to do using traditional static tactile pictures.

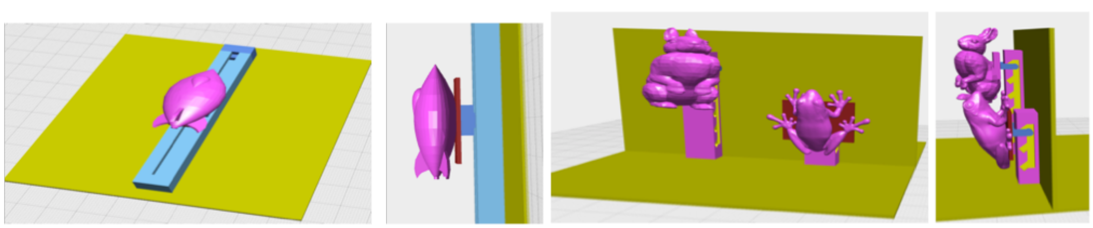


Figure 3.2.8: A rocket can be moved up and down through path(left), A rabbit can "jump" higher than a frog by a lift (right)

Linear Movement: This example conveys the concept that a rocket moves along a straight line. It is achieved using a tactile object (rocket), a canvas, and a track (Figure 3.2.8(left)).

Higher/Lower: This example conveys the concept that a rabbit jumps higher than a frog. A child can pull a rabbit and a frog up from the ground and discover that the rabbit can be pulled higher. It is achieved using two lifts, each holding an object at different heights (Figure 3.2.8(right)).

Front/Behind: This example conveys the concept of a gorilla *behind* a door. A child can slide the door and discover the gorilla behind it. This effect is achieved using a slider movable, two canvases, and a cutout. (Figure 3.2.9).

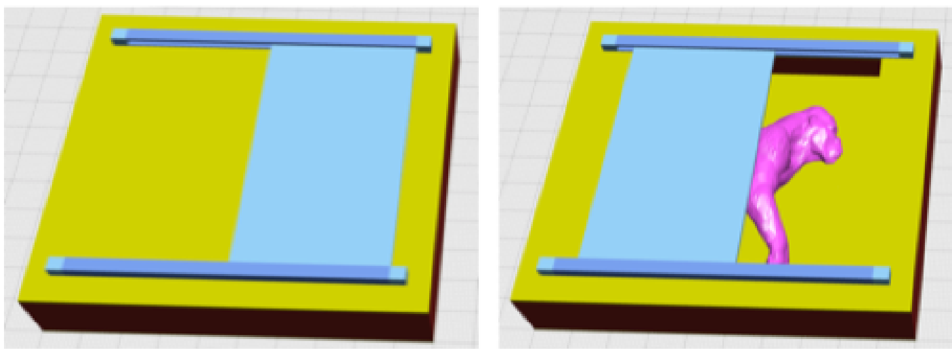


Figure 3.2.9: A gorilla is behind a sliding door.

Motion: The example conveys the concept that the wheels of a car spin. It is achieved using multiple spinner movables, a tactile object of a wheel attached to each spinner, a raised-line model of a car, and a canvas holding everything (Figure 3.2.10).

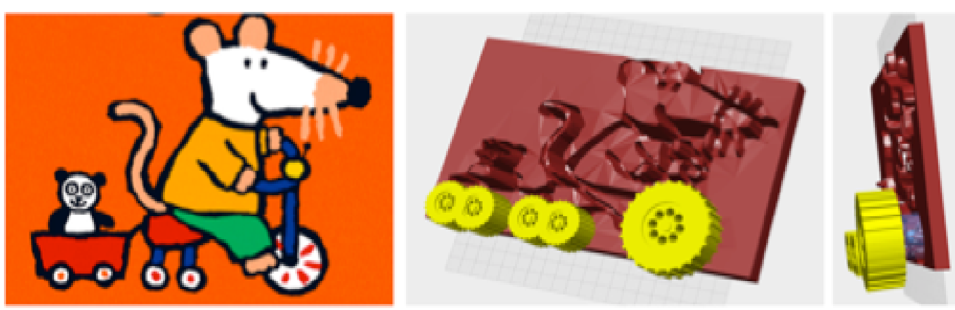


Figure 3.2.10: Wheels of a tricycle and a trailer spin.

I opensourced my models as STL files that can be imported into the design space of a 3D modeling software application. The designer can use a mouse and a keyboard to move, scale, and rotate these models to form a coherent picture.

The design of a suite of reusable 3D printable components, introduced earlier, can be composed into a variety of movable tactile pictures. However, two issues must be considered. First, the composition process is manual and laborious. Second, considerable skill is required to operate the 3D modeling software. The task of designing a page of movable tactile pictures could be made simpler by drawing on the analogy of designing Web pages. The two pillars of Web design are HTML for content/structure and CSS for style.

I propose a design language for specifying a movable tactile picture based on XML and CSS. I chose XML since it is the most popular Markup language specifying "contents". Similarly, CSS was chosen due to its popularity on specifying "styles", that can be applied to unify design on a "set" of pages. Combined XML/CSS makes this approach accessible by the entire web development community, which is far larger than the advanced 3D modeling/design community. Another important benefit is that XML/CSS is text-based and is accessible to blind users via a screen reader. A designer can define the content and structure of a tactile picture in an XML file and can also specify the style attributes of each element in a style sheet (CSS). I do not claim that XML/CSS is at a level of abstraction accessible to everyone. Though, this level of abstraction would empower a much larger user population than skilled 3D modelers to contribute to the 3D movable picture design. Also, CraftML can pave the way for others to build a WYSIWYG editor to further lower the barrier.

Example 1: Hello Squirrel

This basic example puts a squirrel tactile object (imported from an STL file) onto a blank canvas.

```
<canvas>
  <object src="squirrel.stl">
</canvas>
```

Example 2: Complex Example

A more complex example is shown below, to highlight the key features of CraftML. This example defines a rocket situated above a spinner, which is situated beneath a track, as Figure 20 shows. This rocket can be rotated and moved up and down. A door is added to cover the lower half of the canvas (y = 50%, height = 50%). A cloud is added on the door. This door can be opened along the south direction.

```
<canvas>
  <track length="30" direction="north" slope="20">
      <spinner>
          <object src="rocket.stl" x="10" y="10"/>
      </spinner>
  </track>
  <door orientation=south y="50\%" height="50\%">
      <canvas width="100\%" height="100\%">
          <object src="cloud.stl"/>
      </canvas>
  </door>
</canvas>
```

Object Naming This design language allows the naming of tactile objects. Names increase readability and reusability. A named object can be used in multiple pages that share the same object (e.g., the same rocket over several pages). Here is an example of an object specification file (i.e., objects.xml) defining a giraffe, which can be referenced by <giraffe/>.

```
<objects>
  <object>
      <name>giraffe</name>
      <source>giraffe.stl</source>
  </object>
</objects>
```

Style A style sheet can be used to separate style attributes from content and structure. For example, to design a picture to show a giraffe behind a door, I can start with the following style sheet that defines the size of a page and the side of a door.

```
#myPage {width:50, height:50}
.myDoor{width:80\%, height:50\%}
```

Then, a user can specify the page's content below to generate a 3D model to print Figure 3.2.11:

```
<canvas id="myPage">
  <giraffe>
      <door direction="left">
      <canvas id="myDoor"></canvas>
     </door>
  </giraffe>
</canvas>
```

3.2.3 Implementation

To implement the functionality to generate a model from a specification, I had to redesign all my models as programs that can be invoked with different parameters. My initial choice was OpenSCAD; however, I found it lacked crucial features of a real programming language. I found a better solution in OpenJSCAD because it provides modeling capabilities equivalent to OpenSCAD as well as supporting Javascript, allowing both object-oriented and functional programming. For instance, one can represent each component as an object with easy to customize attributes and combined with other objects programmatically. Also, it enables to use existing Javascript libraries to parse the XML and style sheet in the design specification. CraftML is now available for open use and further development by advanced users, available at `https://craftml.io`. Further features and case studies have been reported in Proceedings of ACM SIGCHI Conference on Human Factors [119].

3.2.4 Evaluation

This work aims to make more children's books with movable pictures accessible to VI children. Therefore, I evaluated this work by a number of applications, showing this approach can be applied to the task of transcribing visual children's books into movable pictures.

Dear Zoo

I modeled all eight pages in this book as shown in Figure 3.2.11, titled *Dear Zoo*. Beloved for decades in the U.K., this book was a good test bed for MoveableMaker because all the pages share a common moving mechanism (*i.e.*, hinge) but vary in details, such as the tactile object, appearance of door, the orientation of the hinge (horizontal vs. vertical), coverage (half vs. full), and configuration (one side vs. split). I used the same template and customized certain aspects of this template to generate these models testing the modularity of CraftML.

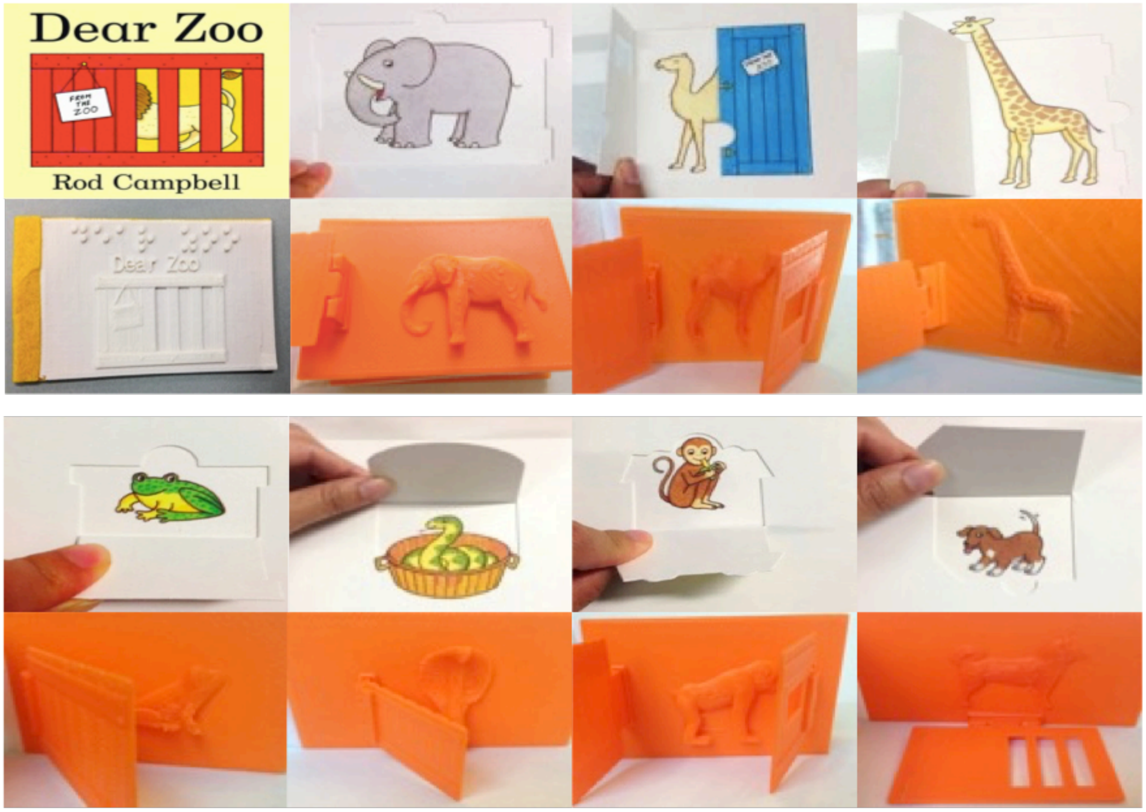


Figure 3.2.11: All pages in Dear Zoo with braille printed cover, with doors of various tactile patterns and cutouts

I used four different types of doors with cutouts to enhance the variety in the touch experiences. These differences allow children to advance from thinking about the simple shape of the door to experiencing different moving directions and unique attributes. Real book spine is still important feature to be given for book reading experience, so we bound pages as book format with the title printed cover page.

All the Fun of the Fair

The second book I chose was *All the Fun of the Fair* by Robert Crowther. This book employs a rich set of moving mechanisms in pages describing scenes from a theme park. Figure 3.2.12 shows the three components from selective scenes of the book, using a variety of movements. A rolling wheel is represented by a spinner, combined with the wheel frame as a tactile picture. A biking roller coaster is turned into a swing with shapes of human passengers. The primitive track is used to represent a bumper car in a playground. Children can move the picture of a boy riding a bumper car to the left and right.

Figure 3.2.12: Selected pages in All the Fun of the Fair. A spinning giant wheel (left), swinging biking roller coaster (middle), and sliding bumper car (right).

When I'm Big

The third book I transcribed was When I'm Big by Paula Hannigan. I was interested in transcribing scenes that include unique elements that go up and down, by showing various transformation of movable books. For example, a rocket moves up by sliding a flap, and a firefighter on the ladder can be located higher. I used a lift movable and a slider movable to achieve these effects (Figure 3.2.13).

Figure 3.2.13: Selected pages in When I'm Big. The slider carries a firefighter riding a ladder up to the roof.

Hop, Skip, and Jump, Maisy

The fourth book I transcribed was Hop, Skip, and Jump, Maisy by Lucy Cousins. This book illustrates the daily life of Maisy mouse. It includes many kinds of interactive mobility. For example, the wheel of a car and a bike are modeled using a spinner movable with a wheel object attached to it. The picture of Maisy drinking juice represents the remaining amount of juice in the glass. Visually impaired children can pull down the pulley, touch the top of it with their other hand, and feel how the relative height of the juice decreases, a situation they will never touch directly in real life (Figure 3.2.14).

Figure 3.2.14: Selected pages in Hop, Skip, and Jump, Maisy. Maisy's riding automobile (left) and bike with spinner(middle) and drinking juice from the glass (right).

What's the Opposite?

The fifth book I transcribed was What's the Opposite? by Eric Hill (Figure 3.2.15). This book introduces spatial concepts in contrast, as children lift the flap and uncover something behind it: a rocket under the cloud, a moving car behind the flag, children emerging from behind a door. Flapping parts of each page are combined with a hinge that enables readers to turn over objects.

Figure 3.2.15: Selected pages in What's the Opposite. A rocket behind the cloud flap (left), a car behind a flag flap (middle), and a door flap opening (right)

Gossie Plays Hide and Seek

The sixth book I transcribed was Gossie Plays Hide and Seek by Olivier Dunrea. This book includes a set of examples of push and pull using a pulley mechanism by which children uncover hidden objects by lifting the flap. One interesting feature is that Gossie bird is getting on the swing that hangs over the tree, as shown in Figure 3.2.16. Connected with tree and bird, this feature will more specifically introduce the concept of a tree swing to blind children.

Figure 3.2.16: A page in Gossie Plays Hide and Seek. A tree swing is defined by the spinner.

3.2.5 Deployment

From this work, I delivered physically printed models to the community with VI children, such as families, schools for special education (more than 50 countries by the time this dissertation is written). I also sent multiple books to the public libraries for people with visual impairments (e.g, Colorado Talking Book Library (CTBL)) for circulation, while conducting workshops at CU Science Discovery (2015), Denver Public Library (2016), and more, for a wide group of audiences. Further, I exhibited various picture books through Gemmille Engineering Library at CU (2015), Future of Storytelling Design Summit in New York (2015), King Abdulaziz Center in Saudi Arabia (2017-present, permanent), Smithsonian Design Museum (2018), etc., as shown in the Figure 3.2.17, to expand the exposition of this work to obtain broader access. Also, I shared the printable file to the online community (Available at Thingiverse.com), recording more than 100 downloads and *likes* per page.

Figure 3.2.17: Exhibitions of tactile picture books (from top right in clockwise) at Future of Storytelling Design Summit, Gemille Engineering Library, Smithsonian Design Museum, Peanas Con Piezas in Italy

3.3 Kinemaker: Computational Tool for Mechanical 3D Objects Design

As described earlier in Chapter 2, sharing personally designed and printed models as digital files has become a common activity. Ideally, this suite of tools would empower end users to create, share, and build on each others' 3D designs in a modular and replicable fashion.

However, despite these tools, the opportunity of end users to turn passive off-the-shelf models into automata toys and mechanical objects was not taken into account. In addition, tools to make these mechanical objects be *reused* and *reconfigured* are limited. Even with the ability to customize parameters with available tools (*i.e.* Thingiverse Customizer), users still find themselves limited in adjusting existing models to their taste. Modification such as adding mechanical behaviors to animate a static object is difficult. For true customization, we should let users handle *mechanisms* as creative manipulatives, similar to shape primitives that can be remixed into freely available objects.

Kinemaker is a creative framework to support mechanical design as remixing *gearboxes* and off-the-shelf 3D models. Lowering the barrier, Kinemaker empowers novice modelers to easily create simple functional objects. Raising the ceiling, Kinemaker also promotes skilled modelers to compose complex designs. The Kinemaker framework consists of (1) a formal specification of a modular, remixable, and composable gearbox, (2) a versatile library of gearboxes conforming to this specification, (3) an algorithm for performing remix, and (4) a GUI tool for preview. It handles a range of issues that arise when

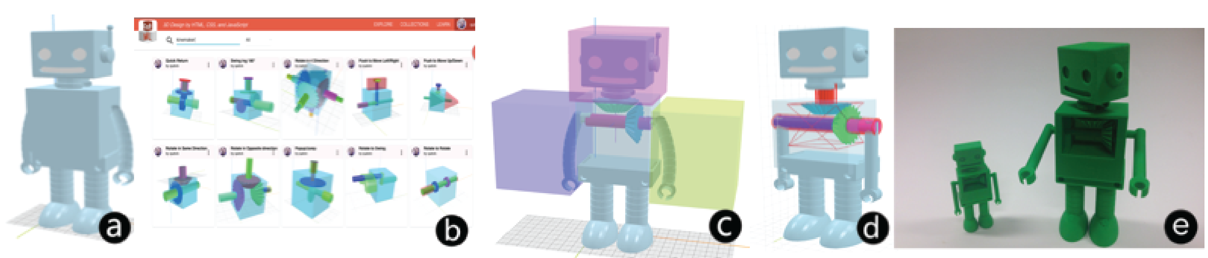


Figure 3.3.1: Kinemaker enables users to embed gearboxes into static 3D objects by (a) selecting an off-the-shelf model (b) importing gearbox from the library (c & d) to make movable 3D object by implanting and aligning a gearbox in position, and (e) 3D-printing in various scales

composing mechanisms into 3D objects, such as how to create the space to hold a mobility mechanism and how to deal with individual components interlocking.

Kinemaker broadly demonstrates the value of creating 3D models that embody computational principles such as *modularity* and *composability*, empowering open-ended exploration to create custom interactive objects. Contrary to prior work that focuses on the computational optimization method of creating and optimizing motion (*e.g.*, [21, 25, 120]), my objective is to enhance what an end user can accomplish by providing them with modular components then advance to the next step. As creative primitives similar to using physical LEGO™bricks or the computational programming blocks of Scratch [72], Kinemaker enables free exploration on the open-ended construction with reduced vocabulary [32]. This exploratory design activity, which is supported by computation, inspires end users to think of various applications to which they can apply similar and/or gradual principles with their own design judgment.

Specific objectives here include:

- Implementing Kinemaker, a set of modular gearbox libraries of mechanical component units and a tool to support remixing them with off-the-shelf 3D models
- Validating design considerations via printed examples and user study, to support end users' explorative design process

3.3.1 Background

Kinemaker is built upon the desire to build 3D-printable *Automata*, mechanical toys. Sometimes referred to as mechanical toys or kinetic art, they are small machines that utilize the mechanical principles which can be found in almost every modern machine employing cams, gears, ratchets and cranks [76]. With the recent advent of affordable 3D printers, there have been approaches to satisfying modelers' desire to create their own mechanistic 3D objects, which I review below.

Systems that Support Mechanical 3D Model Creation

The introduction of mechanisms into 3D objects is of far-reaching interest in domains from toys to robotics. This craft harks back to the creation of automata, a field that has long been a focus for expert craftspersons [15]. More recently, hobbyists have begun sharing cutout templates for automaton mechanism creation [51, 76]. For example, casual users can adapt these templates to create fairly sophisticated mechanical automata. Pinterest Automata toys[4] collection shows great examples of fairly sophisticated models backed up with one simple mechanism. Because of the difficulty of creating mechanisms without templates, recent efforts have focused on increasing the power of the tools for creating mechanisms. For example, computational systems have been developed for optimizing motion paths on automata [12, 25, 122], or fitting scales into a target model [120]. This approach is accessible since end-users simply draw the path a design mechanism should follow. However, the range of optimizable mechanisms are limited to changing the inter-relations among the parts in a predefined template (*i.e.* radius of interlocking gears, length of associated linkages); a designer can not freely introduce new parts to this template. Also, the target model must be pre-articulated; it is not possible to apply to arbitrary off-the-shelf 3D models.

Kits to Support Understanding Basic Principles

An alternate approach, exemplified in physical toys such as LEGO Mindstorms [87], is to provide average users with mechanical blocks capable of a number of atomic motions. These basic units can easily be combined with each other in the context of a physical form made of LEGO blocks. Languages such as Scratch [96], Scalable Game Design Kit [7], as well as electronics toolkits such as LittleBits [9] take a similar approach, deconstructing complex concepts into small, simplified, understandable, modular atomic units. These kits engage end users into critical thinking, where they can then combine, guiding them to understand simple principles, and gradually build complex projects. The popularity of such tools speaks to their accessibility; end-users often build sophisticated projects from these elemental

[4] `https://goo.gl/cfuyrc`

blocks. This approach of creating modular, interchangeable, composable physical blocks is exemplified in CUBEMENT, which provides cubes such as a motor cube, breadboard cube, and crank cube for rapidly prototyping mobility in product design [24].

Open-ended Exploration for Reflective Design

In the literature, open-ended exploration has been shown to promote reflective design. For example, young learners investigate the challenges of designing things with transitive materials [103] and increasingly complex mobility by toy fabrication sets [56]. Recently, FoldMecha applies such an approach to the explorative design of mechanical structures [86]. It provides users a kit of physical mechanism building blocks. Users can *play* with the construction process to learn about the mechanisms and how to build complex movement incrementally, aiding the gradual shift from novice to advanced user levels. Kinemaker takes this position over goal-oriented approach, which simplifies the complex problem into small domains where users' participation takes an important role.

Facilitating Remix and Reuse of Mechanical Parts

Partly due to its inherent re-configurability and expressive representation, 2D pictures and books have been another important domain for mechanism design. MoveableMaker supports novice paper crafters in the placement and customization of common motion primitives (*i.e.* translation, rotation, levering, disclosure, and travel along a path) [3]. I also developed re-usable 3D mechanism primitives such as hinges, tracks, and spinners that can easily be combined to create interactive 3D printed books for children, introduced earlier [57]. Nonetheless, this body of work is limited mostly to 2D or 2.5D output, but highlights the value of thinking about mechanisms in terms of simple, composable components to be remixed.

When moving from 2D to 3D and embedding into existing models, new challenges in space-making and attachment between the components arise. For example, one approach to address these relevant issues is to manually insert alternative materials with pre-defined space to enclose them [27, 46, 100].

It may also be valuable to score different connections based on metrics that capture their strength, durability, usability, and so on [22]. Although only partially focused on functional mechanism design, this body of work highlights some of the complex issues inherent in combining different types of things in a single 3D model, to facilitate remix of such things.

3.3.2 Challenges in Designing Mechanical 3D Objects

I conducted a preliminary study to understand the overall process of creating mechanical 3D artifacts and what makes it hard to design highly custom mechanical objects for novice users. From the finding, I wanted to list what design considerations should inform the development of Kinemaker, a design tool for average users, to abstract away high-level knowledge.

First I conducted informal interviews with a number of skilled 3D model designers. They were first shown an example object with an embedded mechanism that makes the object functional. They were then asked how they might approach designing something similar from an off-the-shelf 3D model that is not segmented as pieces and lacking any movement mechanism. Based on their answers, I performed a hierarchical task analysis and obtained the task description shown in Table 3.3.1.

Among the four steps listed in Table 3.3.1, steps 2 and 3 pose higher barriers to average users to finally enable easy creation of custom mechanical artifacts. The former requires basic mechanical knowledge and the latter involves a series of complex 3D modeling operations. For average modelers, these difficulties may prevent them from proceeding to the next step, if they do not have enough understanding in mechanical engineering. Though, step 2 is non-trivial. There are reference materials one can use to look up to learn about the gearbox configuration necessary to implement the desired motion. Step 3 also involves guess-work to figure out the appropriate dimensions of the various cavities that must be cut.

