Shall We Fabricate? Collaborative, Bidirectional, Incremental Fabrication

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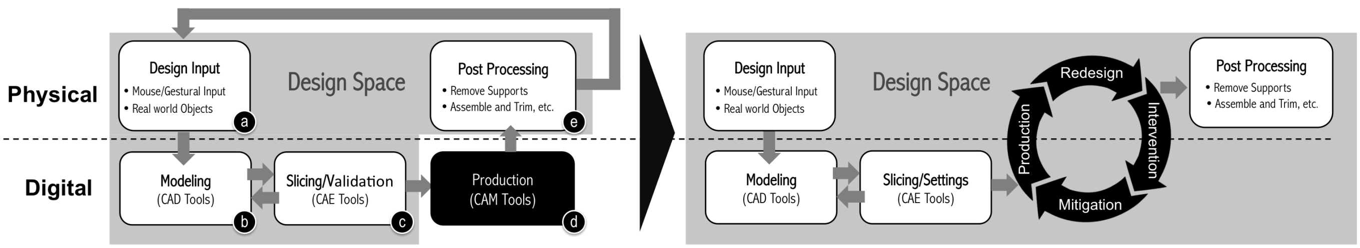

Figure 1. The current fabrication pipeline consists of a) initial design input b) modeling c) processing d) manufacturing by machine and e) post-processing. This linear process makes the production of artifacts solely the domain of machines (left). The new fabrication pipeline allows users to interactively participate in the production process in collaboration with the machine, which supports the designer's decisions with live input (right).

ABSTRACT
The recent emergence of digital fabrication allows everyday designers to make, deploy, and enjoy their creation. However, the excitement over digital fabrication presumes that users have sufficient domain knowledge to create complex models by understanding the underlying principles, can be self-creative without computational supports. This paper presents a new fabrication framework that lowers the boundary of solving everyday issues with fabrication. A formalism and accompanying finite state machine (FSM) model that help assign a fabrication machine intelligence to appreciate humans' design actions was proposed, with a view towards a new fabrication framework empowering collaborative, incremental fabrication. Empowered by the novel framework, this paper envisions a future of fabrication that pushes the ceiling, a collaborative fabrication, processing intermittent, unpredictable events as live input and reflect them in the emerging outcomes by co-design process between a designer and a machine.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): Interaction styles

Author Keywords
Computer Mediated Design; fabrication; creativity support; emerging design.

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INTRODUCTION
Personal fabrication is an emerging field, amalgamating the power of computation and operating humans' intuitive, creative design decisions for human/machine collaboration. The burgeoning of online sharing communities such as Thingiverse and GrabCAD invited users to not only produce pre-designed objects, but also remix and recreate own design. It lets them augment existing things and adapt constraints from the real world to their design. Although a wide range of digital modeling tools is available for users with different skill sets and interests, and despite the fact that they to some degree help novice users to customize opensource models, these tools divorce the process of design from the process of manufacturing (figure1 left). There are definite gaps between a virtual model created with digital design tools and a physical model constructed by fabrication machines since a designer is detached from the pipeline while the machine is producing the outcome.

Current digital fabrication algorithms do not provide channels through which users and machines can iteratively communicate throughout the entire pipeline. It is near impossible for them to be collaborative and to generate the final outcome together, dealing with ambiguity of the initial design, partial outcomes with on-the-fly techniques discovered from the process, and changing design mind. Without the means to engage human users into the manufacturing process, users cannot respond to the artifact as it is being fabricated.

I propose a new fabrication pipeline that focuses on an iterative and incremental process that invites humans to participate in the entire fabrication pipeline including manufacturing (figure1 right). With live and organic interaction, this new framework lowers the barrier for any user without domain knowledge to reap the benefits of fabrication and to augment things they own. I define a finite state machine model of a fabrication process, where a machine can take any physical input at any arbitrary time to process it, to reflect the live events in the final outcome. My vision is to allow users to express themselves with fabrication machinery and control the entire process through organic interaction, enabling a machine to adapt such physical input in real-time. I envision a future for fabrication that further pushes the boundaries, by expanding the design space offered through unpredictable design activities and nature as inputs.

FABRICATION THAT REMOVES THE BOUNDARY

My work aims at removing the lower/upper boundaries that current digital fabrication sits across.