Step 1: Prepare a target 3D model
• Search an online catalog of models • Import the host model into the design space
Step 2: Make a movement mechanism
• Browse an online catalog to collect suitable gear parts, *i.e.* bevel gear, cam, rack & pinion gear set, *etc.* • Import each one to the design space • Design shafts by hand to connect the gears • Design a container to hold them in place • Digitally assemble these parts ensuring they have enough spacing for the movement
Step 3: Prep the host model
• Cut the host model, separating the movable components from the host object into their own parts (*i.e.* robot arm from body) • Move each movable part slightly off the host object, leaving space between them not to get stuck when 3D printed • Cut the hole inside the host model that is large enough to fit the gear systems, but tight enough to keep assembled components in position
Step 4: Integrate
• Move and scale the gearbox to the desired internal location of the host model • Cut a cylindrical hole for each shaft to be detached from the body, connected to each movable part; the hole must be slightly bigger than the dimension of the shaft • Adjust the length of each shaft to make sure it is connected to each moving part

Table 3.3.1: Experiments with a variety of materials and printing techniques show a number of laborious tasks that hinder average users from exploring 3D modeling and high level options for creating mechanistic 3D objects

I also found other issues with the manual approach. First, printability issues can arise at post-processing time. For example, some gears may seem well-connected when viewed in a CAD tool but become stuck when printed. Second, debugging and iterating a design is difficult; each time a designer must change a component (such as the size of a gear), she often needs to manually adjust many others to ensure fit (*i.e* repeating 2, 3, 4 many times). Third, even as a designer succeeds in building a working mechanism for one host model, it is difficult to transfer it to another host model; one often must start from scratch.

Design Considerations

Here I present five design considerations to address the issues identified from the previous challenges.

Modularity (M) A movement unit should be a first-class design primitive. When designing with a *gearbox*, a user can start brainstorming from what mobility presents s/he needs, as well as how to combine it with other shape primitives or modules, as opposed to having to reason with individual components respectively, in low-level gear, shaft, and crank and placement.

Remixibility (R) A gearbox should be easily remixed into an existing model. When designing, a user can reuse any static model downloaded from an online repository and remix it with a gearbox unit to make the model movable.

Feedback (F) A gearbox's effect on an existing static model should be visible to the designer. When designing, a user can explore a remix configuration and see the model's resulting movement. This allows the user to quickly explore different remix possibilities if needed.

Versatility (V) A rich library of gearboxes should offer a versatile range of motion possibilities. When designing, a user can experiment with different types of gearboxes in a remix to achieve various effects.

Composability (C) : A gearbox should work with other gearboxes in a composition. When designing, a user can remix multiple gearboxes with existing models to achieve a complex design.

Together, these design considerations should provide a user experience as exemplified below, not only to enable average users to easily design 3D artifacts in the range of limited examples, but also to empower them to apply the same techniques in much wider design applications:

> **Low floor:** A user downloads a target model, loads it in a design tool, selects and imports a gearbox (modularity), and drag-and-drops it into the robot's body to insert (remixability). The robot's head begins spinning (feedback).
>
> **High ceiling:** She tries a different gearbox (versatility) and the robot's head is now popping up and down. She continues to add more gearboxes and integrates additional host models (composability) to obtain a complex design she can be proud of.

3.3.3 Design with Kinemaker

Here I detail Kinemaker, a design tool to support end-users to insert modular movement mechanisms into existing 3D models. This approach consists of: (1) a gearbox design specification that supports *modularity (M)* and *remixability (R)*, (2) a library of gearboxes conforming to this specification in order to support *composability (C)* and *versatility (V)*, (3) an algorithm to perform insertion, and (4) a visual simulator to provide instant *feedback (F)* for design validations from designer's perspective.

I implemented Kinemaker's four system components described below using CraftML [119] and ThreeJS [5]. Note that it is possible to use other programmatic 3D modeling tools such as Fusion 360 or OpenJSCAD to implement the formal specification given above, albeit with varying degrees of difficulty.

Gearbox Specification

Here I describe a design specification for a gearbox that can represent a 'function' and can be imported into a design space as a modular unit and inserted into an existing host model.

Let $G = \{S, \Omega\}$ be the specification of an implantable gearbox design, where S is a set of 3D shapes and Ω is the required meta-data. First, we further expand S to $S = \{C, M, A\}$. C is the set of mechanism components (gear, shaft, cam, follower pad, *etc.*) that make up the working gearbox in a unit. M is the set of margin spaces that must be cut out from inside a host model, to accommodate the inserted mechanism components and to create clearance for ensuring mobility of shafts through solids. A is the set of bounding boxes adjacent to the gearbox that specify action spaces. The purpose of an action space is to determine which portions of a host model can be separated with the correct offset and become movable. For example, if a robot's arm falls into an action space, that arm can later be automatically separated from the body and can thus spin.

[5] `https://threejs.org/`

Next we expand Ω, the required metadata, to $\Omega = \{L, K, \Theta\}$. L is a set of relative layout constraints among the shapes in S. For example, a constraint $l \in L$ could dictate that a gear and a shaft must be centered along the x and y axes and must be adjacent along the z axis. This allows gearboxes to be mutually compatible when connected. K is a set of kinetic properties (half rotation, up/down, *etc.*) attached to the shapes in S. For example, a kinetic property $k \in K$ could indicate that a gear $s \in S$ can spin in a particular direction or that an action space $a \in A$ can jump up and down in a certain range and along a particular axis. Θ is a set of parameters exposed to users for customization. For example, a parameter $\theta \in \Theta$ could be the shape of a cam (*i.e.* snail, ellipse) or the length of a particular shaft.

Recall in Table 3.3.1 that manual gearbox insertion requires several burdensome steps where one must create and manipulate various geometries. Our formalism abstracts various geometries— C for 2.1 and 2.3, M for 3.3 and 4.2, and A for 3.1. In 2.5, 3.2, 4.2, users must manually enforce various layout constraints, which is now abstracted by L. And 2.1 implies certain knowledge about gear mechanisms, which is now coded in K. In effect, this specification for gearbox design serves to abstract out the burden of knowing, designing, and laying out these geometries.

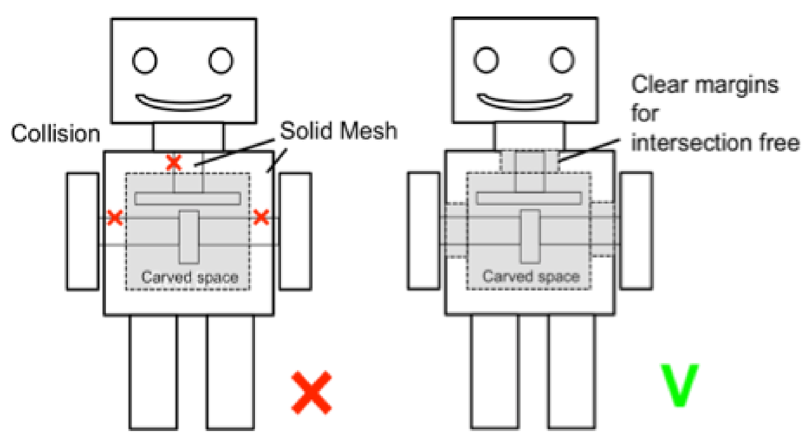


Figure 3.3.2: Margin spaces (M) in our formal specification. This example includes a cubical unit to make a space and to hold components in place (left), and extended cylindrical paths along with shafts (right), providing clearances for free movements.

More details on various components of the specification are provided next.

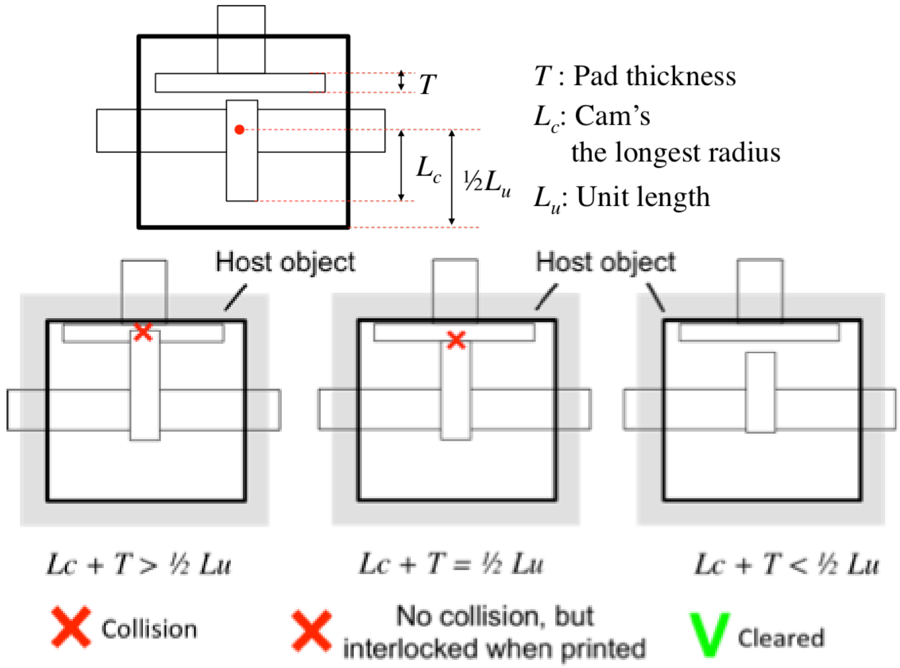


Figure 3.3.3: Internal geometry specifications defined by inter-relations for mechanism elements in the crank unit. Specific relations for each unit—considering printability clearances—are internalized in the gearbox design.

- *M* **(margin spaces)** include a box-shaped space covering the gears, a cylinder-shaped space for each shaft extending out of the box, and any surrounding spaces that the shaft will need to move through (such as the half pipe shape for the swinging lever in Figure 3.3.4 (g), and the extended prism for the slider in Figuer 3.3.4 (i)). Figure 3.3.2 shows an example of a margin spaces design.

- *A* **(action spaces)** include a relatively large box-shaped spaces for each shaft in order to distinguish the moving parts from the host object to be segmented. It can later be changed to a cylinder or a sphere, depending on the shape properties for the moving parts. The sizes of these spaces should be adjustable by users for further customization. Figure 4.2.1 (c) is an example of action spaces visualized as semi-transparent color boxes.

- *L* **(layout constraints)** ensure individual parts in *C* are positioned and sized to maximize inner mobility, motion smoothness, and printability. For example, in Figure 3.3.3, the space between the cam and the follower pad, as well as between the follower pad and the box border, must be at least more than 0 apart to enable vertical rotation; but sum of follower thickness, cam radius must be smaller than half cubicle unit size; otherwise, they would become stuck together after printing, not fully rotatable as the driving handle turns, or the movement effect is not salient. Importantly, all shafts must be centered with respect to the sides of the gearbox they intersect. This constraint makes it easy for multiple gearboxes to cohesively link together.

- Θ (**user parameters**) include a scaling parameter and other parameters specific to each gearbox design (*e.g.*, the range of up-down motion which defines the cam radius). Whenever a parameter is changed, the system computes a new configuration subject to the layout constraints L. For example, if a user elongates the height of the robot shown in Figure 4.2.1 along the z-axis, instead of scaling everything uniformly, the relative sizes and positions of the various parts of the gearbox can be updated automatically to produce another valid design.

Gearbox Library

I developed a library of gearbox modules that conform to the specifications described above. As inspiration, we surveyed hundreds of mechanical models online and found several common gearbox types, based on which we designed remixable gearbox modules. Each gearbox supports a mechanism for translating linear or rotational motion across shafts, powered by one driving crank. Here we describe a selective subset of the nine gearbox modules (see Figure 3.3.4):

Jumper (a) conveys rotational momentum directly across a shaft, without changing directions. For example, a crank attached to the left side rotates at the same speed and in the same direction as a movable part attached to the right side.

Bevel Gear (b) combines a jumper with a pair of beveled gears. Rotational power is conveyed across a shaft and subsequently upward along the perpendicular shaft, used in Figure 4.2.1.

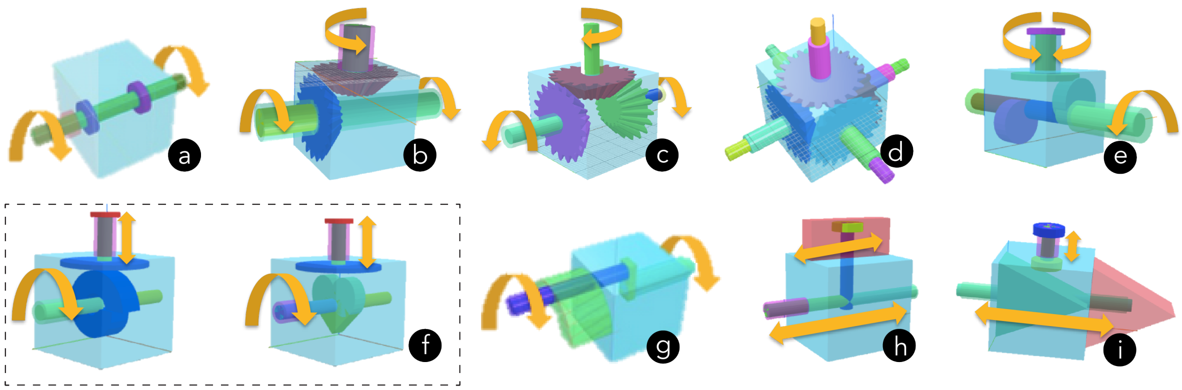


Figure 3.3.4: Remixable gearbox modules. Each box takes rotary or linear power inputs and delivers momentum to adjacent units connected through shafts. (a) Jumper (b) Bevel gear (c) Friction wheel (d) Double Friction wheel (e) Double Cam (f) Cranks with snail and heart shaped cam & (g) Swing lever, that take rotational movement as the driving input. (h) Pulley, and (i) Slider take linear motion as the input.

Angular (c) & Double Angular Wheel (d) both enable their attached parts to rotate in inverse directions on each facet. A double friction gearbox extends the Friction Wheel, providing two more bevel gears and shafts in one unit, as it has five bevel gears across each facet of a cubical unit. This design allows multiple target objects to be controlled by a single crank, transmitting power to four other directions.

Double Cam (e) transforms a circular motion into another orthogonal direction and alternating it into a half rotation. When the first cam rises, the follower pad rotates in one direction, via interlocked facets. When the second cam rises as the first cam drops (Figure 3.3.5), the follower pad rotates in the opposite direction, driven by its differently-oriented facets. The follower pad and the host part attached on top rotates counter/clockwise as the horizontal shaft turns. The radii of two cams determine the angle of half rotation on the follower pad.

Cam (f) allows a target object on the top of a perpendicular shaft to move up and down in various patterns, or back and forth. Based on the size and shape of its internal cam, the cam converts rotary motion to a various range of up-down motion. By changing a cam type parameter (*i.e.* snail, heart, jitter), rather than 'ellipse' as default, a user achieves different movements. As shown in Figure 3.3.6,

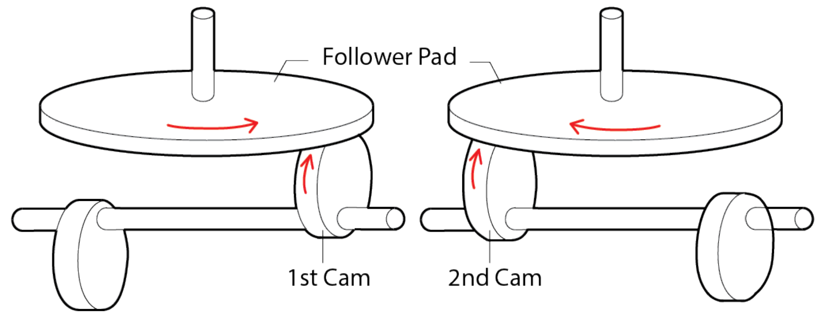


Figure 3.3.5: The half circular motion generated by Double Cam. The upper pad rotates in a half circle in 180 degrees, following the each of driving cam at the time.

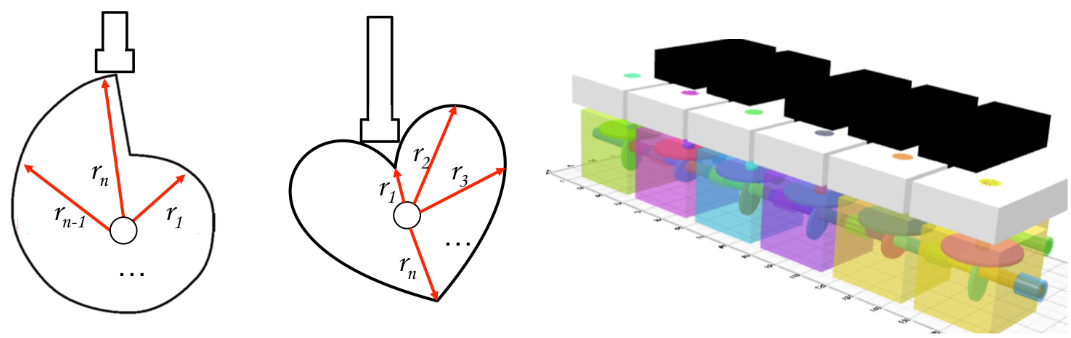


Figure 3.3.6: As the center-anchored shaft turns, the follower shaft moves up and down, representing jumping (left) and waving (middle) in range $r = [min(r_1, r_n), max(r_1, r_n)]$. Setting cam to different placement angle changes the sequence of up/down motion, instigating the piano to play different keys with different timings.

components specification imposes a movement range where the largest radius $max[r_1, ...r_n]$ should always be shorter than the half unit size for full rotation. Being automatically computed when a user sets numerical parameter values to the parameter. Another parameter is the placement angle; a user can control the sequence as shown in the Figure 3.3.6, piano example.

Swing Lever (g) moves in a half circle, which lets an object attached to the shaft follow a curved movement path. Note the unusual 'margin' region shape here, which incorporates the expected path that the shaft will need to pass through, as shown in red wire frame in figure 3.3.7 (left).

Pulley (h) receives a linear motion as its input, pushing a perpendicularly attached shaft back and forth. The final range of movement will differ by the length of paths that attached shaft moves through.

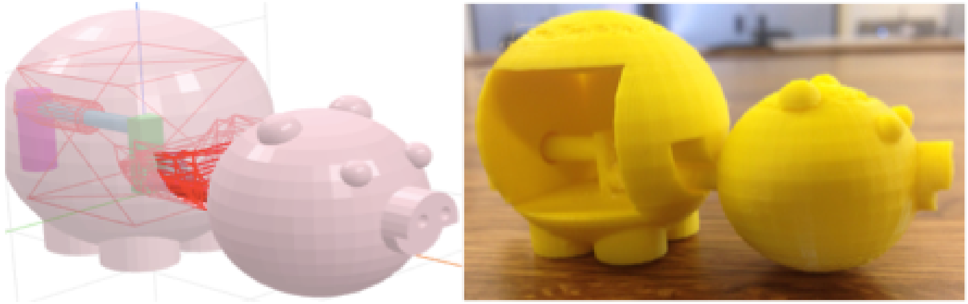


Figure 3.3.7: Example of using a swing lever module. A piggy shakes its head when its tail is pulled.

Slider (i) takes linear motion as input and converts the angle of its motion to the sliding motion of a perpendicularly attached shaft. Internally, an angled region is used to affect the perpendicular shaft's height. The shape and size of the internal region can be modified to change the perpendicular shaft's motion.

Insert algorithm

I present an algorithm for accomplishing the task of inserting a gearbox G into a host model H. Here I assume H is just an ordinary 3D printable geometry, such as an STL file that a designer has downloaded from Thingiverse and has imported into the design space. First, the designer might do some customization, such as translating or scaling G with respect to H, or putting G into the chest of a robot. Let t denote the transformation function that captures this customization. If the designer did not make any customizations, then t is simply an identity function.

In insert function I, the input arguments include H, G, and t, and the output is a new 3D printable geometry H'. Given that $G = \{C, M, A, L, K\}$, our algorithm can be succinctly expressed as

$$I(H, G, t) = (H - t(A)) \cup g(H \cap t(A)) \cup t(L \odot (C - M - A))$$

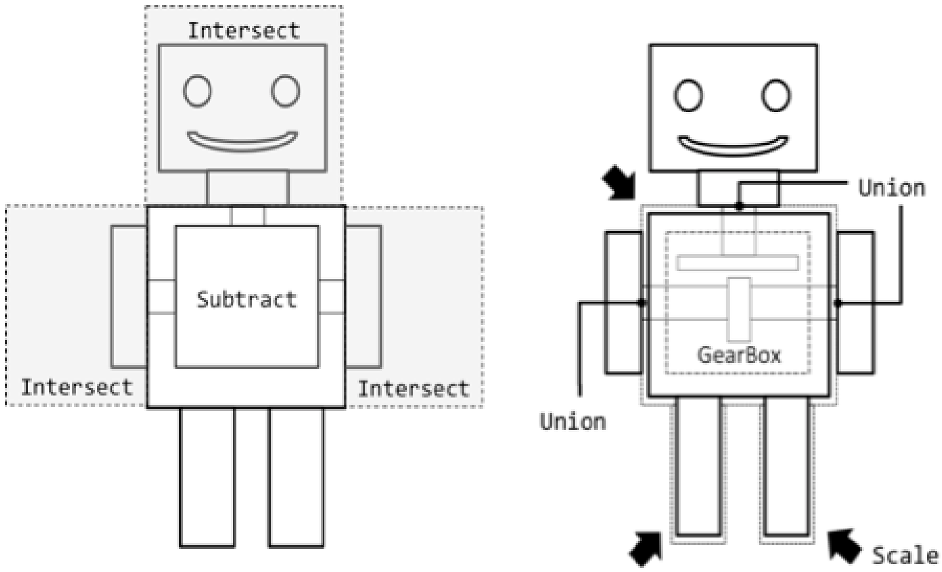


Figure 3.3.8: (left) $H \cap t(A)$ segments the moving part (region in grey) from the body which should remain static (region in white). (right) $H \cup t(A)$ grants the rest of part including mechanisms placed in the space, g adds clearance between moving parts and static parts.

where $\cup$, $\cap$, and $-$ are Boolean constructive solid geometry (CSG) operations for union, intersection, and subtraction respectively, and $\odot$ is a function that applies layout constraints L to a set of geometries. The scale function, g, will be explained later. The term $H \cap t(A)$ gives us the movable parts separated from the host object (e.g., arms of a robot). The term $H \cup t(A)$ grants the rest of the host object (e.g., body and legs). Together, these two terms automate Task 3.1 in Table 3.3.1. Finally, g adds clearances so that the parts are no longer fused to the body. This step corresponds to Task 3.2.

The term $L \odot (C - M - A)$ gives us the various gearbox parts in a valid configuration. This corresponds to Task 2. Then, the two union operators $\cup$ connect the three terms to complete the implantation task. This corresponds to Task 3.3, and Task 4.

Graphical User Interface

Novice users who are not familiar with CraftML can also use a GUI design environment (see Figure 3.3.9) to perform gearbox remixing. Using this, a user first imports an off-the-shelf 3D model into

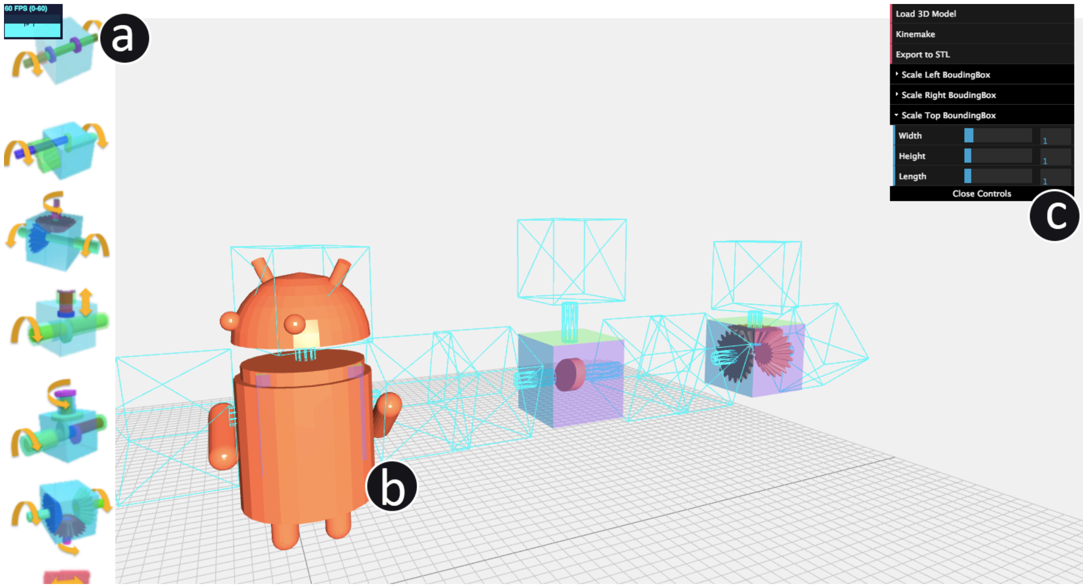


Figure 3.3.9: Animation in a GUI provides a user with real-time visual feedback, to help him choose the right gearbox unit from library to explorer (a), movement applied by insertion (b), with the loaded target object from the dialog, that also enables a user to adjust parameters (c)

the design environment by clicking 'Load a Model.' Next, the user browses the library of gearbox modules in the left panel and chooses one or more to load into the environment. The system automatically arranges several gearbox modules in a row and connects them when loaded, according to the center position of each shaft. It uses the kinetic properties stored in K to animate the movement effect, and synchronize the rotation direction of the connected unit to the next (*i.e.* if a user connects a friction wheel to a bevel, the bevel's rotation direction will be flipped from the direction where a hand-crank is powered). It also provides visualization of the action spaces. A user also can freely rearrange the gearboxes and the host model by drag and drop. Also, he can adjust the action spaces to cover the parts of the host model that she wants to separate in order to make them move freely. Finally, the user clicks the "Kinemake" button to see what the resulting effect is and click "Export to STL" to get a file she can send to a 3D printer.

Summary of Kinemaker function

With a graphical interface and the library of remixable gearbox modules, Kinemaker reduces the complex 10-plus step process illustrated in the mandatory user task (see Table 3.3.1) to a simple 4-step process:

1. Pick a host model H. 2. Pick a gear box G from a library L. 3. Place G to a desired location inside H for preparation. 4. Adjust G's parameters and review the result. If not satisfied, goto 2, 3, or 4.

Table 3.3.2: Kinemkaer simplifies manual and laborious series of work for creating a mechanistic objects with the off-the-shelf models

In this way, Kinemaker allows designers to explore limitless assemblies by remixing gearboxes and existing objects. The *goto* step is where this rapid, iterative creative design exploration happens. A designer can quickly pick another gearbox (Step 2), try different locations and combinations to see how various combinations can yield various effects, or try a different set of parameters (Step 3). Finally, the designer can examine and assess the resulting configuration. (Step 4).

3.3.4 Evaluating Kinemaker

While one of the objectives of implementing KineMaker is to lower the barrier of creating mechanistic objects, my goal is also enhancing users' capability in given affordance of the tool. I set five design considerations in implementing Kinemaker tool for this purpose, thus, I conducted an evaluation to demonstrate if examples created using Kinemaker satisfy these considerations, which aim to open a new door for a creative exploration.

I achieved modularity (M) by applying a formal specification to be encapsulated into a unit. Feedback (F) is provided by animations applied to the units and resulting objects. Here I evaluate my remaining three goals: remixability (R), versatility (V), and composability (C), with printed examples to show they are functionally correct. I printed the selected examples shown in the Figure 3.3.10 using Stratasys DimensionSST with water dissolvable supports. These examples can be printed on a consumer grade dual header printer as well, with water soluble PVA filament for supporting.

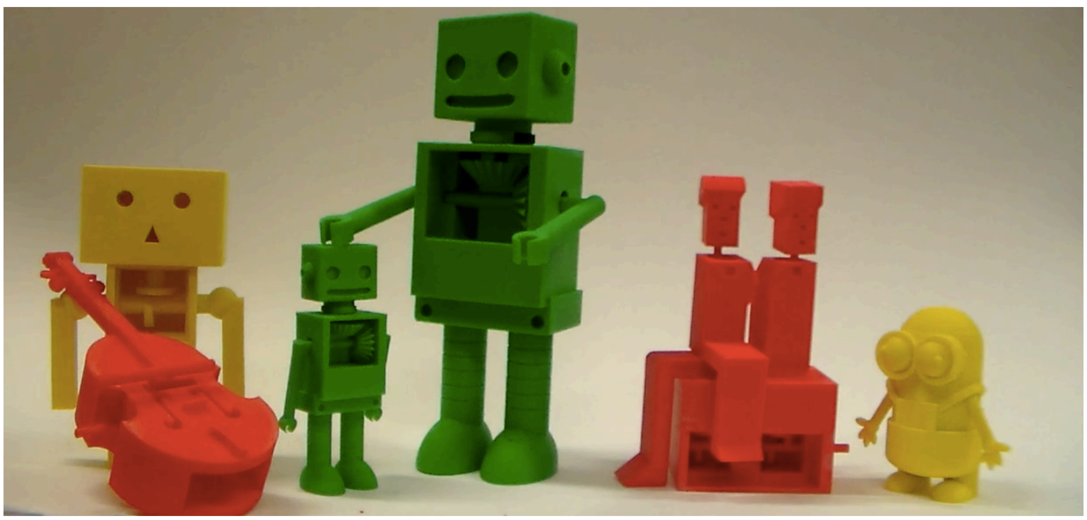


Figure 3.3.10: Selected examples of remixing off-the-shelf models with Kinemaker gearboxes: a pulley in the cello bow, a crank in the cardboard robot's body, a bevel in the Ada bot, two double cams in the kissing couple, and a jumper in the Minion's rolling eyeball.

Modularity (M)

Modularity helps encapsulate high level concepts into homogeneous enclosures. Gearboxes are imported as a modular unit that encapsulates complex constraints of internal components, which are associated with mechanical conventions and rules; a user is not required to understand these sophisticated principles in the process of their mobility design.

All gearboxes are implemented to be a first class unit that abstracts mobility function and exposes

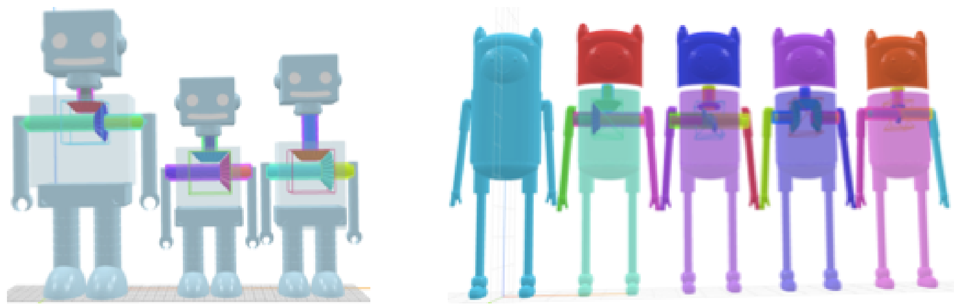


Figure 3.3.11: Three versions of Adabot with parameters (left), four versions of Finn with different gearboxes (right), which together demonstrate the *versatility (V)* of Kinemaker's gearbox library.

the common interface (same cube size and the position of shaft) to the external world, with parameters for user experimentation for easy assembly and alignment of units.

Remixability (R)

Through remixability, users can reuse across multiple projects and remix various gearboxes into a variety of existing models. A designer is NOT obligated to design gearboxes from scratch, and she takes the mechanisms out from the other's design, and can customize her choice of existing models to apply the mobility. As shown in Figure 3.3.11 (left, with an AdaBot), a same gearbox is remixed into a same model taken from another designer, in a different scale and parameters. In each case, the gearbox can be easily customized (e.g., lengths of horizontal shafts) to support proper connections between the head and arms. This gearbox also can be inserted into a different model, taken from an imported STL file (right, with a Finn of Adventure Time), as well as other units with different movement effects.

Versatility (V)

By versatility, (a) gearbox library offers a rich set of gearbox modules to produce various mechanical effects and (b) each gearbox module can be further customized to expand the possibilities—which has been also demonstrated in the above example (Figure 3.3.11, right). Finn's hands became a driving axle, turned to make its head move in different manners. To demonstrate (b), various shapes of cam (right) change the type of motion achieved on the target. Similarly, in the Piano example (left), the

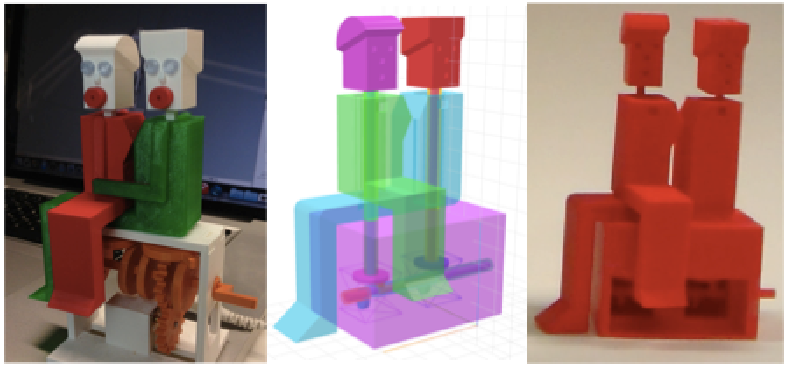


Figure 3.3.12: The Kissing couple, an existing mechanical design (126819, left), can be replicated by *composing (C)* two double-cam gearbox modules, as seen in the design (middle) and printed result (right). I purposely created an opening to reveal the internal mechanism.

different starting angles of cam present different sequence of each keystroke. Also, using the Adabot model (Thingiverse 367226),

Composability (C)

Through composability, I claim that my gearbox modules can be easily combined to compose a complex design, which is a key prerequisite in attaining a high ceiling. To validate this claim, I first used Kinemaker to replicate an existing design involving multiple gears (Kissing Couple Thingiverse 126819). Figure 3.3.12 shows this experimentation, achieved by composing two double cam gearboxes and one hand crank. Note that the original design lacked modularity, thus, creating a working configuration would involve an intensive manipulation of inner components, gears and shafts. In contrast, using Kinemaker, the design task is recast as composing two modular units, which reduces a designer's cognitive load.

Figure 3.3.13 showcases further examples demonstrating composability. Motions are transmitted across adjacent gearboxes when they are assembled together. For the Android showed in Figure 3.3.13, the parameter specifying the length of the shaft has been increased to reach the Android's head. A shaft connects a friction gear to cascade the movements of a single handle to both objects. The Mario (Thingiverse thing:260136) and mushroom (Thingiverse thing:499559) were imported as STL files, then a

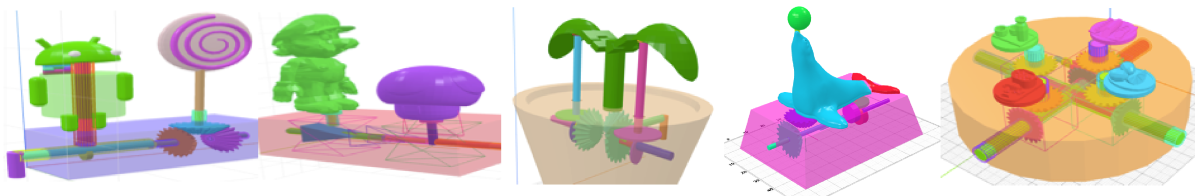


Figure 3.3.13: (from left to right) An Android opening its mouth, standing by a rolling lollipop; Mario jumps to chase and a mushroom slides away from him; flowerpot with fluttering leaves; a seal with a flapping tail has a rolling ball on its nose, and sushi dishes spin along a table with five gearboxes.

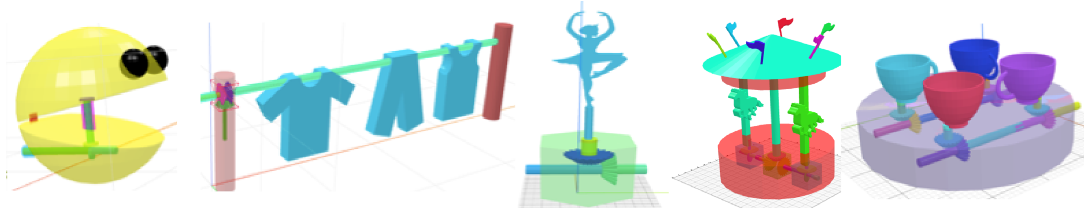


Figure 3.3.14: (from left to right) Examples of design made in study. (P1) Pacman wagging its mouth by crank; (P1) laundry moved by a friction wheel; (P2) ballerina by a jumper wheel , (P3) Carousel by a bevel gear and two cranks, (P4) Disney's teacup ride by four Bevel Gears

slider ingests linear motion to support Mario, moving him up/down to represent jumping, and is connected to a pulley which moves the mushroom away from him across the top of the shaft. With a plant pot, the example shows three gearboxes, a bevel gear is powered by the hand crank, transmitting the rotation to the adjacent crank units. This motion is transmitted through two additional crank gearboxes to two leaves. The Seal (Thingiverse thing:416883) example is segmented into three pieces: a body, a tail, and a ball, which is added onto its nose by two set of connected gears (bevel, double cam). While the ball is rolling, the seal's tail will rotate in 180 degrees, as a result of the hand-crank's power.

In addition to my selected examples, I also conducted a user study, aiming to further validate the usability of Kinemaker, with results shown in Figure 3.3.14. All participants enjoyed the creative exploration of selecting units and seeing effects transmitted through connected shafts.

3.3.5 Discussion

There are a number of scholarly debates on how to best support end-users in designing mechanical 3D models. Here, I discuss these debates and contribute my perspectives.

Experimentation vs. Optimization

There is a debate on whether *experimentation* or *optimization* is a better framing for end-users to approach designing mechanical 3D models. Optimization is the preferred framing when the user is focused on a specific end goal. Systems such as [21, 25, 120] are useful in this case. These systems let users specify desired motion paths simply by sketching it. Although convenient, the design space of such framing tends to be limited, and end users tend to lose space for free exploration and learn from tight feedback given in these explorations. The experimentation framing, however, takes a bottom-up approach by supporting an open-ended explorative approach [96]. To do so, this framing sets the heterogeneous atomic unit as a first class primitive in order to support additive work [32].

As the user is exploring, she may stumble upon a creative mechanical design she likes. While engaged with the mechanism, the user may gradually learn basic mechanical principles through examining the transparent processes. Kinemaker gearboxes are designed to support open-ended experimentation. While experimentation and optimization both have values, Kinemaker takes the former position for end users to take bottom-up-approach to take open-ended exploration. They will be equipped with creative freedom and move forward with limitless design opportunities by adapting basic principles.

Granularity of Building Blocks

Another debate addresses the ideal granularity of the building blocks for designing mechanical 3D models. Along the granularity spectrum of fine to coarse, building blocks can be composed of *triangles*, *shapes*, *components (gear, shaft, crank)*, *gearboxes*, *gear templates*, and *machines*. The finer end of the spectrum offers designers smaller building blocks to work with and greater creative freedom to build complex structure. However, such freedom often has expenses; it is more difficult to ensure that the structure possesses the correct mechanical properties, and it more frequently produces invalid designs. In contrast, the coarser end of the spectrum offers larger building blocks with well-defined mechanical properties for designers to work with. It is easier for designers to predict the effects of combining these larger building blocks as well as arrive at a valid design—applying local rules, and expecting global effects. But such predictability sacrifices creative freedom; designers must operate within a much more constrained environment.

In this work, I explored the middle-ground position of gearboxes as the building blocks for introducing mechanisms into off-the-shelf 3D models. I developed techniques to enable designers to operate at this position. I found that this position is best-suited to support the application of **creative exploration**. This position offers a balance between creative freedom and ease of use. Designers are able to creatively design new mechanisms as well as new structures, as well as combine them to achieve interesting effects. Note that previous works have also explored supporting other positions. For instance, Zhang et al. explored the positioning of gear templates, claiming that a target model has only one specific mobility. While less effort is required with limited target objects, creativity is limited as designers must find another host structure with a compatible topology (*e.g.*, automobile body in different shape and size, or an organism with 5 appendages) and fine-tuning the predefined mechanism to fit the new host.

Integrated to Print at-one-go vs. Assembly

The last debate is about whether a mechanical design should be 3D printed in one piece or in separate pieces for later assembly. Seeing the comparison between download rate of models designed in both cases in Thingiverse, printing-at-once seems to be preferred among many users than a model with many pieces that requires post-assembly. Here I take the option that all the parts in a mechanical design are integrated into a single piece. As Kinemaker's specification is designed to encapsulate inter-relationships between mechanism components into one atomic, homogeneous function, it can also remove the need of post-assembly when printed in one piece. All of the examples demonstrated above were printed whole with no assembly required. Sufficient clearance was achieved by utilizing the layout constraints imposed by Kinemaker's formal specifications. For example, if a design with a cam unit is intended to be printed in a single piece, the gap between mechanisms must be smaller than the box unit's half length for rotation (Figure 3.3.3, $L_c + T < L_u$) in order to maximize the inner mobility, and the placement of interlocking gears do not need to be considered. One constraint of this integrated approach is that printing an integrated model requires dissolvable support materials, for example, PVA filament with dual header FDM printer.

3.4 Limitations

MoveableMakers and Kinemakers are modular libraries and design tools that support novice designers by providing a low barrier to entry in specific domain of interest, including designing interactive, movable 3D objects. Efforts have been focused to abstract away low-level technical requirements, leaving only high-level user-friendly design activities available for users to explore.

However, end-users' composition of building blocks and templates in these works is manual. Compared to existing works that automate 3D modeling processes by an optimization algorithm (e.g., [120]), this work requires more works by an end-user. Even though it was my choice of implementing, some amount of automation, such as readjusting the scale and position of a gearbox according to a target 3D object, will greatly reduce end-users' workload.

Creating tactile picture books and moveable 3D objects as topic areas are chosen for practical reasons, as they may call for participation in 3D design from a wide array of enthusiasts. However, 3D printing proposes nearly boundless application areas beyond tactile picture books design and interactive objects design. Without validating the topic area where real users are interested and understanding their capabilities to use 3D printing, tools and libraries would not be able to be designed to lead them acquire proper skills to advance to the next level.

There's no sign that computers are getting any better at creativity, design, or any form of innovation.

Ken Goldberg

Chapter 4

HCI-Collaborative Systems: Understanding Users' Design Activities and Characterizing their Abilities

4.1 Preamble

Towards a collaborative partnership between humans and machines, I need to understand hidden challenges of users, especially in design activities. Here, at the intersection of HCI and collaborative systems, I ask: "What are hidden challenges for end users in 3D design and printing, and what is the state of their capabilities to address them?" to characterize their abilities and to improve process through the technology development. Then I also ask "How can a modular approach accommodate errors resulting from design activities?"

Fabrication using design tools and 3D printers presents many challenges and barriers to end users, preventing them from having right assistance from computational design tools as part of collaboration. Enabling designers be aware of common mistakes that end users often take is essentail, as it will help reduce the amount of work required for correcting those issues.

In this chapter, I introduce a work to address an important challenge in 3D design, particularly in adaptive 3D model design that augments existing real world objects. Every individual has different constraints arising from his unique objects and distinct settings. Despite precise rapid computation, current design tools do not support users to enter accurate specifications onto adaptation targets because of error-prone practices in measurement. I conducted empirical studies to understand common causes of uncertainties that arose during measurement, developed a set of strategies for designers as a guideline for the community that often reuse 3D models. Stepping further, I introduce FitMaker, a parametric tool and modular libraries for end users to embrace these strategies, in order to accommodate uncertainties that arise during measurement in adaptation designs.

4.2 Understanding Uncertainty in Measurement and Accommodating its Impact in 3D Modeling and Printing

One popular application arising in the fabrication domain is to augment one's *personal* physical environment. This is common among assistive technology models found online (e.g., [17, 85]). Nonetheless, as diagnosed in chapter 2, many end users simply print models created by others, rather than creating objects from scratch themselves. If the original designer and the novice modeler who prints the model do not have the exact same object or environment, such augmentations may require further customization to be made usable.

Here I explore a specific area of model design that is a challenge for end users: measurement. When a model must conform to a specific real world goal once printed, it is important that the goal is precisely specified.

Many models, modeling tools, and much of the current research in personal fabrication use *parameterization* to address this customization need. Given a suitably parameterized model (for example, one based on the diameter of a doorknob) and a correct measurement (the dimensions of the actual doorknob), the model can be adjusted to the measurement. In theory, the resulting model fits precisely. This approach is in line with the skills of novice users who may only be comfortable with parameter entry and simple scaling [45]. However, in practice, correctly measuring a real world object is a sur-

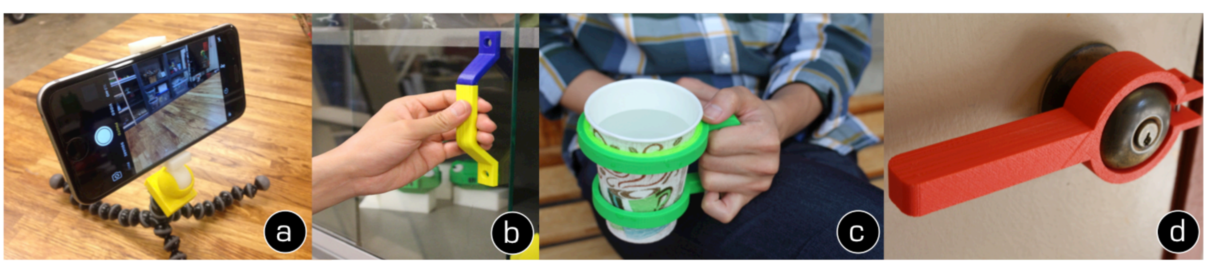


Figure 4.2.1: Physically- adjustable 3D augmentations accommodate measurement error. A tripod mount with ball joint for angle adjustment (a), an assistive cabinet door handle with a second-iteration update (in blue) (b), a cup holder with a flexible ring (in light green) (c), and an assistive door lever with an inserted cylinder joint to adjust diameter (d).

prisingly difficult task for novices; this can have a significant impact on the customization of 3D models. Although 3D scanning is an alternative to gather accurate dimension data, even then the measurements may need to be extracted digitally. Also, the quality of such scans is not dependable, especially given the limited tools available to average users.

In a study I describe in detail in the next section, I found that issues with user error (e.g., mis-aligning instruments and misreading units), measurement instrument precision, and even task definition combined to make measurement errors common. This is compounded by the fact that 3D printing itself is not perfectly precise, given the limitations of current commonly-available printers. For example, some materials shrink slightly as they cool. Put differently, measurements are at best approximations that contain some degree of *uncertainty*. A model that is robust to this uncertainty will be less likely to fail.

In this work, I address these problems through the following objectives:

- Conducting studies to explore uncertainty in human measurement behavior and categorize common causes of measurement error in everyday measurement practices.
- Proposing modeling strategies that accommodate uncertainty, particularly in adaptive 3D design.
- Implementing *FitMaker*, a design tool that encapsulates these strategies and provides re-usable modular parts that can be integrated into existing models.
- Demonstrating printed objects modeled using these uncertainty accommodation strategies and the tool.

4.2.1 Background

One of the most common design activities in 3D printing communities is adapting 3D artifacts into existing real world objects, sharing, and remixing these adaptive objects [85]. However, for novices who just started learning 3D printing, designing augmentations can be difficult to accurately execute for several reasons. First, it may be difficult to design the *right thing* that fits individual needs. Although measurement error represents a design problem in any domain ([10]), in the personal fabrication domain, researchers have paid little or no attention to the impact of these errors.

Many subtle details arise when augmenting real world objects (*e.g.* how to attach [22]), which increases the chance of an error. Second, design often involves several iterations, particularly when it is open-ended. Speed is an issue particularly for novices who may need to iterate more because of design errors that are only caught after the model is printed out.

Designing the Right Thing

Designing the right object or part for a specific need can be a daunting task for novice designers. One effective way to improve upon this challenge is to narrow the design space and provide a specialized tool that encapsulates design knowledge about that space. For example, as briefly introduced in chapter 2, Reprise supports the design of assistive augmentations for people with motor impairments [23]; Pteronyms supports the design of model airplanes [110]. Alternatively, it is possible to provide tools that abstract away some common aspect of the design process. For example, Encore specifically helps with the sub-task of attaching a 3D printed object to a real world object [22]. Facade helps by specifying what buttons to label when fabricating tactile overlays for inaccessible physical interfaces [34]. A variation on that is making the interaction with the modeling tool simpler. For example, Tactum allows on-body design using a direct prototype device [30]. These tools share a common goal: helping users design right with speed and ease.

Measurement for Design

The precise measurement of existing objects is a long-standing necessity in engineering, industrial design, and architecture. A few standard guidelines for beginners along with a precise process to reduce errors is introduced in [10]. To be aesthetically-compelling and functionally-competent, a protocol for accurate measurement was proposed in the product design area [43]. However, measuring ten times to get a relatively exact value, or stepping through a ten-phase process to reduce error (as suggested in [43]), is not practical, or viable, for novice modelers to follow.

To summarize, recent work has begun to tackle a wide range of difficult problems that currently stand in the way of a widespread uptake of personal fabrication for users from beginners to professionals. However, for the most part, such advances are not based on empirical studies of the problems designers face, nor do they tackle challenges such as measurement that arise outside of the design and printing process. My study will attempt to address some of these issues.

4.2.2 Measuring Measurement

To understand human practices of measurement and the uncertainty involved, I conducted two studies. The first study was designed to give us an initial glimpse into the measurement practices of everyday users. The second attempted to guide users and improve on the results of our first study.

Study 1: Understanding Typical Measurement Practices

The first study was designed to elicit information about how people approach a measurement task. In addition, I wanted to both qualitatively examine what sorts of errors people made and quantitatively determine how large those measurement errors were. Thus, I designed the study to be open-ended for which measurement techniques might be applied, but specific about the target values to get from the process.

Method

To reach a wide sample of people, I deployed the study as an online survey on Amazon Mechanical Turk for approximately four weeks (27 days). The survey tasks included measuring *(i)* the height of an iPhone (specified models only), *(ii)* the angle of a fully-opened Mac laptop, and *(iii)* the diameter of a standard lightbulb. These objects were selected to target cases where 3D printed augmentation would apply, such as a phone case, lampshade, and laptop stand. Also, each of these objects are manufactured in standard dimensions, making it possible to compare the reported value with industry-established standard dimensions. Participants were asked to report the model of the object to be measured so that I could determine the correct measurement. For example, given a lightbulb's manufacturer and model number, I was able to retrieve the physical dimensions reported by the manufacturer as a reference.

Participants were told to measure each item twice (with two different tools or methods) so that I could observe not only individual skill levels, but also the uncertainty generated by different instruments and methods. This repetition was completed on separate pages of the electronically-presented survey to minimize copying. I also asked participants to upload photos of the object and the measurement instrument to show how they conducted each task. This prevented cheating and gave me insights about the source of specific errors. At the end of each round, participants were asked to describe how they conducted the measurement.

Data Preparation and Inclusion Protocol

The study was completed by 62 participants who each completed multiple measurement trials. I eliminated trials in which participants measured the wrong target; for example, if a participant (*e.g.* measured the laptop's display length instead of the largest opening angle, that trial was omitted from the study. I also removed responses lacking valid photos, including photos lacking a demonstration of how the participant performed the measurement, duplicate photos, images retrieved from the Internet, and irrelevant photos. In the case of lightbulbs, I removed two trials for which I could not retrieve ground truth by the bulb model name. A total of 10 iPhone length trials, 19 laptop hinge angle trials, and 10 lightbulb diameter trials were rejected for these reasons. Thus, after removing invalid measurements, the total sample size for each task is different.

I also cleaned the data where possible. If numbers were reported without units (or with obviously wrong units such as inches for laptop hinge angle measurement), but if I was fairly certain of the correct units, I fixed them. For example, if the participant typed "6.25" without unit for an iPhone 6 Plus's height, I marked its unit as inches based on a comparison to the manufacturer-reported dimension of 6.22 inches.

Next, I converted all measurements for a given task to the same units (*e.g.*. For example, I converted inches and centimeters to millimeters. Finally, I calculated measurement accuracy. Because I allowed multiple models for each task, with different true (ground-truth) values, calculation of average error and accuracy was completed with the following formula:

$$E_{d,t} = \frac{\sum_{m_{d,t} \in M_{d,t}} \|T_d - m_{d,t}\|}{\|M_{d,t}\|}$$

Where T_d is the correct measurement for device d, $M_{d,t}$ is the set of all measurement instances for measurement instrument t and device d, and $m_{d,t} \in M_{d,t}$ is a specific measurement instance.

Note that this qualitative data analysis considered all completed surveys as well as partial answers with valid photos (following the same criteria as above).

Study 1 Results: Measurement Approaches and Errors

Overall, participants chose a wide variety of measurement instruments (as summarized in Table 4.2.2); some were quite surprising (such as a garden spade, eraser, string, electric tape, and coffee mug) and others more ordinary (such as a ruler or protractor). Some of the odder choices may have been driven by the requirement to measure each item two different ways. Figure 4.2.2 shows the distribution of accuracy across the measurement trials. Accuracy was highest for length (leftmost boxplot) with a mean of 98.2%. Since iPhone models range between 123.8*mm* and 158.2*mm* tall, actual errors ranged from 2-3*mm* in most cases (enough to affect the fit of a case, for example). The angle measurements showed the most variables with a mean accuracy of 93%. Diameter accuracy ranged from 87.2% to 97.6%. Viewed another way, I can say that the box (or box plus whiskers) in Figure 4.2.2 represent the *measurement uncertainty* associated with each task.

1. Measurement Technique	Frequency
Not correctly aligned with the start or end of the measurement target	31
Number rounded imprecisely or in the wrong direction (*e.g.* 24.9 to 24)	29
Measured the wrong target	23
Reported incorrect units	15
Inappropriate measurement instrument choice	14
Not correctly aligned with the start of ticks on the measurement instrument	10
Incorrect placement of measurement instrument (*e.g.* slanted, not perpendicular, used wrong reference point for angle)	5
Viewer perspective when reading measurement not straight on	5
Incomplete preparation of target object (*e.g.* did not take out accessory case, measured Mac laptop on the stand)	3
Viewer read the wrong indicator	3
2. Measurement Instrument Limitations	**Frequency**
Calculation error (trigonometry, circumference to diameter)	15
Measurement instrument distortion (*e.g.* curved, stretched)	11
Measurement instrument units too large for sufficient precision	9
Vague reference (*e.g.* thumb, forearm, screw driver, sharpie, cardboard, eraser)	9
Imperfect ticks (*e.g.* worn out, hand drawn)	3
Hidden zero tick (causes alignment issues)	2
Short measurement instrument (requiring multiple end-to-end measurements)	1

Table 4.2.1: Types of errors and practices observed in the study. *Frequency* indicates the number of participants with that type of error. Note that this is not an exclusive count. For example, if a participant measured an angle with sewing tape by trigonometry, I counted this case in both "measurement instrument distortion" and "calculation error".

Given the presence of uncertainty, I qualitatively explored two sources of error (Table 4.2.1): Measurement technique and measurement instrument limitations. As is demonstrated by the measurement technique section, human judgment plays an important role in measurement uncertainty. For example, people may make errors in deciding *what to measure* and *how to measure*. Similarly, Table 4.2.1 demonstrates how *measurement instrument limitations* (such as precision) can affect accuracy.

What to measure?

The very first problem participants encountered was the difficulty of determining the exact measure-

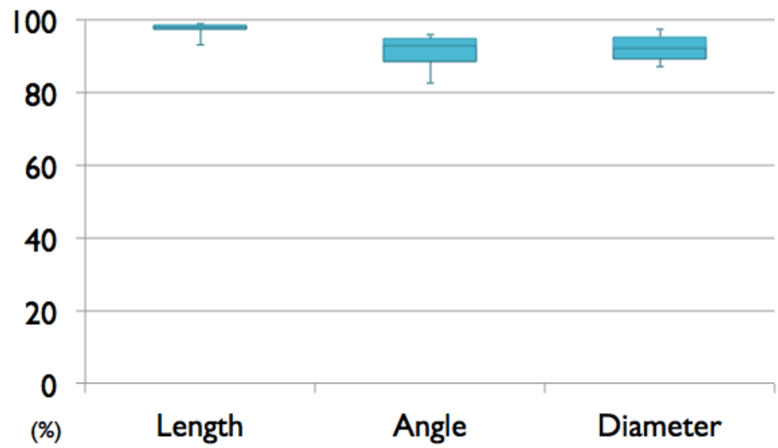


Figure 4.2.2: Distribution of measurement accuracy for iPhone height *(left)*, laptop hinge angle *(middle)*, and base diameter of lightbulb *(right)*.

ment target. This was driven by the fact that real world objects often have curves, bumps, and other design characteristics that make them beautiful or usable, but not necessarily easy to measure.

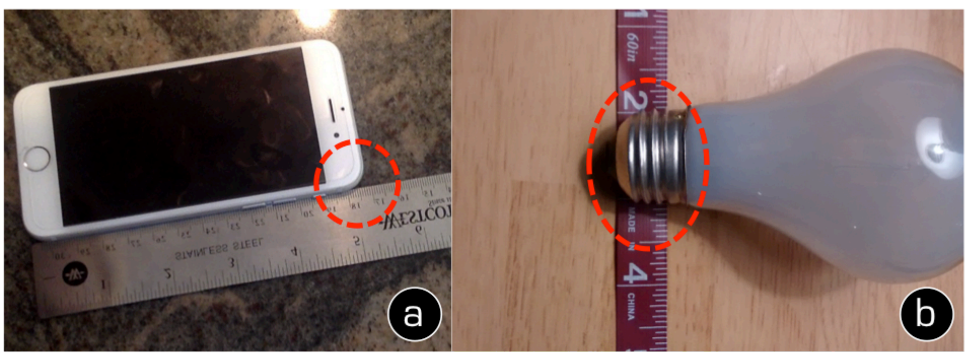


Figure 4.2.3: Unclear measurement target. Rounded corners *(a)* and zigzag surfaces *(b)* make it hard to align the measurement instrument correctly.

For example, the iPhone 6 has rounded corners and edges (Figure 4.2.3a). If a participant does not notice, he or she might not measure from the true top to bottom, especially if the measurement instrument is aligned with the edge of the phone as in Figure 4.2.5a. If a participant does notice, then questions arise about what to measure and how to correctly account for the curve. A participant may also introduce additional errors (such as holding the measurement instrument away from the rounded edge, which causes an unnoticed slight angle that introduces an alignment error). Most participants chose to measure along the edge rather than through the center of the phone, which better captures the full length. For example, P32 stated:

> *"I laid down the phone on the table, and laid down the tape ruler on the side of it."* (P32)

Another difficult example is the zigzag surface of the lightbulb screw base as shown in Figure Figure 4.2.3b. Should a participant measure at the minimum or maximum circumference? This is not a straightforward question and depends upon the reason for measurement. In addition, this makes it difficult to align the target and measurement instrument correctly. It is similarly difficult to decide what to measure on a flexible or non-static target such as soft fabric or a piece of yarn.

How to measure?

Table 4.2.2 summarizes the range of measurement instruments and frequency of them being used, as well as the average measurement accuracy for each instrument. The table only shows measurement instruments used two or more times; all instances used by only one participants are categorized as "others."

Several participants conducted the measurement tasks with digital applications such as level apps, computer vision applications using a photo of the target object with a U.S. quarter as a reference, or the Adobe Illustrator tool path (*e.g.* Figure 4.2.4). Some of these applications function almost identically to a physical measurement instrument once loaded on the screen. Others allow users to manipulate the location of the zero tick to match the item being measured. Some others involve taking a photo of the item and measurements are then conducted in the application itself. In this case, users specify the reference size using a fiduciary marker, then tap on key points for measurement, possibly with the help of zoom to carefully align the marker with the edges of the object as reflected in the photo. Many digital applications just transform the physical phone into a measurement instrument, leaving the user with all of the same alignment issues as standard measurement instruments. In addition, the accuracy of photo-based measurement depends heavily on the angle at which the photo was taken; if the photo

iPhone Length(Count)	**(%)**	**Laptop Angle(Count)**	**(%)**
Tape measure (22)	98.2	Protractor (8)	93.0
Ruler (20)	98.7	Protractor app (8)	88.0
U.S. quarter (2)	98.2	Paper (5)	93.0
Plain paper (2)	96.9	Tape measure (5)	92.4
Printed ruler (2)	97.4	Image application (4)	94.5
Screen ruler (2)	99.0	Printed protractor (3)	95.8
Other (13)	93.2	Ruler (3)	95.8
Bulb Diameter(Count)	**(%)**	Drawn protractor (2)	88.4
Tape measure (51)	94.8	Lever app (2)	96.1
Ruler (36)	89.8	Compass (2)	88.4
Online ruler (4)	97.6	U.S. quarter (2)	82.6
Other (6)	87.2	Other (11)	93.2

Table 4.2.2: Measurement instruments used at least twice (Numbers in the show a total number of times and % shows the average accuracy). Not listed are measurement instruments used only once, including the following: *e.g.* Length: eraser, laptop case, cat tape, image application, compass, screwdriver, thumb, caliper, and garden shovel (with embossed ruler ticks); *e.g.* Angle: clinometer, eraser, mug, book, screwdriver, speed square, mini draft; *e.g.* Diameter: string, screw driver, paper, wire, image application, electric tape.

angle is not precise, a perspective error can occur, even with a known fiduciary marker such as a quarter in the image to provide a baseline for size.

Participants made a variety of errors when using measurement instruments. Most originated from misalignment between the measurement instrument and the target. For example, the tick marked in Figure 4.2.5 (a) is not positioned in line with the actual top of the phone. Other variations on this theme included slanted placement of the measurement instrument, not lining up the zero tick on the measurement device to the target correctly (Figure 4.2.5c), or not centering the protractor.

Even assuming correct alignment, errors can occur when reading the measurement with both digital and physical measurement instruments. Especially for physical measurement instruments, reading the measurement requires correctly interpreting tick marks and aligning them with the correct edge of the object. If the user's observation perspective is not straight on, this may cause an error. This type of error is increased when measuring objects with higher curvatures or multiple surface planes.

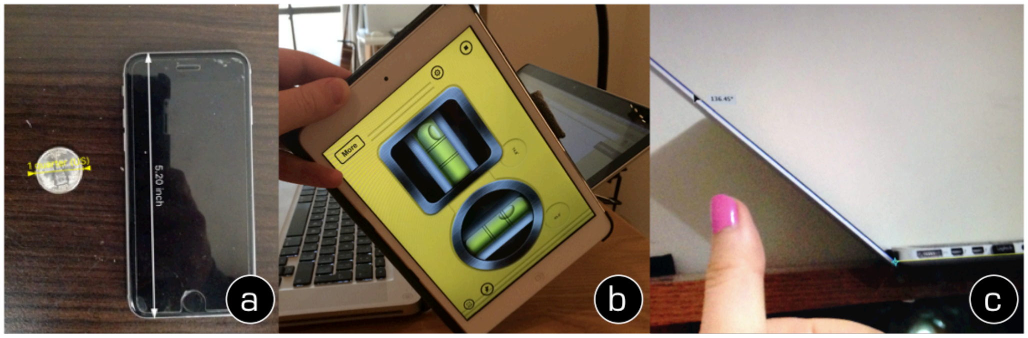


Figure 4.2.4: Digital measurement applications used by participants: *(a)* a photo editor with a fiduciary marker for size reference, *(b)* a digital level, and *(c)* Adobe Illustrator tool path to calculate the angle between the two lines.

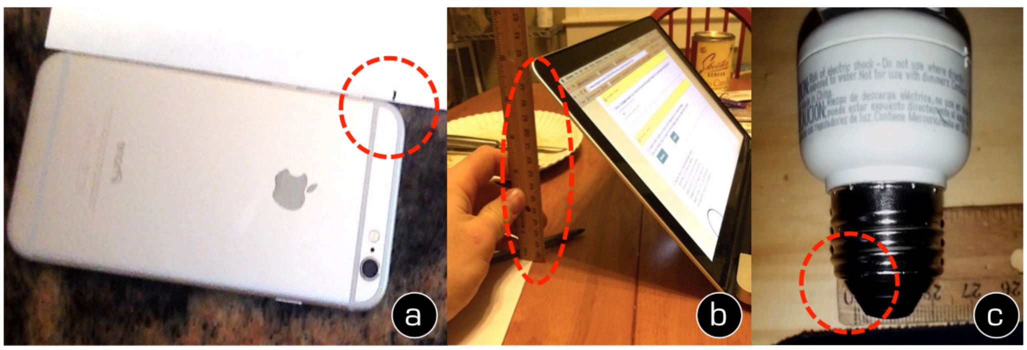


Figure 4.2.5: Examples of human choices that might increase error including: *(a)* measuring with a piece of paper instead of a ruler, *(b)* measuring angles with multiple lengths rather than a protractor, and *(c)* misalignment of the object with the ruler's tick.

Another source of error is selecting an inappropriate measurement instrument. Measurement instruments chosen by the participants were sometimes designed to measure a different type of object; for example, if a participant used a ruler to measure an angle, errors occurred (Figure 4.2.5 b). In the most extreme cases, this error also led to issues with the measurement instrument itself. For example, P24 wrote *"I used a hard cardboard like substance and put it on the laptop and folded it according to the angle of the screen and hold it there for few seconds so it does not change its shape."* (P24).

Even without a protractor, more precise alternatives were available to this participant but it seemed that the participant did not know these tools existed or did not know how to use them properly.

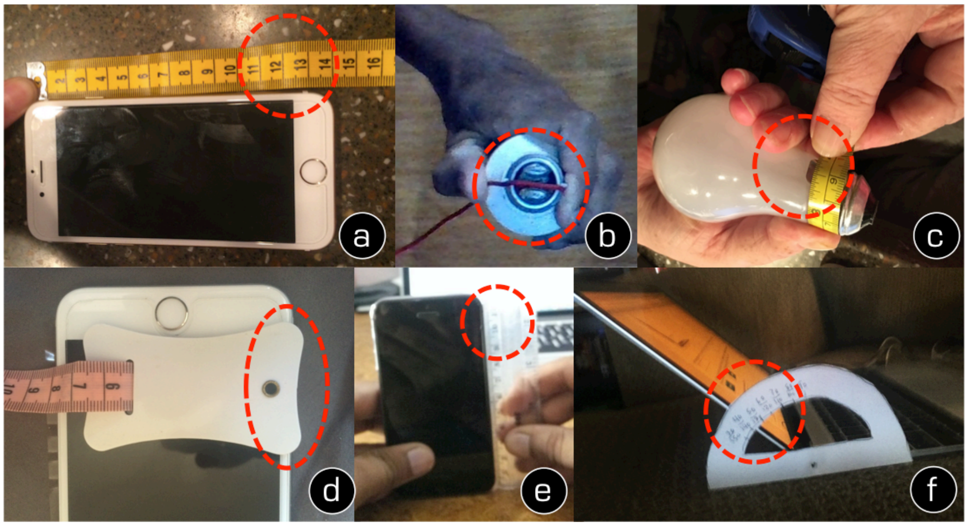


Figure 4.2.6: Measurement instruments limitations can increase the chance of error, including: *(a)* tape that is not naturally flat; *(b)* stretchy string; *(c)* requiring calculation (diameter derived from circumference); *(d)* hidden 'zero' tick, making correct alignment difficult; *(e)* shorter than the item being measured (introducing potential gaps or overlap); *(f)* difficult to align precisely.

Measurement Instrument Limitations

The final category of error is driven by the limitations and characteristics of the various instruments used for measurement. Limitations that arose in this study included instruments that could change shape if used incorrectly, measurement instruments with ticks that were difficult to interpret accurately (like the garden shovel), as well as precision limitations.

- **Changing length:** Measuring tape (used for sewing) is easily curved or bent, which may introduce error (Figure 4.2.6a). Flexible measuring instruments need to be tightly wrapped or flattened. Also, using yarn, string, or electrical tape to measure length can lead to errors, because they can stretch and it is hard to define the starting point (Figure 4.2.6b). On the other hand, if the measurement instrument is shorter than the target, the user has to combine multiple measurements (Figure 4.2.6e), which may introduce overlaps or slight gaps.
- **Difficulty interpreting tick marks:** Blurry tick marks from old or worn measurement instruments make it hard to read the labels accurately. Similarly, sewing measure tape with a hidden

zero tick is hard to read (Figure 4.2.6c and d).

- **Precision:** The measurement instrument may lack the precision needed for correct specification of a 3D model. For example, multiple participants used body parts, such as

  "I used my thumb and it was one thumb length which was equivalent to an inch." (P11)

  "I know my forearm is 30cm in length, so I took a thick thread and measure the size of the bulb. I took three measures with the thread and put them aside separately. Then I converted each thread's length into centimeters by fitting them in my forearm." (P59).

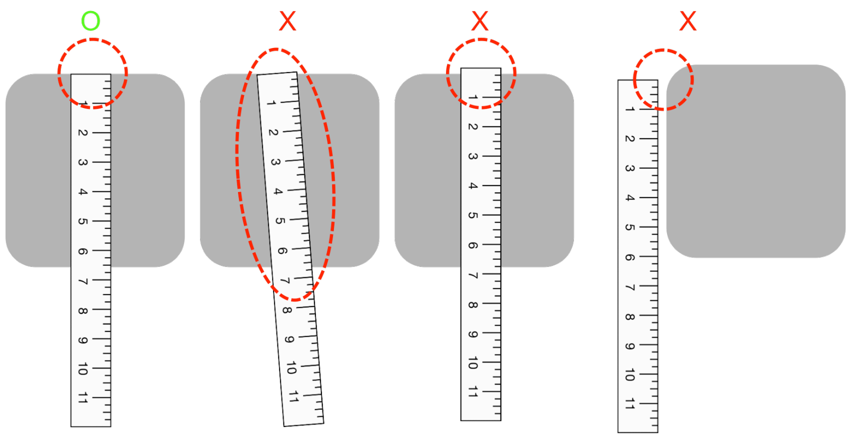
  While many measurement units were originally derived from body parts (foot, cubit, *etc.*), the precision of using body parts as reference is limited; human variability makes such measurements error prone. P59's strategy to address this by measuring multiple times is unlikely to significantly improve the accuracy of the dimension gathered. Overall, 11 measurements involved measurement instruments that are limited in precision. For example, one participant used a gardening spade that showed inch marks but no precise sub-divisions to accurately determine length. Another used an eraser:

  "I placed the eraser upright on the laptop (90 degrees) and tilted it until it touched the monitor. It appeared to be halfway down, making it an additional 45 °, and 45 + 90 = 135." (P36).

Other examples included a screwdriver, a Sharpie brand marker, and a piece of cardboard. Measurement instrument limitations can be compounded by user error, such as faulty calibration of calipers, the curved tape in Figure 4.2.6a, the over-stretching string in Figure 4.2.6b, or calculation errors.

Instructions for Length Measurement

1. Identify the [measurement target] you plan to measure.
2. Remove any accessories that could impede exact exact measurement.
3. Place the item to be measured and the measurement instrument on a flat surface.
4. If your measurement instrument is flexible (tape measure), flatten it and make sure it is not curved or over-stretched.
5. Place your measurement instrument on the object along an axis that has no indentations, bumps, or other artifacts that could affect measurement.
6. Align the edge of the item to be measured with the "zero" tick of your measuring instrument correctly.



7. Hold the measurement instrument to the surface of the object and read the length straight off the instrument.

Table 4.2.3: Instructions to improve accuracy of length measurement. Similar instructions were provided for other tasks.

Study 2: Improving Measurement Processes

Although not available in all situations, one possible way to reduce errors is to provide well-designed instructions for taking measurements. To test whether this could significantly reduce error rates, I developed a set of instructions for measurement and tested their impact on measurement error based on the type of errors and common factors leading to incorrect measurement I found in Study 1. I designed the instruction set to be general for a variety of measurement goals and objects, but specific to either length, angle, or diameter. An example is given in Table 4.2.3, which describes a set of instructions for length measurement. Unlike existing complete measurement instructions (such as [10]), the instructions were designed to be simple enough that participants were likely to thoroughly read them and understand the contents.

Method and Data Preparation

The study method was very similar to the first study, with the addition of instructions and a scenario, both meant to motivate more accurate measurement. I told participants to imagine that they were measuring with the intent of augmenting the measured objects (e.g. designing an iPhone case or selecting a lampshade for the lightbulb). Similar to Study 1, I required that they upload a photo of the measuring task for verification. I used the same rubric to eliminate incorrect photos.

A total of 79 crowd workers completed the survey, including 27 workers on an iPhone, 26 workers on a laptop, and another 26 workers on a lightbulb, respectively. With the same data inclusion protocol as Study 1, 22 valid responses were collected for the iPhone (5 failed attempts), 18 for the Mac laptop (8 failures), and 21 for the lightbulb (5 failures). All responses included units of measurement, which were required as a part of the instructions.

Results: Improved Practice

Table 4.2.4 summarizes participants' measurement practices. As the participants practiced their measurement techniques, I saw particularly large improvements in angle measurements and no significant improvement in length measurements. Negative and positive 1% changes are likely within the range of natural variation. When I examined the images participants submitted, I could see that some of them very carefully followed the instructions to use a flat surface during measurement and carefully aligned the zero tick of the measurement instrument with the correct location on the item to be measured. Some new strategies I saw included using measurement instruments with more precise units (such as *mm*) and using background lighting to help with alignment.

These improved practices led to improvements in average accuracy, which increased from 93% to 96.7% primarily due to an improvement in the minimum from 82.6% to 90.8%. However, not all users

lightgray **iPhone Length(#)**	%	**Laptop Angle(#)**	%
Tape measure (10)	98.3	Digital app (10)	93.2≫
Ruler (9)	98.3	Protractor prints (5)	94.1<
Sewing tape (2)	97.7<	Protractor (3)	96.5≫
Digital app (1)	99.4		
lightgray**Bulb Diameter(#)**	lightgray%		
Tape measure (10)	94.9		
Ruler (6)	90.9>		
Sewing tape (5)	90.8		

Table 4.2.4: Range of measurement instruments and accuracy. Where possible, I show comparison with the previous study (>= 1% increase; ≫= 10% increase; <= 1% decrease).

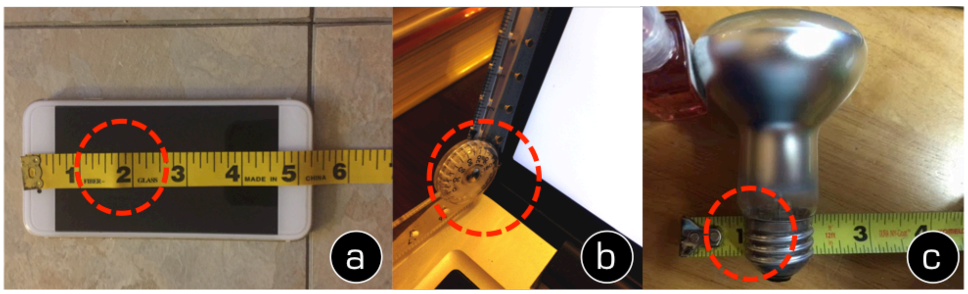


Figure 4.2.7: Participants tried to follow instructions, but still made errors. Measurement instruments were: (a) curved; (b) mis-centered; and (c) not aligned at the zero tick.

exactly followed the instructions, and many of the bad practices found in the first study were still repeated (Figure 4.2.7). For example, flexible measurement instruments were still bent Figure 4.2.7a, and measurement instruments were still misaligned with the target Figure 4.2.7b & Figure 4.2.7c.

Study Recapitulation

The first study showed that measurement is a surprisingly error-prone process. Even digital tools cannot overcome all sources of error. Although accuracy is high in some cases, inaccuracies as low as 1% could still pose problems for fit; in any case, better instructions did not eliminate errors. The impact of uncertain measurement depends on the application. Some adaptations require precise measurements to function correctly, whereas others can handle some amount of imprecision. For example, some imprecision for a lampshade is acceptable, as gravity helps to hold it in place with the widest part of the bulb. Thus, a set of solutions to measure uncertainty should function under a range of precision requirements.

4.2.3 Strategies for Accommodating Uncertainty

As my studies have demonstrated, measurement error is likely to be an ongoing problem that better instructions or even digital measuring applications alone cannot completely solve. The current *status quo* is to work around this problem with iterations through a prototyping process. However, in the realm of 3D printing, even a single iteration can be quite costly. Novice modelers or casual users are unlikely to behave like expert designers, who are accustomed to and can afford multiple design iterations to improve a prototype. Instead, they are likely to become very frustrated after one or two failed prints.

I made a case for design principles in 3D modeling and design for reusable adaptive 3D objects—**accommodate measurement uncertainty**. I argue that designing with this principle in mind will reduce the negative impact of uncertainty and reduce iteration. I propose two accommodation strategies that can be applied not only to the design of a new model but also to the modification of an existing model. They are: *(i)* inserting modular joints for the replacement of minimal parts and *(ii)* adding flexible buffers. These strategies involve integrating geometric structures specifically for handling regions where uncertainty may arise. Such modules could either be importable modules (for novices) or quickly built from scratch (for experts). I introduce the strategies below and present a tool in the next section that allows users to import any off-the-shelf model and insert these strategies into the model to accommodate measurement uncertainty.

Strategy 1: Modular Joint/Clamp Insertion for Partial Replacement

Inserting a modular joint or clamp allows part of an object to be replaced, or adjusted slightly, after the first print is completed. For example, a lampshade mount needs to be big enough to fit above a bulb's neck, but not slide down. This could be designed to be a separate part from the remainder of the lampshade, so that the entire lampshade does not need to be reprinted if there is a measurement error.

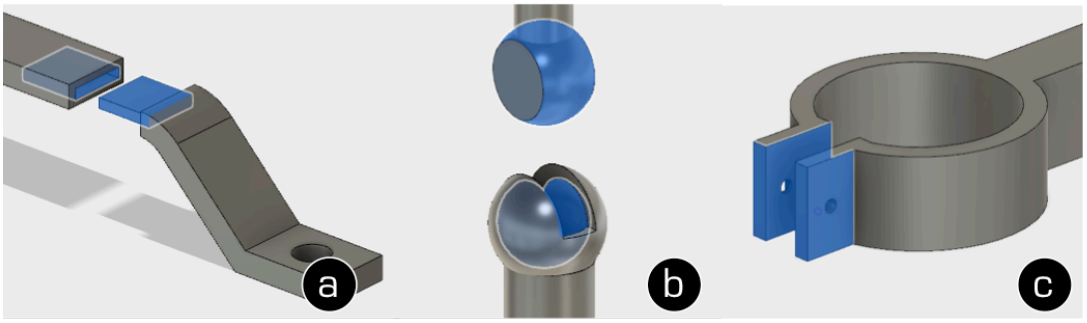


Figure 4.2.8: Joints (in blue) can accommodate uncertainty. Shown are applied examples for modifying: *(a)* length; *(b)* angle; *(d)* diameter. Both (a) and (b) support adjustment or replacement, while (c) supports only adjustment.

Joints and clamps can be characterized by the degrees of freedom they provide, and thus allow adjustments in multiple directions in addition to replacement [18]. As an exemplar of modular joints, I designed three types of joints: a simple connector (one dimension; Figure 4.2.8a and Figure 4.2.9); a ball joint (two dimensions; Figure 4.2.8b and Figure 4.2.10); and a clamp (one dimension; Figure 4.2.8c). A connector joint can also be used to make slight adjustments to length as illustrated in Figure 4.2.9, while a ball joint can be used to make adjustments to angle and a clamp to diameter (without reprinting). These positions can be finalized using glue (in the first two cases) or a bolt (in the latter case). In the case of the connector and ball joint, where the model has been split into two parts, the user also has the option to reprint another version of one part as a replacement, instead of printing the whole model again (shown in Figure 4.2.8a).

To insert a joint or clamp, a model is split at the insertion point. The male and female connectors are then attached so that the model can be assembled once printed. For example, for the ball joint Figure 4.2.10, the male part would be inserted through a parallel slot and be twisted in 90 degrees to be locked in position for a later adjustment of the angle (shown in Figure 4.2.8b).

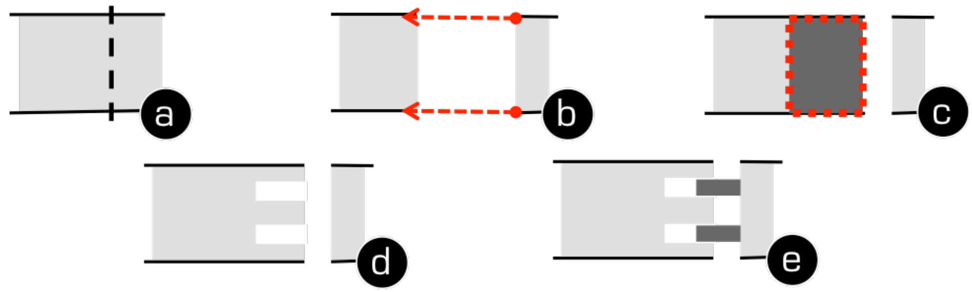


Figure 4.2.9: Operations to adjust the length of a model: *(a)* Slice the model in two; *(b)* translate one part perpendicular to the slicing plane; *(c)* extend the model to fill the gap; *(d)* create female slots by subtraction; *(e)* create male joints by union.

Figure 4.2.10: Operations to insert a modular ball joint in a model: *(a)* Slice the model in two; *(b)* subtract space to create room for the joint and add the female connector; *(c)* add the male part.

The clamp is created using a pair of planks and cutting out a segment of the cylindrical part of a model. In this case, a bolt and nut are needed to pull the planks together at assembly time.

Strategy 2: Flexible Buffers

My second strategy is a flexible buffer that can be added to a model. Such a buffer can support a small diameter or length adjustment. This structure can be printed in a soft material such as NinjaFlex. To maintain the integrity of the model despite the use of a different material, it is ideal to use buffers for very small scale (millimeter) adjustments. This approach is effective for items like a cup holder or phone case.

I created examples for length and diameter, shown in Figure 4.2.11. The added buffer structures are highlighted in blue. If a dual-extruder printer is available, hard plastic can be used for the main structure and a flexible, soft material can be used for the second extruder for printing the buffer. Alternatively, the two structures can be printed separately and glued together. This technique also allows for the replacement of the buffer if it is the wrong size without reprinting the entire object. A further advantage

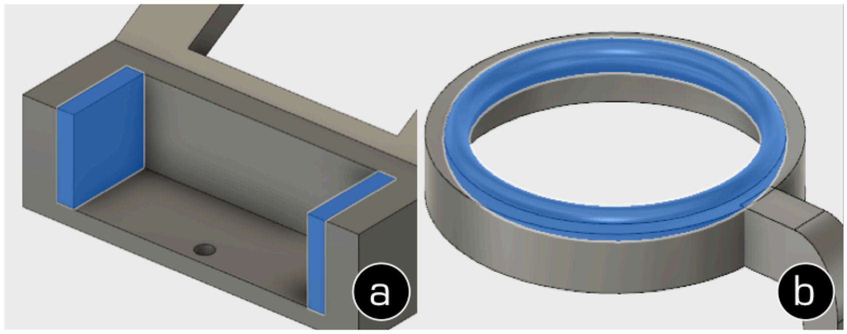


Figure 4.2.11: Two buffer designs (in blue). Shown are buffers that flex *(a)* in a linear direction and *(b)* in diameter.

of the buffer approach is textural: buffers can be designed to reduce slip.

4.2.4 FitMaker: An Uncertainty Accommodation Tool

The designs shown above represent conceptual solutions to the problem of uncertain measurement. These principles could be used by an experienced designer. However, there are thousands of 3D models online on sites such as Thingiverse that were not designed with these principles in mind. Many of these models are downloaded and used by novice modelers who have little ability to modify them (and are also more likely to make measurement errors than experienced designers).

To address this, I developed *FitMaker*—a parametric tool that allows novice modelers to adapt off-the-shelf 3D models to handle uncertainty. FitMaker includes a library of modular components that modify geometries of off-the-shelf 3D models, implemented as a plug-in in CraftML.

FitMaker provides a library of parameterized models for addressing uncertainty. As of now, the library includes a simple linear male-female connector, ball joint, and jigs as illustrated in Figure 4.2.8. The library is extensible, meaning that new modules for alteration of physical properties can be added. As CraftML is an open-source 3D modeling engine, any users with the skillset to model modular components with the required operations in mind can contribute to the enrichment of the library.

To demonstrate how FitMaker works, I describe a hypothetical user, Stacey, a fabrication enthusiast who has limited time and modeling skills. Stacey's daughter is having a hard time opening a sliding cabinet door because the handle is too high.

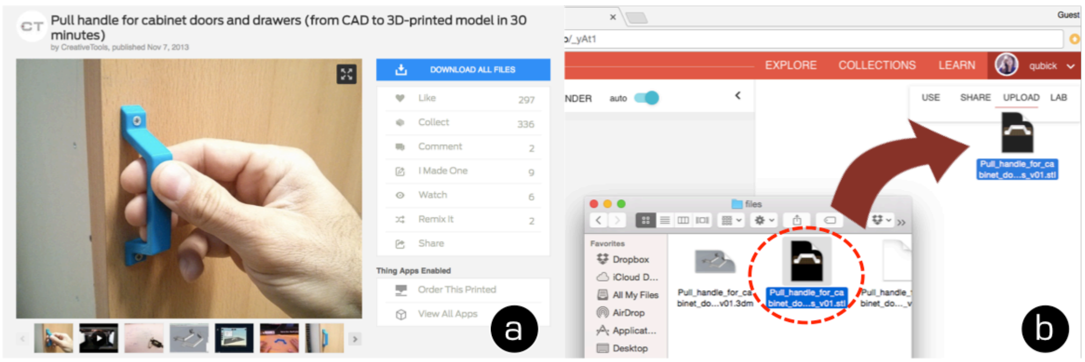


Figure 4.2.12: Stacey starts by searching for desired 3D models from online repositories with the intent to download *(a)* and import a model. Next she loads a modular component for addressing uncertainty from the library *(b)*.

Step 1: Search Off-the-shelf 3D Models

Stacey searches for 3D handle designs from popular online resources, such as Thingiverse or GrabCad. Any 3D model available online and numerous CraftML designs could be also used. She finds a satisfying example, but is concerned that it may be the wrong size. She realizes that simply scaling it before printing will change the size of the handle. However, it will also affect the shape of bolt hole, resulting in its oval shape that does not fit well with the regular bolt.

Step 2: Import STL and Modular Component

Instead, Stacey imports the handle model into CraftML. She clicks the *Insert* tab to search the CraftML library for a modular component that can be used to adjust length. Clicking the button "insert" from the popup browser confirms selection of the connector module.

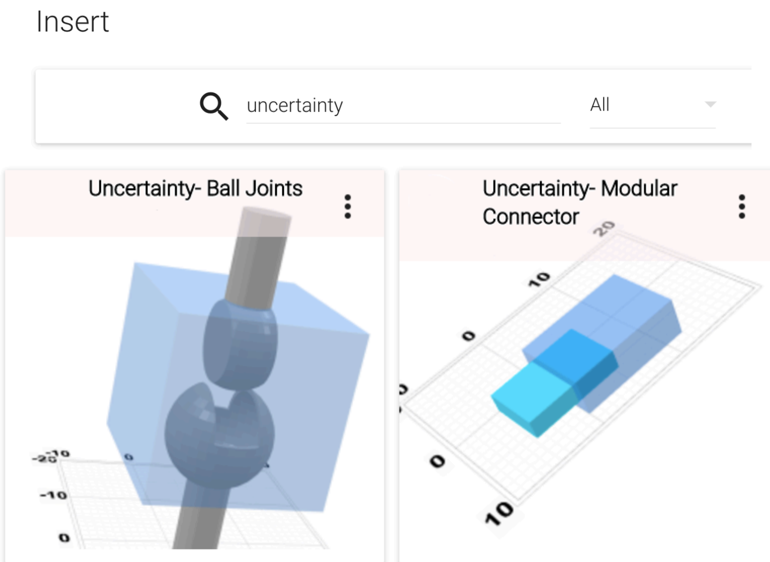


Figure 4.2.13: Stacey clicks the "insert" button to see modules available in the library for handling uncertainty. Shown are the ball joint, linear joint, and jigs for clamp.

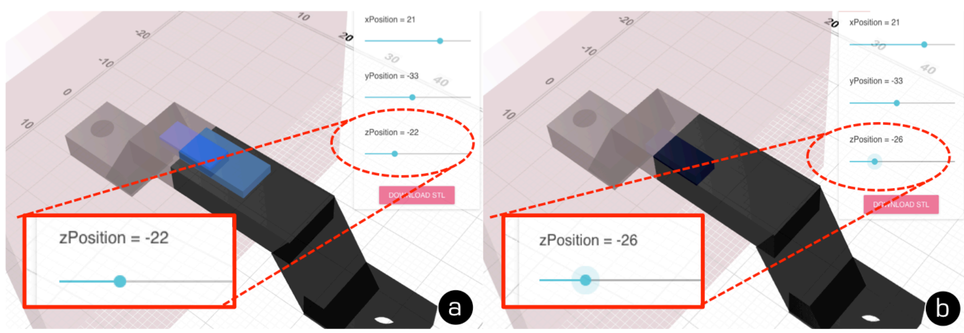


Figure 4.2.14: The connector is in the wrong place, cutting through the wall of the handle *(a)*. Stacey adjusts the z-position of the connector to place it inside the cabinet handle by moving the slider to adjust the location of inserted module *(b)*.

Step 3: Scaling and Rotation

Once both parts are imported, Stacey has the opportunity to adjust the position of the handle and connector with sliders until they are lined up as shown in 4.2.14. If the default size of the connector is too large or too small, she is also able to adjust parameter sets that define physical dimensions of the connector, as shown in 4.2.15.

Whenever parameters related to the location, rotation, and physical dimensions are adjusted, CraftML shows real-time adjustments in the model. Stacey can pan and rotate the scene to check whether the modular component is safely inserted, as illustrated in the geometry operation diagrams (Figure 4.2.9-4.2.10).

Figure 4.2.15: Stacey widens the joint to strengthen it by adjusting a parameter. If she feels the inserted male connector is too narrow *(a)*, she can increase the width of both the male connector and the female slot *(b)*.

Step 4: Export 3D Models and Fabrication

When the model is ready, Stacey can export it for printing. She can assemble the handle and attach it to the cabinet door for her little daughter. If the handle turns out to be too short, Stacey can go back to CraftML to modify the model for reprinting as shown in Figure 4.2.16.

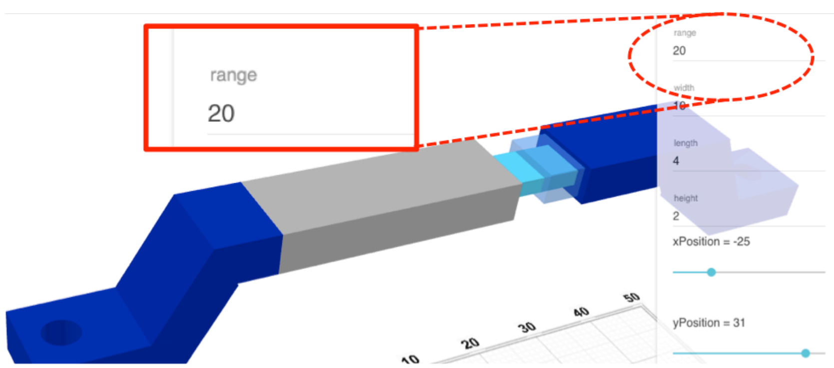


Figure 4.2.16: Stacey can modify the model for reprinting without affecting other parts of the model. The gray part shows the extended piece, whose length is controlled by the range parameter.

Examples

To demonstrate FitMaker's usefulness in addressing uncertainty, I created a set of diverse printed examples, shown in Figure 4.2.1 earlier. These were chosen based on real world augmentations found on Thingiverse. I focused on models that were liked more than 50 times by community members. Note that I did not test the items used in my studies; those were selected because the dimensions were standard, allowing us to validate the ground truth with factory manuals and not because of their need for uncertainty accommodations. In contrast, my approach is ideal for augmenting less well-defined items that require measurement, such as cups, door knobs, and utensils.

My examples demonstrate the use of ball joints for a phone camera stand (with angle adjustment), connectors for a cabinet handle (with length adjustment), clamps for a door knob, and a buffer (with diameter adjustment).

- **Length uncertainty:** I implanted a connector joint into an assistive cabinet handle from my scenario (Figure 4.2.1b). In the figure, I show how this allows part of the handle to be reprinted if the handle is too short (the replacement part is shown in blue). This example highlights the power of the tool to reduce iteration time, allowing users to reprint partial models rather than the entire part.
- **Angle uncertainty:** I integrated the ball joint into a phone attachment for a tripod. This application highlights the fact that uncertainty may not only arise from user error, but also from the nature of the task itself. The ball joint allows repeated adjustments of angle (Figure 4.2.1a), accommodating uncertainty in how the tripod will be used in the future.
- **Diameter uncertainty (b):** I used a buffer to create a cup holder that can accommodate diameter uncertainty. In this case, the height at which to measure the holder may be unclear (Figure 4.2.1c). This also demonstrates a situation where uncertainty is contextual– the cup chosen in the moment.

- **Diameter uncertainty (a):** I printed an assistive door lever with an inserted cylinder joint to adjust diameter and clamp the knob tightly with a bolt (Figure 4.2.1d). This example highlights the potential value of combining methods – a buffer could help with a door knob that is not perfectly round and reduce slip, improving the reliability of the solution.

Discussion of FitMaker

The above four examples demonstrate the range of contexts in which uncertainty might arise and the value of my solutions for addressing them. Here, I discuss additional topics surrounding FitMaker's usage.

- **Need for Automation** One challenge for future work is to improve the tool so that it can automatically generate modular components that are intelligent about how they integrate with existing objects. For example, a tool could automatically resize components to fit a specific model, identify an optimal location or direction of insertion, or alert the user if they intersect some other part of the object.

- **Solidity of Model** Inserting a joint or buffer requires segmenting a model into two parts, raising concerns of mechanical rigidity. My cabinet handle print was assembled without glue and used in a public setting for 3 months. No fragility issues arose. A more formal evaluation could provide additional confidence in each design.

- **Applicability** Depending on the target object's characteristics, there are limitations to the techniques that users can apply. For example, the original model might be too small to fit a ball joint or buffer. However, since the frustration of iteration mostly comes from long printing tasks, I would expect my strategies for reducing iteration time to have more benefits for large model prints.

4.3 Limitations

In this chapter, I stepped back a little from identifying a specific application area to find my modular approach that may help users' design activities. Instead, I took a close look into the common design activities as well as end-to-end design processes. In so doing, I tried to understand and characterize their design abilities. Although I believe design principles are useful for adaptive 3D model design, it may be common in "universal design", particularly in mechanical engineering. Here, users' choice of modular mechanisms and aligning them are still manual. Also, users' challenges not only lie at the measurement, which is the beginning of design. There are remaining areas that my studies have not discovered yet. One example area is identifying the right attachment mechanism to augment real world objects with 3D printed adaptations. End-users with no or less skills with mechanical engineering may have hard time to decide what exact mechanisms they should work to accommodate uncertainties. As briefly stated in discussion section, an automation algorithm generate modular components that is intelligent to integrate with existing objects, optimizing the point of interest and insertion would improve this limitation.

In addition, currently, the communication between humans and machines are via values, resulting from measurement in this case, to let the design tool recognize the design context. There exists the potential for simplifying this end-to-end design process if users closely communicate with the design process and materials. What if communication is more direct, and thus an existing object becomes a direct communication medium between designers and machines— "This is the size of the object for which I am designing an augmentation." However, for this communication between users and machines, currently, machines' capabilities are limited in that they cannot recognize users' design intentions. I introduce the work to address this issue in the next chapter, enabling existing real-world objects to be a communication medium, getting rid of the need of measurement from augmentation design process.

The most important thing is to put the right materials in their hands and let them create whatever appeals to them.

LEGO brochure from 1974

Chapter 5

Collaborative Systems-Digital Fabrication: Collaborative Fabrication Machines

5.1 Preamble

At the intersection of Collaborative systems and Digital fabrication, I ask a question: "How can a 3D Printer become intelligent, to proactively communicate with humans as a collaborator in creative processes?"

In previous chapters, I introduced modular systems and tools to support their creative explorations, inviting novice users to design custom objects. These approaches have been limited in that users interactions are trapped only at software level, before 3D printing starts operating. The remaining task is to turn the 3D printer into a collaborative machine that operates to bridges users' in-time design decisions to the output expressions, through seamlessly communicate with people during a creative work process. Supporting fluid, iterative, and collaborative design processes are critical to supporting users' creativity, as they are provided with more opportunities to express their design ideas. These in-situ design decisions arise during the creative process with many uncertain conditions, which helps them to advance their product incrementally, with many improvisations.

In this chapter, I introduce *Compositional 3D Printing*, a concept and technical implementation for this novel framework, and example design workflows, expanding various design/craft scenarios towards collaborative 3D Printing. Departing from a conventional digital fabrication workflow which is linear and batch— so that the user can only involve in the design using virtual design tools (e.g. CAD systems)—, I developed a new pipeline that empowers users to participate in the process end-to-end even when a 3D printer is operating. With the Compositional 3D printing framework, users can improvise their designs during 3D printing, to update their in-situ design decisions into the current design, by intervening in the 3D printing—this is now a part of the design process, not a final production process. Previously, a 3D printer was a passive command executor; now I turn it into an event-driven, intelligent machine that takes users' on-the-fly design activities that are presented in any form that they are familiar with (e.g., sketches, gestures, existing objects) at any time during the production. I suggest four important principles to realize Compositional 3D printing: timing of creative input, interaction style, input modality, and the role of the machine.

I conclude the chapter with the vision that a 3D printer becomes an active design partner or agent to human designers, with many potentials to provide people with recommendations and guidance, and even teaching new skills that advance designers to the next level.

5.2 Compositional 3D Printing: Expanding & Supporting Workflows Towards Continuous Collaboration with Machines in Design

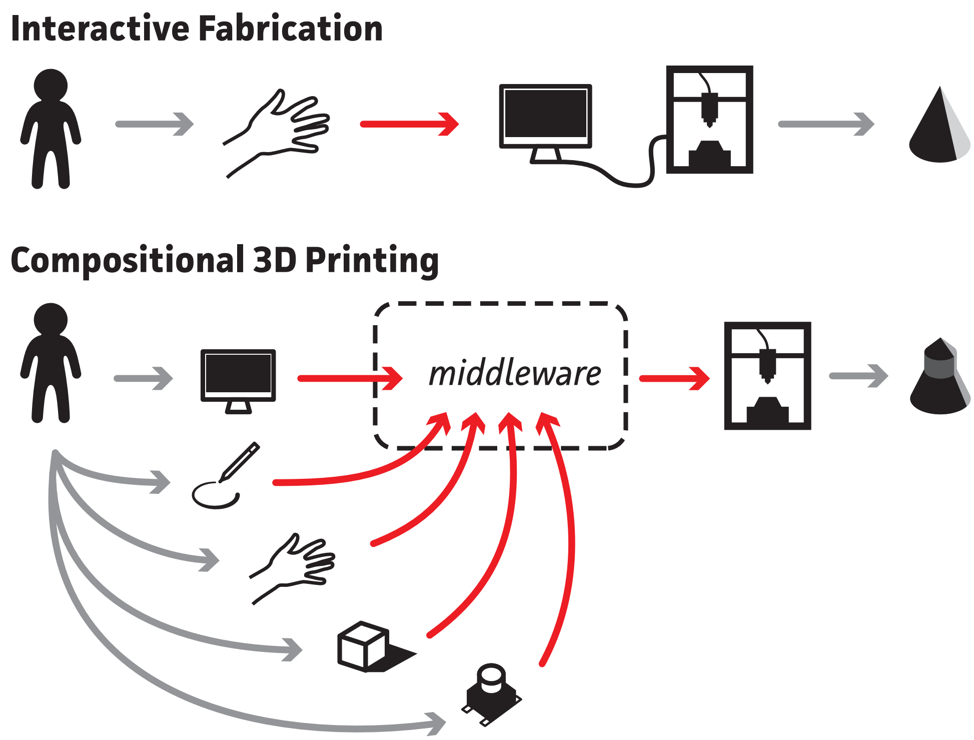


Figure 5.2.1: Compositional 3D printing (bottom) compared to current interactive fabrication concept (top). A user can directly "compose" a 3D model in a manner analogous to composing music, by (1) a rich set of vocabularies to express creative intent, and (2) continuous, reflective interactions to add creative elements.

The emerging field of personal fabrication leverages computational power to enable human/machine collaboration for creative endeavors. Beyond a low entry to the filed, it provides a medium for a myriad of expressions, from engineered mechanical parts to artistic and playful sculptures.

Yet, digital fabrication today is not fully *interactive*, as traditional makers are experiencing their crafts and design-by-doing practices. Similar to early days of computing code is first composed by a programmer using one type of interface. It is then submitted for execution, and a user loses control over the code until processing is complete. The current digital fabrication paradigm echoes this mainframe computing model—where computer-aided design (CAD) files are loaded into a fabricator. Here, *design* and *production* are strictly separate. Input is often a single file that is entered to the machine. Aside from starting, pausing and stopping jobs, machines do not permit any interaction, such as real-time edits that a user might want to make. Furthermore, these CAD inputs are often created in software packages using conventional graphical user interfaces, leaving no room for other embodied processes in creative work such as free-hand sketching and manipulating physical tools and objects.

Compositional 3D Printing is inspired by composing music with a music synthesizer, where a composer interacts continuously with the device to layer and modify sounds as *composing* process proceeds. The composer has a rich set of bodily vocabularies to express musical ideas, also using various instruments. The music mixer takes an initial input and constructs a base sound. A composer adds and edits the beats, pitch and rhythm on-the-fly.

Compositional 3D Printing recasts a creative process to enable users to *compose* a model via real-time design decisions and expressions while interacting with a 3D printer directly (Figure 5.2.1). This shifts 3D printing away from a print-and-forget paradigm. Compositional 3D printing shares two key principles with music composition— **continuous interaction** and **multiple vocabularies**.

Objectives of this work here are threefold:

- The Compositional 3D Printing, supporting continuous interaction and multiple design expression on-the-fly,
- Developing novel workflows that show the design space for Compositional 3D Printing, how different user groups compose a 3D model,
- Implementing an open-source framework to support the Compositional 3D Printing and to help expand the design space.

5.2.1 Background

Compositional 3D Printing is inspired by tools to aid computational crafting that allow interactive information exchange between a user and a computer, and recent advances in interactive fabrication that work within these paradigms.

Tools to Support Computational Craft

In a traditional craft process, the designer's input appears directly as a physical output, allowing designers to think about the next step with immediate feedback. Recent computational tools have explored this interactive nature of this process, reinforcing an inter-relation with the materials and tools for crafting [**?**]. Parameters exposed to end users provide an explorative space, to test features in the digital system and observe emerging outcomes[53] Craft is the process of making with existing objects and materials, as MixFab invites users to bring existing materials to the digital design space [112]. From hobby creation to fine products, these tools lead the making process to benefit from the precision of computation when the design activities of the user are imperfectly precise.

Craft Inspired Fabrication

Today's interactive fabrication takes into account the relation between the human and the tools, inspired from traditional crafting tools. The goal is not to leave *production* solely to machines, but to facilitate the participation of users in the entire pipeline through close conversation between them. There have been many attempts to make the personal fabrication design task interactive.

Constructables [79] involves end users in directly manipulating the workpiece, observing the instant result created by the machine. This process synchronizes design input and output, by the user and the machine taking turns. As envisioned in Interactive Fabrication [115], improvised physical design input influences the work-in-progress. In addition, D-coil and FreeD add intelligence to a machine, which assists designers actions with haptic feedback during production according to the original design input [89, 124]. In a similar bi-directional information flow, ReForm allows a user to update physical models, propagating changes to the digital model and vice versa [114]. On-the-fly fabrication [91] helps a designer update the model with her intention during design production. A designer can focus on one feature at a time, first creating the rough body shape of a pot, then moving to the next step, handle and spout.

While existing frameworks establish the basics of continuous fabrication to update the model along with users' in-situ design decisions, design interactions are often limited to screen based CAD tools, embodied interactions are one or set to a few specific types per machine. These works do not supporting *experimentation* on in-place design, which provide users opportunities of creative exploration. Remaining area to investigate needs to be looking at more collaborative approaches, letting users move from physical prototype to printable design.

5.2.2 Compositional 3D Printing

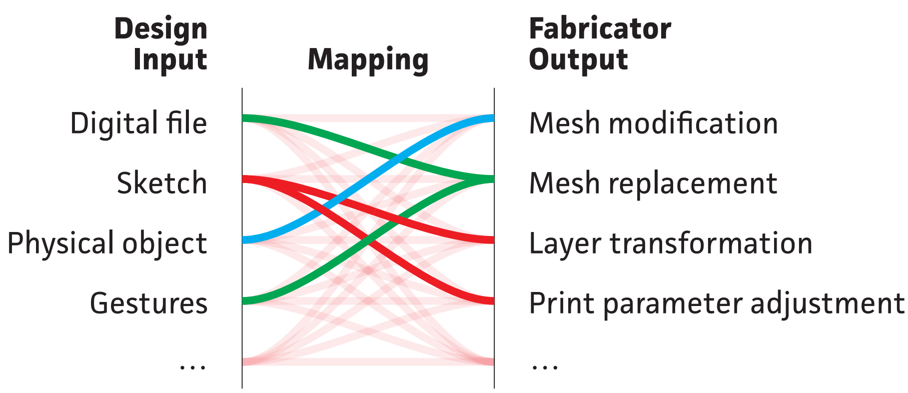


Figure 5.2.2: I support various mappings between current/future design inputs to the number of design outputs during 3D printing

While a diverse spectrum of people approach 3D printing with a variety of design literacies depending on their domain knowledge and goals— from hobby projects to professional product design, design novices often struggle with the steep learning curve that professional CAD programs impose, and may better express their ideas through hand sketches and craft materials, which intelligent systems (e.g., [79, 99]) can translate into a 3D model. On the other hand, although design professionals can employ the plethora of CAD programs and digital fabrication processes available to model and fabricate their designs; their creative process may also include other modes such as sketching and model making by hand.

Compositional 3D Printing is developed to *expand* users' respective design spaces, so the design

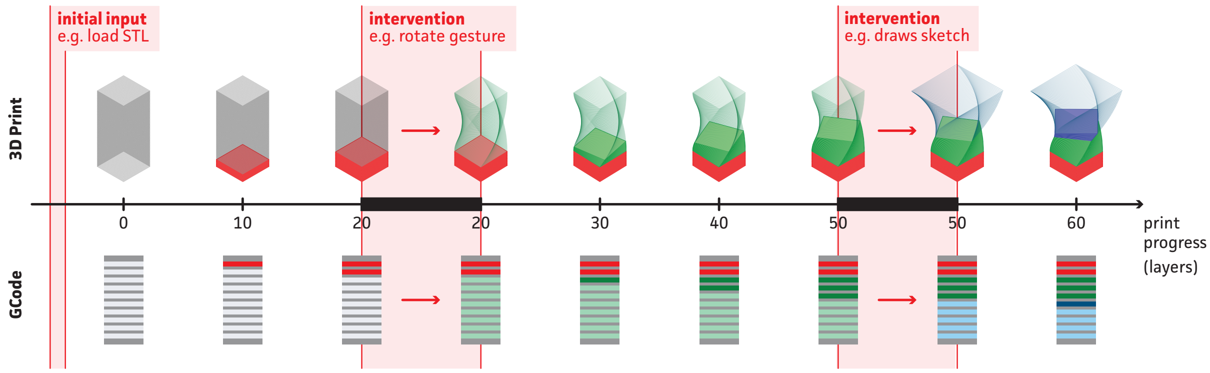


Figure 5.2.3: Compositional 3D Printing intakes multiple inputs during the process by segmenting Gcodes in two parts. It accepts just-in-time design inputs to apply changes on the model currently being created, returns physical feedback to a designer, providing an opportunity to test their design actions presented by various literacy

can include various design literacies and expressions, instead of completely replacing previous efforts towards bi-directional interactions. Furthermore, we harness the machine's affordances for richer creative output. For instance, directly manipulating the machine's operating parameters can yield atypical outcomes that serve designers as an experimental design source for a product design; yet are difficult to model and plan for in a conventional CAD environment—such as, varying filament extrusion rates to create different surface textures.

Apart from supporting a wide array of design literacies, digital fabrication tools should also facilitate the iterative design alteration while the production is operating. Schön describes designing as a conversation between reflection and action; and reflection can take place as a response to a design action (***on*** action), or during the action itself (***in*** action) [102]. Currently, a design iteration employing 3D printers is only as granular as the complete design to fabrication cycle. We want to support users to effect design changes during the 3D printing process as well, facilitating reflection and action at any time during the planning to fabrication process.

Compositional 3D Printing supports designers to engage with a FDM 3D printer through multiple input modalities, as well as implement design decisions and actions even as fabrication is happening. To demonstrate this, I developed and implemented a system that functions as middleware between design input and fabricator output. This middleware supports associating inputs with different fabrication outputs based on a user's intent (Figure 5.2.2), while managing synchronous communication with the 3D printer to effect changes (Figure 5.2.3). Also, it provides channels that future interaction designers and developers can use to create new input modes for digital fabrication systems.

5.2.3 Design with Compositional 3D Printing

Compositional 3D Printing is established upon two core principles: enabling continuous interactions with machine [60] and supporting multiple modeling design styles that raise design considerations for future design of personal fabrication.

Principle 1: Continuous interaction

A user of Compositional 3D Printing must be able to keep refining a model until production finishes, rather than simply waiting for her digital model turns into the physical form. A designer must have a better understanding of process and so may have more control. She should be able to express how to modify the model on-the-fly to explore effects, whenever she desires. In this process, the information should flow bi-directionally, not only from user to printer, but also from printer to user. It facilitates turn-taking between the machine and human; the user expressing inputs via interventions (as demonstrated in the red zones in Figure 5.2.3) and the machine accepting them that effect changes and modifying its behavior accordingly (illustrated as G-code transitions). The machine should listen to any real time event that might occur at any time, so the production task may be changed by the user's arbitrary interventions.

Principle 2: Multiple Design Vocabularies beyond Boundaries of Modeling Tools

Compositional 3D Printing encompasses a wide array of interaction styles to compose 3D objects, not limited to loading an STL file. It encourages the use of a variety of embodied ”design languages” to express a rich set of design intent that can influence different stage of design/production. Model composers can use body language such as gestures, a pictorial language such as sketching, or a tactile language such as showing a physical object to create a digital model, directly change a machine's toolpath or printing parameters. These embodied interactions can be associated with many different meanings at different stages of making. Richer vocabularies allow users to more flexibly convey their creative intent using the best-suited actions to convey it, regardless of their different literacy skills that are understood by a specific modeling algorithm which may be far from human's design language.

Example Workflows

In this section, I introduce example design workflows of Compositional 3D printing, incorporating interventions in the fabrication process as part of many creative endeavors.

Augmentation Using Real-world Objects

Augmenting designs to real-world objects is a common practice in digital fabrication [23, 34]. Measuring the objects' physical dimensions and entering them into a digital model is non-trivial task in this practice. Although many online open-source repositories provide off-the-shelf models that can be customized by modifying parameters, measuring to get a 'right' model can be error-prone process for novices. [59]. Novice makers may be inexperienced with customization, often iterating several times to get an artifact to fit correctly. Our system eliminates this tedious process of measuring and digitizing values, prototyping, and iterating.

To make a shaker lid with unique holes (See Figure 5.2.4), a user first follows the contour line of a jar. Without measuring, the user gets an exact physical dimension by following the physical outline (a). She fills the surface with color, leaving white spaces for holes (b) with her unique drawing. She then places the sketch on the printing base for the 3D printer to recognize the shape. When the printer

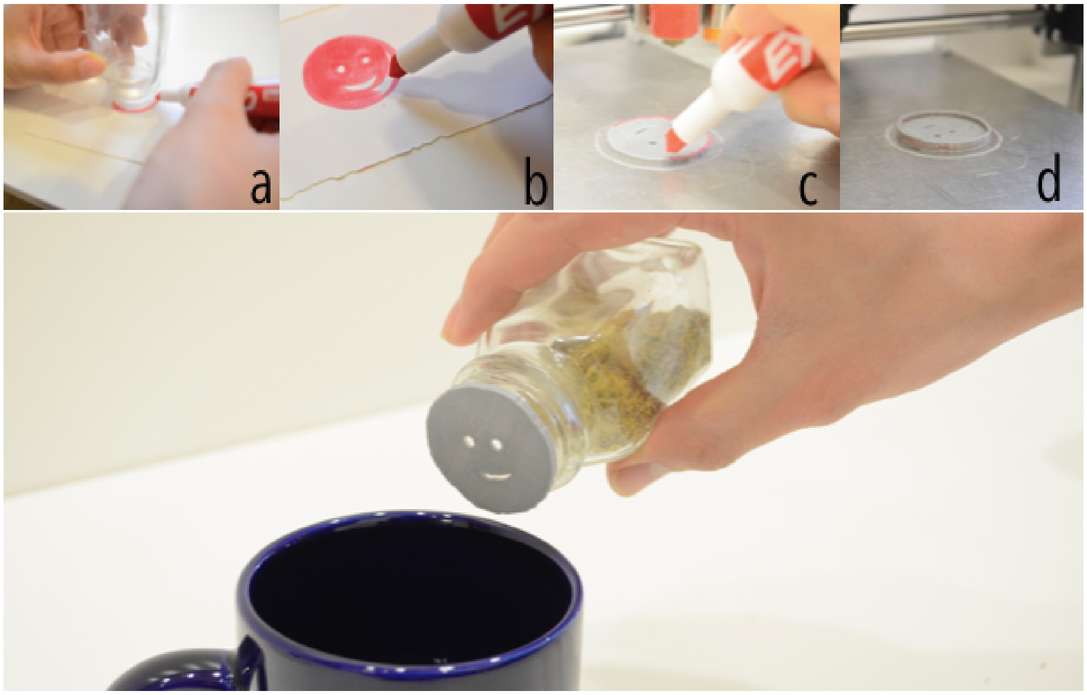


Figure 5.2.4: (top) Process of making a jar lid, by drawing the outline of a real-world object using surface filling to facilitate expressions. (bottom) The design results in a tightly fitting shaker lid to spread lemon pepper on the soup in a mug.

completes several layers, the user realizes that the jar needs a lip for mounting, so she stops printing to draw an outline of the shape (c). The printer then prints walls around the lid, based on the new drawing, to form this new lip (d). The user then stops printing when she is satisfied with the shaker lid.

Similarly, to design an assistive key turner for children and people with fine motor impairments, the user starts by creating a sketch of an outline of three fingers (Figure 5.2.5a). Then she places a real-world object, a door key, to measure its size (b). The 3D printer recognizes the sketch placed on top of the build plate and prints the first few layers. While the key turner is being printed, the user pauses printing and places the key on top of the model to indicate that she wants to modify the model; creating an empty slot. The printer recognizes the shape in relationship with the holder (c). After printing additional layers up to the height of the object with slots (d), the user can embed the object into this space. Then the printer completes the rest, securing the inserted object in place.

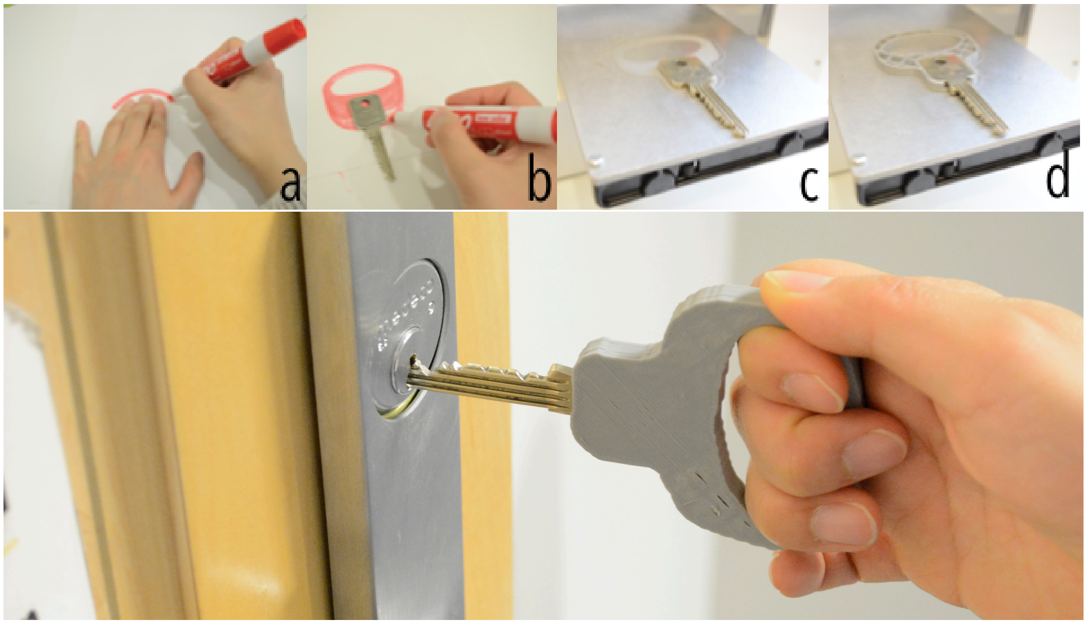


Figure 5.2.5: (top) Process of design an assistive key turner, without measurement of an existing object. (bottom) It results in an augmenting key to create a large adapter

Handcrafted Prototype to 3D Model

Cardboard prototyping is one of the most common methods for designing physical objects [86]. In this craft-oriented design process, a user quickly builds a prototype and allows improvisation and consideration of physical factors using flexible materials and tools. For example, a user can test force and gravity on a phone stand, using everyday materials such as masking tape and a knife within a short amount of time. In this workflow, a user wants to make a stand to hold her phone at a comfortable angle.

She finds the right size and angle by experimenting, fixing the design using masking tape (Figure 5.2.6 a & b). She marks the shape with a red line and places it on the build plate (c). She then orients her physical prototype, so that the system can recognize the shape from the top view. The system then creates an STL model from the physical prototype (d).

Embedding Materiality in Off-the-shelf Models

Remixing and combining diverse materials are common approaches to designing a product [28]. In

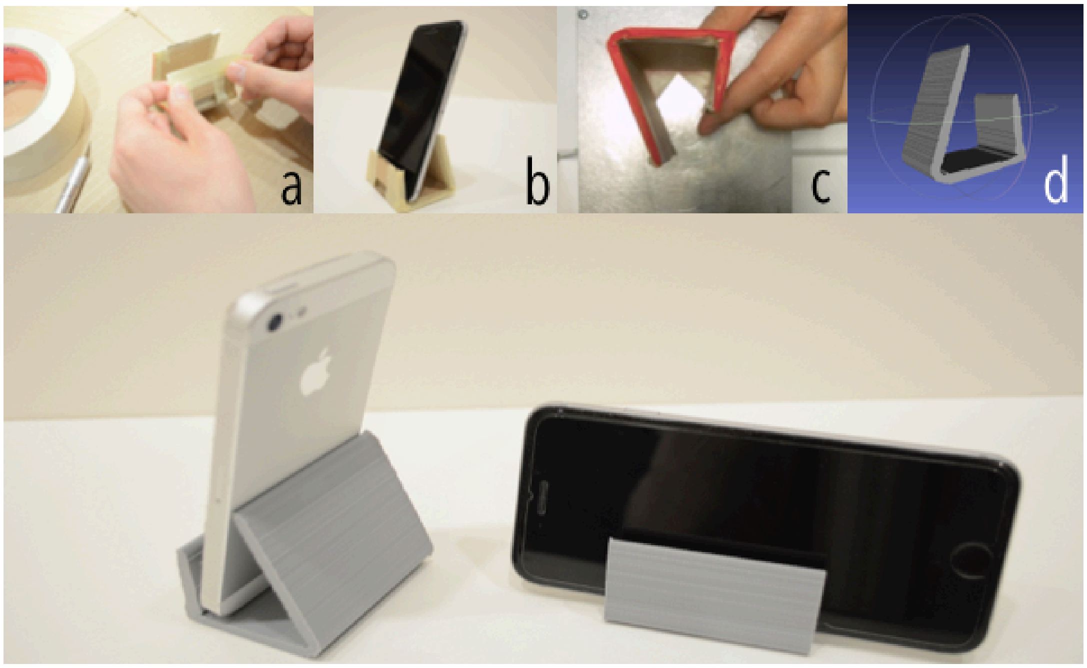


Figure 5.2.6: (top) Creating a 3D object from a handcrafted physical prototype. (bottom) The phone stand is first created using a cardboard, to test the physical attributes.

many cases, users start making things with off-the-shelf models downloaded from online repositories. However, modification and customization of the model depend on the original designer's predefined parameters.

The Mechamagnet project [121] is an approach to help industrial designers create tangible interactions by inserting magnets into objects at various points. The designer may want to test form factors with a 3D printer as a physical prototyping tool: for example, finding the distance between magnets that provides the most effective force feedback. With our system, the designer can load an initial STL file found from a repository for printing and start printing (a). When she finds the position to insert a magnet, she pauses and places real magnets to create slots. Strong magnets can attract each other if placed too close together, so a designer indicates positions of remaining the magnet placements by annotations (b). The designer then waits for the printer to print a few more layers before automatically pausing, indicating to the designer to physically insert the magnets in place. She then follows the required tasks, inserting the magnets (c), and resumes printing.

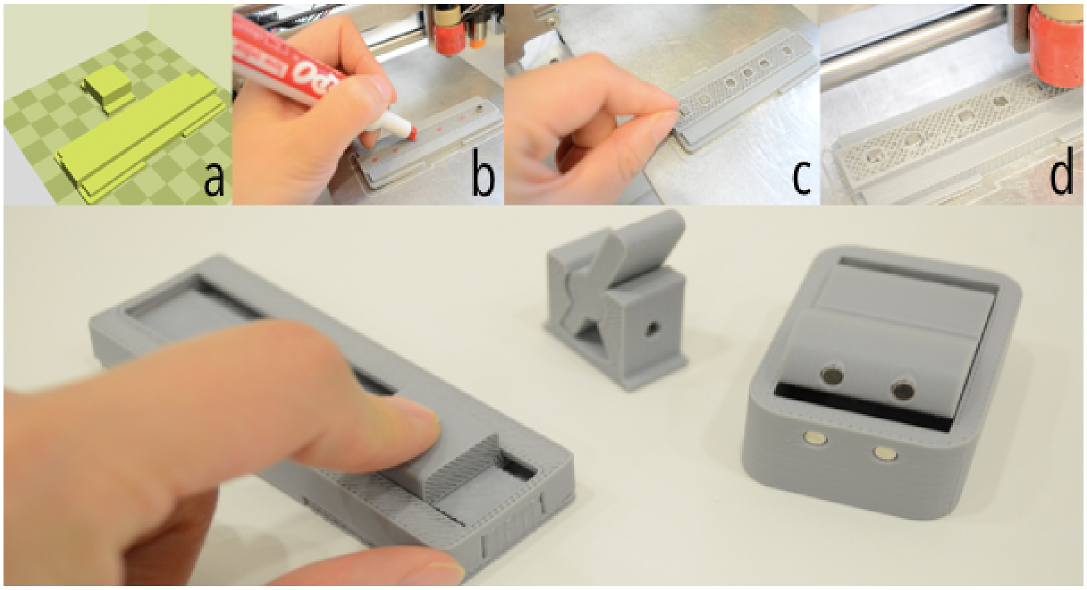


Figure 5.2.7: (top) Inserting a physical object. Starting with an off-the-shelf slider, a user places a foreign object to modify the original geometry. (bottom) One example could be the experimental creation of a Mechamagnet.

Pattern Definition and Repeat

Experimenting with a 3D printer's printing parameters has been applied in many artistic practices [67, 94]. By nature, the physical creation of an artifact relies on environmental factors, such as gravity or the speed at which material solidifies at room temperature. Designers may explore physicalities and artifacts created by these factors as input sources.

In this example, a designer draws a cylindrical outline with bumps as a primitive shape with which to initiate printing for testing variations that she might want as basketry textures (Figure 5.2.8). As a ceramic designer, she wants to explore how material moves and solidify by physical factors, and know which will fit her taste, among many potential variations. Thus, when the printer has completed the first few layers, she rotates the layer using finger gestures (b). The previewer shows what the rest of the prints will look like. With the user's confirmation, the printer prints the same layer patterns but with a slight modification; with the rotation in xy-plane. When the printer completes a few more layers, she claps to define the pattern from the history, (print three layers, and rotate at a certain angle) to repeat (c).

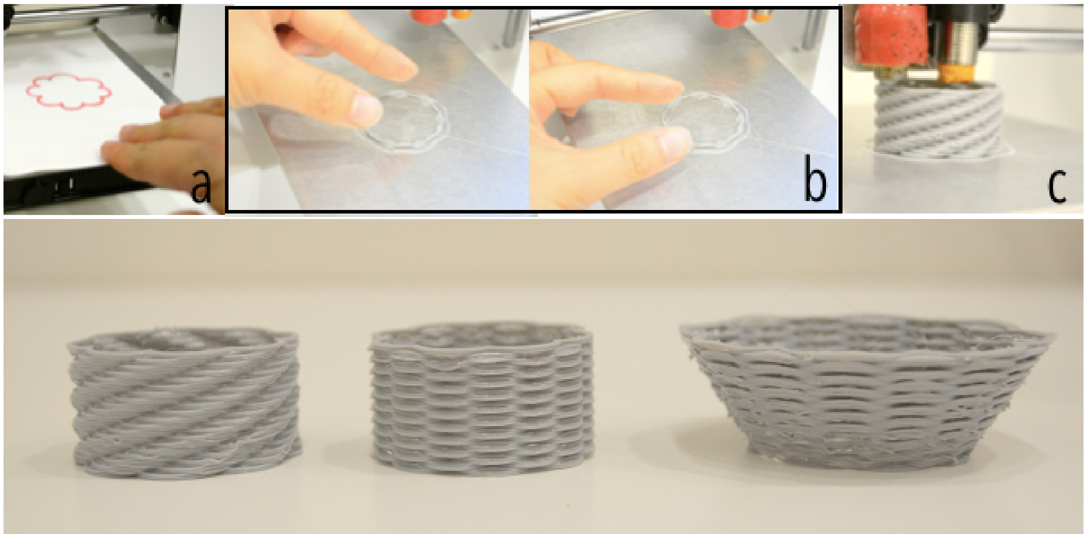


Figure 5.2.8: (top) 3D sculpting with interventions. (bottom) Drawing and hand gestures (rotation using two fingers) allow a designer to experiment with various texture effects of weaving.

5.2.4 Elements of Compositional 3D Printing

Figure 5.2.9 demonstrates how the system caters multiple channels (Figure 5.2.9 A-D) to a user with which to change the model using various interaction vocabularies. Internally, the system provides communication channels with real-time design inputs and translates them to factors that influence the various granularities of a model (e.g., into meshes, 2D layers, or machine parameters).

System Architecture

The middleware consists of three parts: (1) a core that controls communication during execution, interpreting design inputs into machine language, (2) a 3D printer with a webcam and external hardware such as LeapMotion to recognize interactions, and (3) a previewer for an end user to visually validate design actions applied to the physical model.

The system establishes a serial communication channel with a 3D printer to send G-code line by line. It keeps track of the 3D printer's status, while checking for any event interruptions triggered by

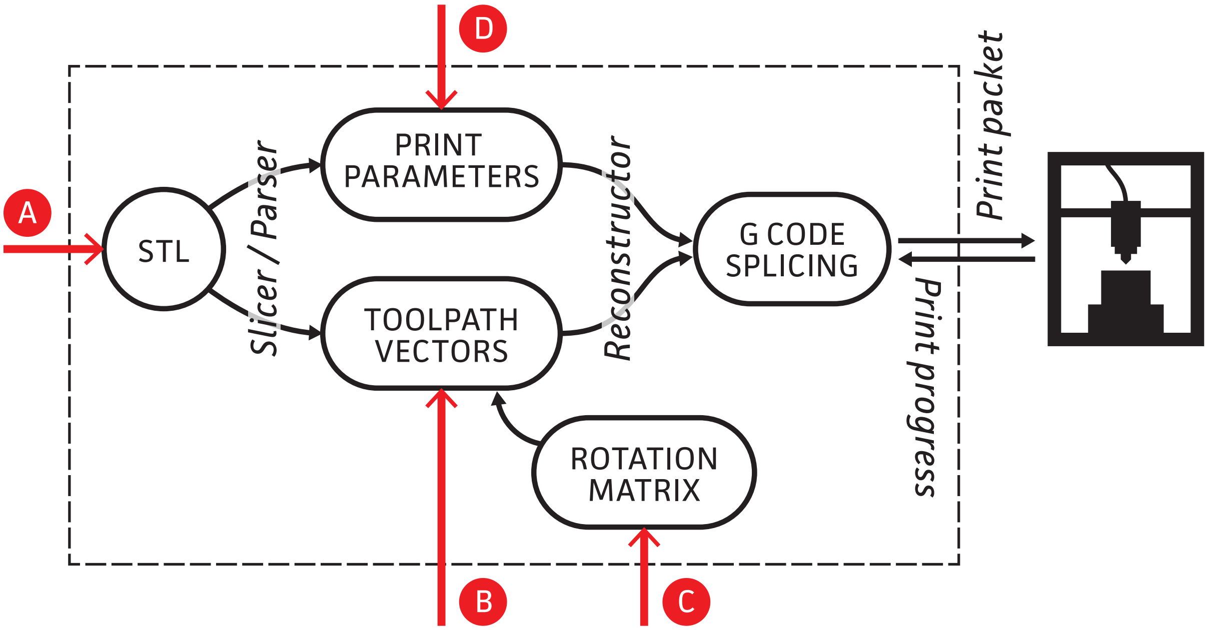


Figure 5.2.9: A multiple entries during the production of 3D model to harvest the in-situ design decisions that define changes on-the-fly.

users' intervention. A user's real-time design expressions are recognized by an RGB camera and an external sensor mounted on the 3D printer. As these external devices sense design expressions, such as sketches with patterns and gestures to transform layers, the information is fed back into the system to create changes on a model.

In the system core, CuraEngine[1] CLI runs to generate a G-code file, from the off-the-shelf STL, or generated by an algorithm modeling tool (currently we support OpenSCAD and OpenJSCAD). CuraEngine enables the system to take care of printer parameters that are hard to manage using a traditional CAD system (e.g. changes infill). Once a G-code file is created, the system executes a separate G-code parser, to keep track of the 3D printer's movements in 3D vector format. The system syncs to the 3D printer to monitor its status, by listening for an 'ok' message. Through a previewer that shows the printer's movement paths, a user can visually validate what will be executed as G-code lines. This provides immediate feedback about the user's design expression. Our ultimate goal is to enable an onscreen-CAD free design process, but a user still may want to see what would be the result of her actions before the execution.

[1] https://github.com/Ultimaker/CuraEngine

The system is developed in Javascript using Three.js and OpenCV.js, aiming at wider accessibility for designers/developers to expand the design space, using contemporary libraries of node.js, NPM open-source packages.

Synchronization Between System & Printer

To enable fluid communication and bi-directional information exchange between humans and 3D printers, the system sends G-code commands using a synchronous channel. This process prevents the system from sending the entire G-code at once, granting a user to intervene the process anytime. The printer sends a batch of commands in the size of its buffer at a time, monitoring the status of the event and holding the event until the printer completes tasks in the buffer. The printer's state machine accepts multiple input conditions, waiting for an event interruption in the background. It triggers the transition between states of the machine from pause to resume, to modify the queue that stores G-codes. When an event interrupts, printer goes into the resume state.

Design Inputs

In this section, we describe techniques that we adapt into our Compositional 3D Printing, and how these techniques are used as channels for expressing design intention. Any design input can replace any red zones presented in Figure 5.2.3, to initiate the printing task or to intervene in the process.

Input 1: Free Drawn Sketch

Sketching is an activity that uses humans' muscle memories in making process, and thus helps a beginning designer engage their own cognitive reasoning in spatial modeling. In addition to the sketch-based on screen CAD systems, our technique provides special cases that are suited for realtime design expression. Using sketches a user can indicate a drawing to linearly extrude to make a volume, create vertical

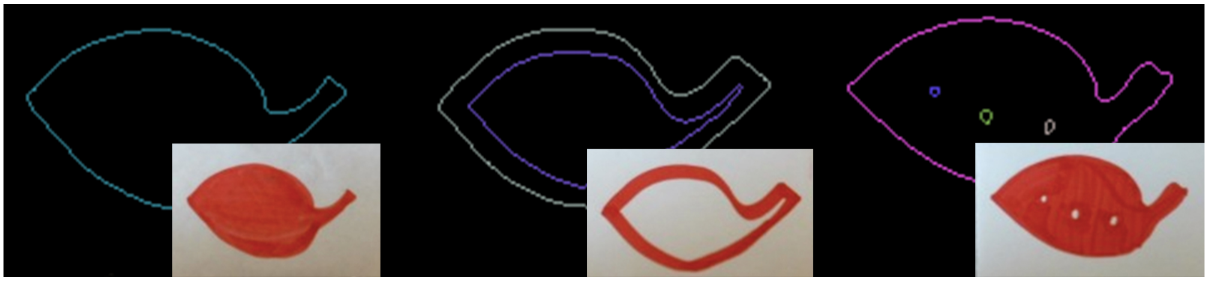


Figure 5.2.10: Three different contexts of a drawing: (from left to right) drawing in filled surface, drawing with thick stroke, and drawing with holes. Inset shows original sketches

walls, revolve the line to generate cylindrical object, or extrude with holes (Figure 5.2.10).

To capture sketches shown in the print bed, the system first extracts a foreground image to ignore background noise using an iterated graph cut algorithm [98]. In the case that a user draws sketches on top of the model partially printed, the system removes the dominant color of the foreground image. This helps get rid of filament color, to extract the user's new drawing (lips of a shaker) except the top layer of a model being printed (lid cover). The system then obtains the binary image to get pixel density and categorize them in two groups by thresholding. By cropping the image by the size of the printer's substrate [2], the system finds all contour lines in a closed loop, constructing 2D polygon vectors $P_1, P_2, \ldots, P_n$. To control the fidelity of the model, we apply polygon approximation using the Ramer-Douglas-Peucker algorithm [93]. Among the obtained area size S_n of 2D polygons P_n, the system discards polygons using filtering, by areas that are too small, to remove noise. Empirically we set $S_{min} = 30$ and $S_{max} = 10,000$, values can later be recalibrated. The system counts valid contour lines with reasonable area sizes. These processes can recognize three unique drawing types that result in different numbers of closed 2D polygon lines as shown in Figure 5.2.10: line drawing ($n = 1$), drawing with filled surface ($n = 2$), and drawing with holes ($n > 2$).

For line drawing, capturing two different polygons (See Figure 5.2.10 middle) rather than extracting the center line of the stroke, enables the system to recognize thickness of the stroke as one of design expression. The scaling factor for each polygon is calibrated by the depth (from bottom h_0 to the height

[2] 150 by 150 pixels, starting at position x:50, y:10 of the camera frame. These numbers can be adjusted by the relative position of the camera mounted to the printer gantry and the 3D printer's build plate size.

of camera h_{max}) where the sketch was placed, and in a relation with the printing bed size. The following process to create 2D polygons and 3D meshes based on these sketch contexts is described in a later section (5.4.1)

Input II: Physical Objects

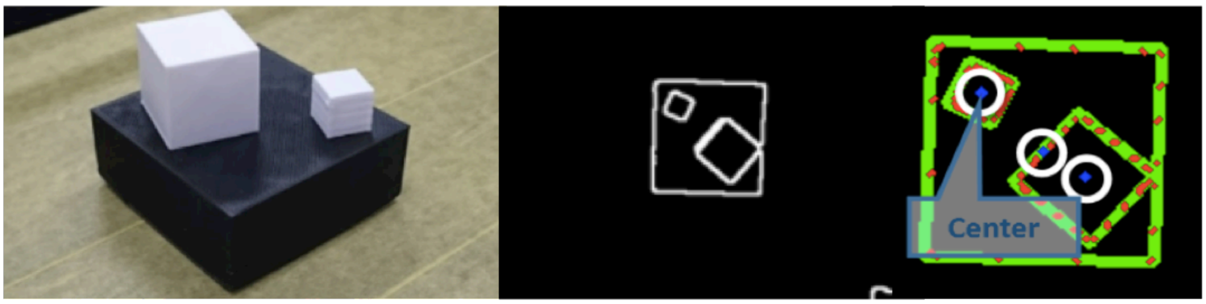


Figure 5.2.11: Inserted objects (left) are detected to retrieve relative position by comparing the position of their centers. Arbitrarily shaped objects are localized by bounding boxes.

Physcial objects can be inserted into a model to employ unique materiality (e.g. magnets), or be used to create a space inside a model (e.g. key holder). To localize an inserted object, the system remembers the center of each contour line of the sketch. Models are translated by the distance between center points given by $d = ||C_{x,y_{buildplate}}, C_{x,y_{sketch}}||$, where C refers to the 2D center point, relative to the printing base. A user locates the insertion by directly placing the object on top of the printed portion. The system then instantly captures the current scene of printing base from the top view when a user pauses, and captures the second scene when a user localizes an object and resumes printing. The system extracts the foreground image of both, so it can extract contour lines of the printed portion of a model (σ_1) and the inserted object on top (σ_2), to determine the positions of inserted objects, could be one or multiple. The system then subtracts the dominant color of σ_2 from σ_1, and thus keeps the inserted object's outlines only. Now both images follow the same pipeline described in earlier section (5.3.1), to get contour lines in 2D polygons and center positions.

Input III: Gestures

To support embodied input detection, we implemented a sensor value detection framework using Cylon.js [26]. A LeapMotion gesture sensor is used to capture three common gestures, (1) draw lines in mid-air by index finger movement path (2) scale with pinch, and (3) pause/resume, as shown in the Figure 5.2.12. We defined (4) clapping to indicate 'repeat the history'. Whenever the predefined gestures are detected, the system pauses the current task, interprets the gestures and create an appropriate rotation matrix to apply to the layer, encoded into vectors.

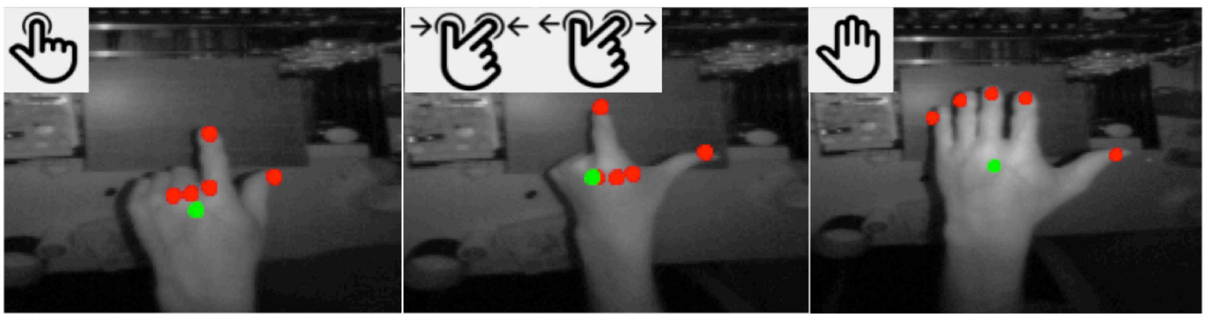


Figure 5.2.12: Common gestures that are defined in commercial LipMotion sensors are recognized by capturing thumb and index finger position detection

Input IV: Physical Sensor Values

Cylon.js robotics framework is also used to detect generic sensor values. Once an Arduino microcontroller with desired sensors is connected, the system reads a pin number to get sensor values that presents non-visual design expressions. Based on these values, designers can control printer specific parameters, for example, increasing extrusion amount as a physical knob turns, adding bumps according to background sound. In addition to the sketch identification by counting the number of 2D polygons, we also offer the user the ability to indicate their drawing context using a pen type, identified by RFID tags. In this manner, designers can specify which 3D effects they want to generate using different pen that similarly replicate crafting practice. For example, using a pen with a sharp tip, the drawing could indicate creating a dent.

Design Output

Our middleware maps the captured design input into machines output behaviors coded in G-code. When a new G-code is created reflecting changes, the middleware replaces it with the old one in the queue.

Output I: STL model Creation

Sketch context known from the sketch input, (See section 5.3.1) is used to create step by step constructive geometry operations using known 2D polygons in Open(J)Scad scripts. If the number of valid 2D vector polygons found equals to 1, the system generates simple script to linearly extrude the polygon in z-axis. If more than one closed vector polygons are found, the scripts collects all polygons $PG_1, PG_2, ...PG_{n-1}$, except PG_n with the largest area, into one array A_{pg}. Then the union of linearly extruded polygons set A_{pg} is subtracted from E_{PG_n}, the linear extrusion of the largest surface. We set the extrusion height of polygons in A_{pg} always higher than that of PG_n by 1 mm, then center all in z-axis, to avoid manifold geometry. After all designated CSG operations (linear extruding, subtracting, translating, etc.) completed, the system generates an STL from the resulting polygon and calls CuraEngine to create instant output as machine language.

Output II: Geometry Modification by CSG operations

As shown in the assistive key turner and MechaMagnet creation workflows, inserting physical objects produces a space inside the 3D model. First, the system extrudes the contour line detected from the captured image of inserted object σ_2 vertically. As a user enters the object height by value using the GUI, the system creates a vertical volume of this object δ, localizes it in x,y-axis, then translates from the build plate's center by its own center point. This polygon is localized in xy-plane inside the original model by the height of current extruder. Taking the original models' geometry (Φ, as an STL), Open(J)Scad scripts are created to perform the CSG subtraction ($\Phi - \delta$) to generate the space for insertion. It also creates additional G-code commands to sync the printer's behavior and the user's action, pausing printing at the height where a designer's action is required, waiting for the designer to complete this action, and resuming to complete the rest of the layers as shown in Figure 5.2.13.

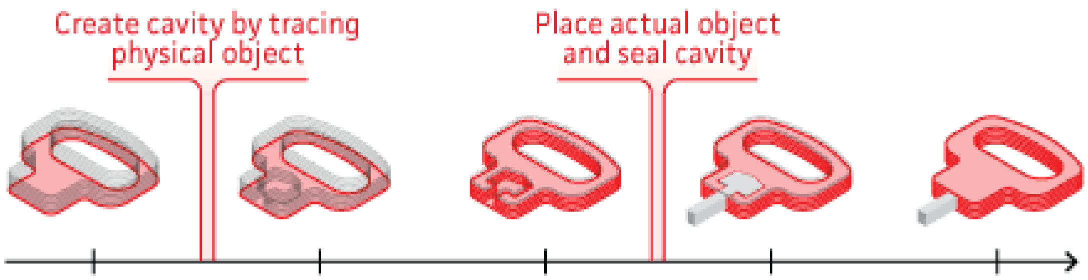


Figure 5.2.13: A physical object insertion results in a new model with the space inside that changes user's interaction with the machine

Output III: G-code Parsing & Splicing

When the G-code file is created, the system automatically parses it into 2D movement vectors in the same layer, by capturing toolpath commands (Ω, parsed by lines starting with G0, G1), and saves meta printing parameters (ε, lines starting with E, F, M, etc.) respectively. This step is for taking in-situ design inputs that might affect each layer in different ways. If a designer interrupts printing, the design input is represented in a transformation matrix (θ), then applied to this vector ($\Omega^{\intercal} \times \theta$), as shown in Figure 5.2.14.

Output IV: Apply Transformation Matrix

As illustrated in the basketry example (Figure 5.2.15), hand gestures presented one of 'additional input's to enable continuous interaction with physical objects [66]. Our system transforms users' direct input as captured by camera sensors into a transformation matrix. The G-code parser saves the header movement of each layer in a 3D vector with the same z-value. Once the rotation matrix is created, the vector is transformed by multiplying it.

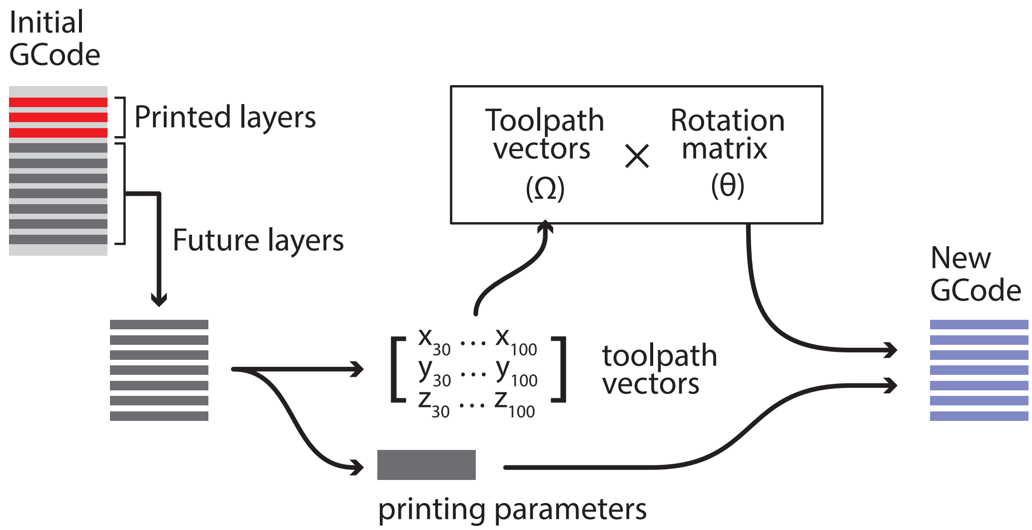


Figure 5.2.14: G-code is parsed and stored in vector(Ω) and meta data (ε). These information are used to update the model New vectors are spliced into a new G-code.

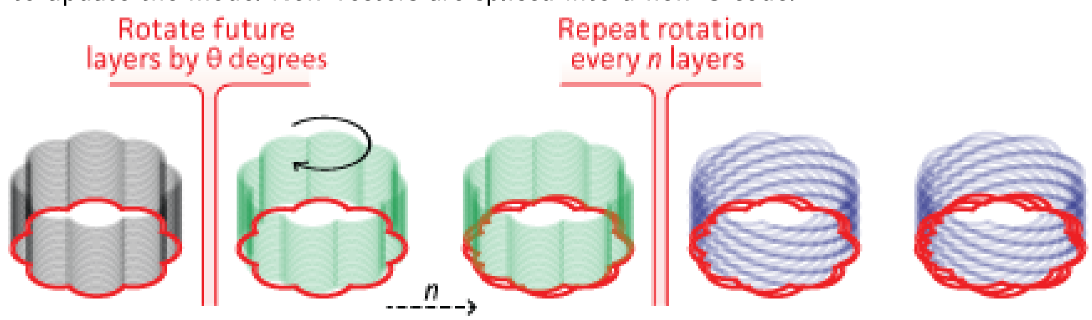


Figure 5.2.15: Intervention with a gesture, rotate with fingers, tweaks current toolpath on-the-fly. Another intervention with clapping can define the printing history

When new G-code is generated, the system splices new G-code according to these movement vectors (Ω'), recovering meta information from ε (E and F, fan on/off, printing temperature, etc.). Now the printer gets this new G-code, replacing the old G-code it was executing.

Output V: Expressive G-codes and Customized Printing Parameters

3D printing is controlled by 3D printer's printing parameters, for example, the ratio of extruded material to movement speed. These parameters are printing time parameters that handle the quality of printing not the shape of object. Prior work tested tweaking G-codes to directly change the appearance of 3D shapes [63, 107], demonstrating the 3D printer as a tool capable of promoting its own expressivity.

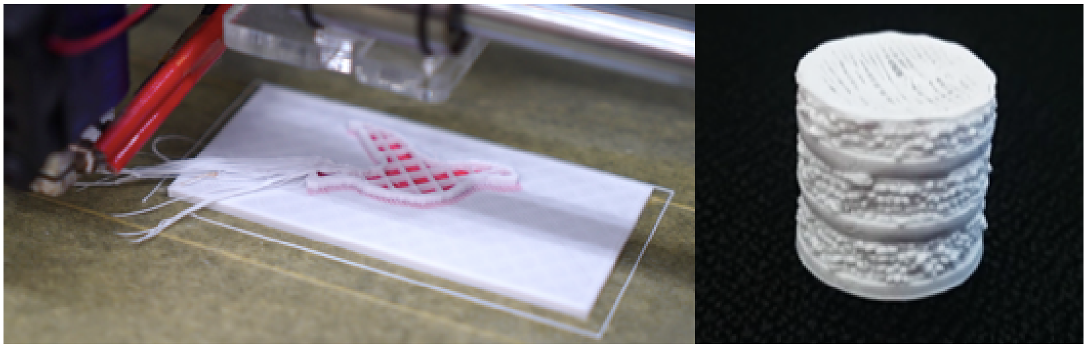


Figure 5.2.16: A line drawing gesture in the mid-air can present strands effects (left), and physical input to increase extrusion rate (stepping up the extrusion motor speed) generates interesting texture effects (right)

However, these techniques have not been reused by end users, because managing G-codes directly to change printer's behaviors is not a trivial task in traditional onscreen CAD systems. We encoded three expressive printing templates, stranding, drooping, and drooping with droplets. When a user draws lines in the mid-air, the system captures the direction of the movement and inserts the template coded in a few G-Code lines into the current queue (See Figure 5.2.16 left). After finishing, the process returns to the original task and complete printing.

Using expressive G-code templates, the system enables integrating non-traditional 3D printing effects. This technique is especially useful to present textures to promote users' tactile experiences from 3D printed objects, such as tactile pictures [57]. Also, as the system stores vector information in one layer, a gesture to 'auto-complete' can be set by the adding the pre-defined templates at each point in polygon vectors, stored by G-code parser, calculating the direction by multiplying the normal of each point in constant intervals.

Our system also supports later replication and iteration. Thus, the system supports to save the final G-code created by users' on-the-fly design action to replicate the model if needed. Design actions that incorporate important design parameters can be reversed into an STL form for sharing [71].

5.2.5 Discussion

This work is part of my long term vision to enable close interaction through seamless information exchange and checking in to sync up towards a common goal, between a human and fabrication machines. Here I discuss points that we and the future fabrication community will need to take into account.

Supporting Exploration over Efficiency

Digital fabrication made great advances in speed, material, and precision. Recent efforts have focused on using a 3D printer to validate their design by physically fabricating the digital model. The 'efficiency' of fabrication is not the target of our work. Rather, our focus is on the exploratory nature of design, by involving the printer as a tool during this process. Although current 3D printing does not support physical undo unless special hardware such as milling pin integrated, similar to crafting or model making with physical materials, we imagine that Compositional 3D Printing will enable makers to be on-site during production, effecting real-time design decisions based on ongoing observations and reflections.

Fab Machines as an Intelligent Assistant

The ultimate goal of developing a middleware and design space for Compositional 3D Printing, empowering a user to continuously design with improvised design expressions, is to facilitate users' participation in the entire pipeline including the physical production. In this work we explore the possibility of casting digital fabrication machines such as 3D printers as a music mixer. We envision a new pipeline that catalyzes co-working with fabricators as an intelligent design assistant. Fabrication tools must understand the design context, perceive the human's actions, and proactively assist with arbitrary design actions by incorporating its precise, rapid computation in the production process. To carry the benefits of humans' artisanship to the digital fabrication world, machines must support the designer's fine control of tasks, and to allow refinements of design by being intelligent, supportive, and revealing of their own processes. We gain inspiration in this matter from the field of Human-Robot Interaction (HRI): machines can be supportive members of teams [40] and co-make decisions when unexpected situations occur [36], all through sensing the task context. Our vision is to evolve future fabricators in conjunction with advances in HRI, to become more collaborative and supportive agents. As a smart fabrication machine, we envision a fabrication machine that recognizes design context by more fluid information exchange, being told or reading sentiment, learning from the previous process or habits to intuitively interpret the designer's design intent. Ultimately, the fabrication machine's potential is as an assistive design collaborator, rather than a dumb command executor, or simple design interpreter.

5.3 Limitations

First, while I provide more options for interaction techniques to directly communicate with a fabrication machine and those techniques are common in natural communication (e.g., sketch, gesture), currently-available modalities may not represent 'all' means that users will use to interact with computers. With the current 3D printer's physical capabilities of layering materials from bottom to top, many natural crafting techniques are not supported, such as subtractive methods (e.g., sculpting materials out from sharp corners).

Second, though I opened the framework for Compositional 3D Printing with modular libraries for public access, it is not very extendable by an end designers. Recognizing even further design contexts and mapping these to a variety of printing expressions along with the future hardware innovations (e.g., design context recognition by future AR/VR devices) might not be an easy work. Currently, intermediate/advanced developers' involvement in engineering is required to extend this design space and workflows. For future work, I will push my efforts to close this gap, between the needs of designers and the ability of developers, to reflect designers' needs. Providing a high-level interface to bridge a new input modality type and desired output expression would a potential solution.

Last, depending on an application type and the fluency of a designer, this 'design-while-print' may not be appropriate in all circumstances. Certain types of applications need more precision instead of creative exploration, such as gear-rack mechanisms, for example, to upgrade commodity objects with 3D printed adaptations with robotic movements. Potential theoretical research to follow could help to understand the underlying purpose and principles of design task in order to suggest the right type of design approach to take.

Artificial intelligence and Robots will help people diversify thinking with multiplicity, not singularity.

Ken Goldberg

Chapter 6

Conclusion and Outlook

In this section, I summarize the research completed for this dissertation, recapitulating key research questions and contributions of this work, with reflections. I then discuss some remaining challenges the current research left and introduce future directions to overcome these limitations.

6.1 Summary

I began in **Chapter 1** by introducing the motivation for and the background of this dissertation followed by a discussion of the key research questions and an examination of why the answers to those questions are important. I introduced the contributions and key definitions of terms.

Chapter 2 provided a literature review, an extensive overview of the foundation work in digital fabrication, followed by a discussion of how machines currently support on-the-fly design, and the existing nature of collaborative machines. I described late-breaking projects that strive to solve under-covered questions in those domain, about remaining challenges and suggestions for better approaches to addressing such issues.

Chapter 3 documented two modular systems that I implemented at the intersection of HCI and fabrication: *Tactile Picture Books* and *Kinemaker*. These were efforts to address a key question in personal fabrication, "How can end users fabricate custom complex artifacts using existing resources without requiring expertise?"

Chapter 4 introduced empirical user studies to understand and characterize end users' design abilities. Studies were conducted at the intersection of HCI and collaborative systems. Studies tackle to answer the research question in understanding and characterizing end users with a question: "What are limitations of digital fabrication and unsolved challenges for end users in 3D design and printing?" Then I introduced a design principles and a library of modular parts to accommodate measurement errors to integrate those principles for advanced designers. Descriptions of a parametric tool as a possible solution follows, to answer the research question of "How can a modular approach accommodate errors resulting from design activities for end users?".

Chapter 5 introduced Compositional 3D Printing, a work conducted at the intersection of digital fabrication and collaborative systems. Compositional 3D Printing transforms a 3D printer from a passive command executor into a responsive event-driven machine, to operate as a collaborative design partner of users. This work addressed the key research question, "How can fabrication machines become collaborative as a design partner of users in a creative process?"

6.2 Reflections: AI as a Mean of Supporting Creativity

Having implemented collaborative digital fabrication machine that help people be more creative, *"Can computers create art?"* becomes an interesting controversy. It also recalls people's fear that AI and automation can replace people's jobs, including creative endeavors. This debate has yielded subsequent binary statements that (1) creativity is only for humans, and (2) people do not care whether humans or computers created the creative works. However, this binary is artificial. The former contains philosophical concern for artists and creators, while the latter comes from the functional standpoint, and they can go together. In that sense, people's question of "why should we prevent robots from creating things?" is less engaging, as our goal is NOT preventing them creating. I would like to stress that our goal is not to imbue robots and AI with certain qualities that allow them to create without the assistance of a human user. Rather, we propose IA, encourage people to be more creative with robot assistance.

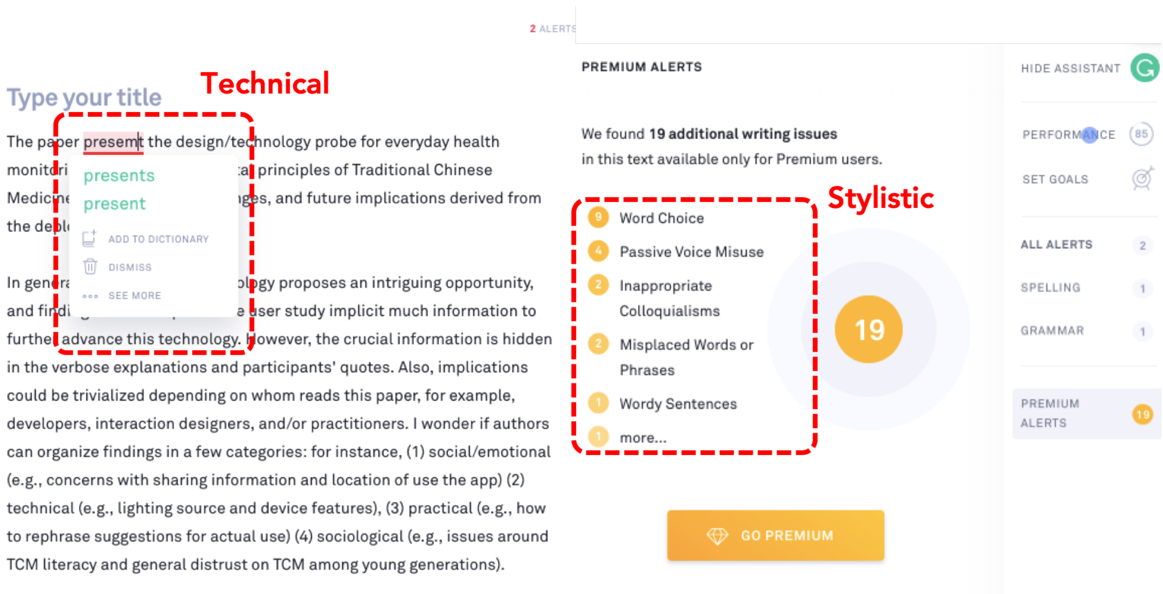


Figure 6.2.1: The Grammarly writing application offers technical and stylistic assistance for human writers. Ultimately, it is the writer's choice whether to take these suggestions to improve the quality of writing, through fluid conversations with a writer.

We can see an analogy in creative writing. People have been writing for thousands of years, and will write in the future regardless of the existence of an article-writing bot. Writing is a synthesis of complex skills that empowers people to present ideas through creative narratives that have never before existed. While the public now has access to a range of writing assistance from spelling and grammar check, which is technical to elaborating expressions based on stylistic suggestions, people are ultimately the owner of their work. They have their own unique style of authoring to produce *creative artifacts* in spite of the machine's help, choosing to take or not to take those suggestions.

Some may argue that certain types of writing do not require any creativity. However, regardless of genre, from the subjective writing of essays and novels to the objective writing of grants and theses, the writing process inevitably undergoes many iterations. Examples include expressing abstract ideas to elaborating expressions, intervening contexts and switching sequences, inserting more details here and omitting descriptions there to leave space for a reader's imagination. Although writers may receive assistance from intelligent systems, it is still up to a human author to finally complete the masterpiece. Through the writing of a draft, editing expressions, and improving story lines and contexts, a master writer gradually improves and revamps the article to better communicate their ideas reflected into the piece of their creation—a final masterpiece of writing. Machine's role I claim to help those writers is to suggest options for them to be more fluent and let writers proceed to the next step, not to take a writer's whole manuscript and replace it with totally new content.

Here, then, is a dichotomy of innovating technology: (1) advancing machines to *mimic* and replicate all tasks that people can do to simplify their lives; (2) advancing machines as platforms to *assist* people's tasks who want to retain their own unique opportunities of being creative. Murali Doraiswamy, Professor of Duke University stated in World Economic Forum Annual Meeting:

> *"AI generally refers to efforts to replace people with machines. But AI has a counterpart, known as intelligence augmentation, or IA, that instead aims to use similar machine learning technologies to assist — rather than replace — humans."*

In either direction, there is no easy pathway that is achievable in the next couple of years. Then it is our choice on which direction we want to advance our technology. If creative designers want to be better than machines at creative tasks, isn't it our job to support them by advancing technologies towards this direction?

Among the two directions of developing future fabrication machines, my chosen direction is to innovate digital fabrication machines to *aid* people and support them to be even better at their own tasks. I argue that those two directions are equivalently complex and hard to achieve. This process can be built based upon an understanding of the unique roles that humans and machines play within certain contexts, then innovating the machine to be *collaborative*. Collaborative digital fabrication machines enable the exchange of information with humans for the fluid execution of tasks, finally providing the right assistance in the right context based on an accurate context recognition. This brings about potential for new research program.

6.3 Future Directions

I envision a not-too-distant future where digital fabrication becomes the *enabling technology* that broadens the capabilities of designers and crafters who will freely be using these tools in place of a sketching pen, a sculpting spatula, or an electric drill, and many more. Designers will be able to employ digital fabrication tools immediately and with ease to express and physicalize their initial design ideas into tangible artifacts, without hesitation or concern about failing or wasting time. If necessary, designers should be able to adjust their ideas mid-production through a collaborative process with tools and machines, creating on-the-fly prototypes through continuous conversations with machines and materials using various interaction techniques. Applying in-situ design decisions, designers will finally generate their own creative objects in a explorative manner. Digital fabrication then must provide channels for designers and fabricators to communicate throughout the entire fabrication pipeline.

6.3.1 Observation and Data Collection: MAD(Machine-Aided Design) from CAD

As opposed to existing research that seeks to innovate computational design tools (e.g., CAD systems), I aim to propose physical machines purposed to support machine-aided design (MAD), not on-screen design tools that still separate the design and fabrication processes. For this purpose, I have transformed the 3D printer to be an active event-driven machine instead of a passive command executor (Compositional 3D Printing). Thus, utilizing 3D printers as one instance of agent robot, as they will be ready to execute users' situated design expressions into their operation. However, at their current level, these machines are not able to anticipate a user's next behavior and are simply executing in-time commands iteratively (if any) at the moment. To this end, I would like to revisit Ken Goldberg's quote, *'Artificial intelligence will help people diversify thinking'*. The next step to turn these communicable machines into collaborative ones is to teach them to anticipate users' design actions and provide assistance based on

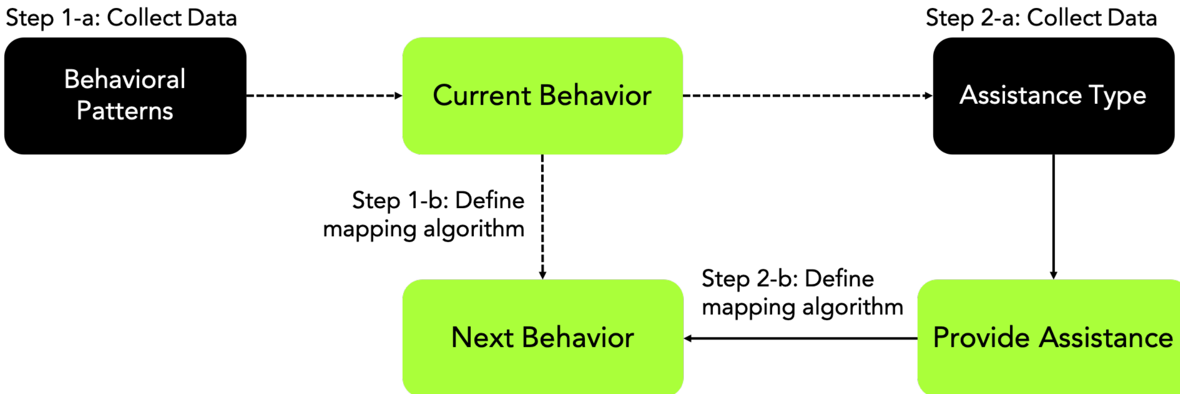


Figure 6.3.1: From collecting data of human behavioral patterns, my future work will be developing a mapping algorithm to predict and anticipate users behaviors in the creative process in order to provide proper assistance according to the context.

these predictions.

I will first observe what kinds of human behaviors occur during the creative-making process in sequence.

Take the situational context of kindergarten children as an example: if a child picks up a paint brush instead of a pencil, the teacher, as an assistant, may need to provide a set of acrylic paints, a palette, and watercolor papers instead of thin scratch paper in order to meet the child's artistic objectives. In this case, the child's action of picking up a brush is a clue that signals their next likely behavior. Certain actions allow one to anticipate the overall intentions. Based on this anticipation,*assistance options* can be defined and related objects of a palette and a white paper can be provided by an agent, as seen in Figure 6.3.1.

6.3.2 Technology Investigation: Expanding to Generic Robots/Systems

From these observations, it is clear that technological investigations must involve many other AI techniques, such as machine-learning to classify human behaviors and use them as clues, e.g., motions of grabbing (an object), gluing existing materials onto certain positions, inserting foreign materials, and others that show a user's intention. Also, a computer must have the deep learning ability to recognize context. For example, among many available options, the system must be able to recognize and choose (crafts) materials or tools to anticipate the user's intention of performing an action. When this initial anticipation is made, Generative Adversarial Network (GAN) could be used to generate various user options as a seed to aid users make design decisions. Caitlin et al. proposed a collaborative design between machines and architects of large-scale projects such as bridges [125]. An architect provides a base design concept and the AI generates design alternatives for creative exploration, which includes structural analysis. The designer can then make the final decision built upon their own aesthetic criteria.

6.3.3 Metrics: Definition of & Measuring Creativity

It is inevitable that this research will ask the question, "Can we measure creativity?", because the success of this research can be measured by the increased creativity of the user.

The related research questions are:

- RQ1: What are the primary factors that drive people's creativity?
- RQ2: Is the person's creativity increased in the process of using this [method, tool]?

Historically, there are two definitions of creativity: personal creativity and historical creativity, as stated in *Artificial Intelligence* [13]. In defining personal creativity, the emphasis is on the individual value assigned by the owner of the creation, whereas historical creativity focuses on the novelty of the work. Even if the consumer of the end product may not think of the work as creative, the work is, in fact, as creative as the creator feels. Interestingly, this discussion circles back to the introduction of this dissertation, the direction in which we want to advance the technological development of robot *creativity*. To reiterate, the first step is programming the robot to mimic people's work in order to perform its own creative work (AI). The second step, as I previously discussed, is developing the agent robot to be advanced enough to aid in people's creative exploration (IA).

As I give much more value to the IA in the development of intelligent collaborative machines, it is critical to that humans maintain their influence and control over the machine's operation. Once the robot has taken away the authority of the work and the designer is under the robot's control, the results may not fully reflect what the designer had *intended* to do; thus, that work can no longer be said to be a valuable (personal) creation of the author. Similar to an article written by a bot versus one written by a human writer, readers (consumers) may wonder about the objective description of the situation, and will also wonder how diverse people will interpret the same situation differently from various points of view.

While the bot could be better at being objective, we as readers still long for stories written by the human hand. There is an eagerness to consume creative narratives, just as there is an eagerness to produce stories by those who express their creativity through their writing. My goal here is to support those who wish to continue to create but with the addition and assistance of intelligent machines. Only this way we are able to guarantee that humans and human factors will continue to affect the development of future technology, and not to diminish or replace people by automation and robots as we concern.

To measure the success of my research, it will be important to measure a novel system that nurtures people's creativity from creators' stand point. For several decades now, there have been long research discussions around how to measure creativity in various fields. In field of literature for example, researchers tried to measure creativity, particularly when assisted by computing systems, by measuring *Autonomy, Intentionality, Valuation, and Consciousness* [88], *Transparency, Control, Quality, Agency* [109], and/or *Flexibility, Guaranteed Success, Ownership & Achievement*. Following this precedent, I will measure people's increased creativity with an agent's help by measuring:

- **flexibility** to express ideas,
- level of **achievement** of executing the design intent, and
- **ownership** of the final product,

These should be also tested under the critical condition (which also needs to be measured) that users do not lose their *original intentionality and autonomy* over the robot's operation. It will also be critical to measure whether increased creativity is brought about by a robot's assistance and/or without any significant causal effects.

6.3.4 Future Outlook: Investigating AI's Role and Engagement

Depending on the goal and type of task, people may seek different levels of engagements with AI. As described in this dissertation, I have focused on the process and needs of people's creativity, aided by machine assistance. Regardless of the type of creativity, whether personal or historical, creators want different results from every single creation (novelty) to which they can assign values.

Nonetheless, it is also true that even in the creative process, there are many tedious and manual tasks that people do not want to take on anymore. When the goal of a task is iterating the same process as exactly as possible over and over again and to produce identical items every single time, the expectation on AI or automation's engagements would be higher as it does not require the owner's distinctive intentions nor their stamp of ownership.

Thus, one interesting future research effort would be to collect the type of tasks and to classify them based on the level of required engagements with AI. This will be a useful resource to understand the appropriate level of AI investigation, for developing decision algorithms to support users' activities.

6.3.5 Theoretical Expansion: AI's Fairness and Transparency

Another promising pertinent research direction is to consider AI's role in group settings: AI's fairness and measure how it affects people's creativity in group work. People frequently put together their efforts in a team to achieve common goals throughout the creative explorations, especially in finding a new solution to design problems. As advancements in robots with various applications continue, improving collaborations between humans and robots has been a lively topic of debate among researchers. Malte et al. further suggests variations in the human-robot teaming structure, where a robot can serve either as an agent or a boss [44, 54], with interesting possibilities in involving robots with its unique benefit (e.g., being objective) in group work. In either case, we can pose questions associated with ethics and its governance. There are two main research questions to ask in this direction:

- RQ1: How does biased AI's fairness affect group creativity?
- RQ2: What are the key aspects needed to enhance AI's transparency for future collaborative robot development?

For the first research question, I ask the following subsequent questions to examine its effects: *"When a robot agent is likely to support one person's decision over another's in a collective work, what is the reasoning behind that decision?"* When two designers' decisions conflict, I hypothesize that there are two underlying logical reasonings that are based on (1) technical ramifications vs. (2) stylistic ramifications. If it may also affect agent robots' support for their creative decisions, what should the robot's responses be in order to not disturb both participants' creativity?

For the second research question, if it becomes clear that the agent's decision is not based on the quality of creativity but is rather based on technical or practical reasoning, it is viable that the member of the group is not offended by its decision. In that case, the member can still stay vocal for expressing their ideas for exploration, seeking practical assistance from agents to overcome technical obstacles. To make this happen, it is critical to make the AI's algorithm more transparent so that people can understand what is happening behind the scenes. The task for researchers is to develop the machine's interface to provide more hints about its underlying algorithm.

Regarding the transparency of an AI algorithm, currently, autonomous vehicle services (e.g, Uber, Lyft) *hide* why a certain passenger is assigned on the way to the original destination, whereas other passengers are not, making drivers feel that they are unfairly treated by the system, or simply put, the system is ignorant. Through research into AI technology, we can show these companies how to improve their interface for drivers to be more transparent. For example, the interface could show the shortest paths and maximized earnings by adding a passenger on the way, to provide an option for choosing passengers based on the distance to travel, proximity to the driver's next destination, etc., thereby assisting with the driver's own decisions. My goal is to develop advanced user interfaces for people who are coping with machines and systems, and principles to improve user interface designs as even wider implications to support HCI researchers in this domain.

6.4 Conclusion

In this dissertation, I investigated how human factors affect the development of future digital fabrication machines as an intelligent design partner to form a collaborative partnership between humans and machines. People's ideation processes necessarily take time to develop until they are expressed in visual or tangible form. Speaking, writing, and making are all parts of the creative process and help people stay in loop to get what they want in the end product. They need physical workpiece to validate whether this work-in-progress fits their original idea and to evolve to a final artifact throughout improvisation and moment-by-moment decisions.

I envision a future where machines and humans seamlessly communicate to exchange information in a creative process towards a common goal. I believe AI will helping people to make better design decisions on-the-fly and to be more creative in their critical *thinking-by-making*. In this way, humans and machines will evolve to the future where they complement each other as partners; humans can continue with tasks that they excel at, while machines will keep evolving in the direction where they can assist people with tasks they inherently perform better.

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Appendix A

Kinemaker Gearboxes Implementation

Kinemaker gearbox designs are available for reusing and reengineering in CraftML (`https://craftml.io`). While these can be searched by typing *Kinemaker* from the top search bar, here I provide direct links to gearbox modules.

- Jumper `https://craftml.io/4keqX`
- Bevel gear `https://craftml.io/VJlTc`
- Angular wheel `https://craftml.io/4JEfn`
- Double Angular wheel `https://craftml.io/V1Omb`
- Double cam `https://craftml.io/N1wgo`
- Cranks `https://craftml.io/41cOf`
- Swing lever `https://craftml.io/VkxmZ`
- Slider `https://craftml.io/N1n5p`

Appendix B

Fitmaker Modules Implementation

Fitmaker adjustable modules are available for reusing and reengineering in CraftML (`https://craftml.io`). While these can be searched by *Uncertainty* from the top search bar, here I provide direct links to modules.

- Length Adjustment `https://craftml.io/OQ0S2`
- Angle Adjustment `https://craftml.io/CNWyR`
- Radius Adjustment `https://craftml.io/VhnOr`

Appendix C

Opensourced Code From Dissertation

I have open-sourced the code for the Compositional 3D Printing (available under the MIT License) on my github project repository: `https://github.com/qubick/HFI-controller`. Note that this software platform is based on research code, at the time of publishing this document, I have not fully cleaned and documented them for easy and straightforward use by others.