Lowering the Hurdle

Digital fabrication should get rid of the requirements for a user to have sufficient skills. A non-expert user should be free from any implicit prerequisites in domain knowledge. Such demands users are required to have include, computer graphics to understand how a 3D model is manipulated, (i.e. data structures, meaning of meshes, relations to volume and shape), mechanical engineering to consider constraints and principles (i.e. clearance, center of mass, component interaction), or material engineering to understand the properties of elements used in the fabrication (i.e. viscosity, elasticity, adherence), and so forth. These factors are best handled by optimization algorithms and computations, whereas users do not necessarily need to manually associate with their conceptual design. Once users have the flexibility to embody their design thinking into their live interactions, machines need to understand what designer's intentions are and to process these into manufacturing.

Pushing the Ceiling

Collaborative fabrication should extend the range of viable applications particularly regarding material, scale, and place. Current fabrication systems limit the type of usecases, mainly process one material at a time, be kept within a desktop size, and operate indoors. Although restraining fabrication machines to a uni-material process in a laboratory setting saved cost and reduced the risks, human creativity is curbed by such limitations. The creative nature of humans' desire to utilize a variety of materials, employing a broad range of tools and to explore functions anywhere they want to deploy the fabrication target. By removing limitations, the expected artifacts could break the shell that confining the size, type, and place of creation.

AUGMENTING EXISTING ARTIFACTS

My work has been in augmenting various existing objects, focused on lowering the barrier for novice makers to realize that the benefit of digital fabrication. My augmentation target objects include 2D visuals, off-the-shelf 3D models, flat physical interfaces, and everyday objects. In the real world, nearly everything is built on something that already exists; also users often do not start a design from scratch. Augmenting existing object involves initiating a design process based on existing things, adding a new value to them. Augmentation is the means of binding a virtual model to a physical product. Users want to find a solution for issues that arise in existing things, for example, a sliding door without a handle, an inaccessible door knob, and flat control panels on common appliances. Fabrication is a great approach to address the challenges that arise in everyday life with the objects users own [1]. Augmentation fills the gap between the physical world and the desired features, meeting the challenges using existing solutions by tweaking a small part of a current solution. This translates additional information and functions from one source to the other.

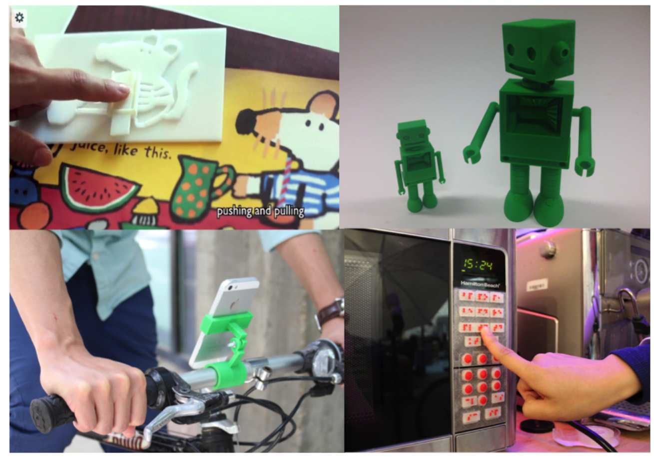

Figure 2. Fabrication is a great approach to augment target objects that exist in the physical world, for example, a 2D interactive pictures, off-the-shelf models, flat interfaces, and everyday objects.

Interactive Tactile Pictures

My first exploration in augmentation started from transcribing and augmenting 2D flat pictures in children's book into 3D printed tactile pictures [5]. Experimenting with a wide array of aspects that affects the tactility and moveable parts in hundreds of picture books, I prototyped a set of mobility primitives that encapsulate various tactile aspects. This helps users in remixing 3D objects with a parametric 3D modeling platform that I developed to facilitate the process.

Off-the-Shelf Models

Novice users often reuse and remix off-the-shelf models to customize. Thanks to the boost given by online communities (i.e. Thingiverse, Instructables), there are a million 3D models downloadable with only a few clicks. However, modifying them to have new features, especially kinematics, is still hard; as long as the target models are not optimized to embed gear systems in them. Even with individual gear parts, virtually fabricating them in the right place so that all teeth are interlocked, but without conflicting with the existing volume, also considering the printability of construction, is at near impossible for novice users. I implemented a parametric system and a library of complete gear mechanisms for end users, to enable them to freely combine multiple gear units, extending movements like LEGO blocks and to explorer open-ended construction of kinematics. The construction of a gear system can be embedded in any passive off-the-shelf 3D models. The tool is available as an extension on the opensource 3D modeling platform craftml(https://craftml.io).

Flat Physical Interface

I augmented flat physical appliances with tactile overlays to address common accessibility issues [2]. The system allows a blind user to take a photo of control panels and use computer vision to retrieve the actual size and shape, if there is any distortion. The image is then sent to a crowdsourcing platform to label spatial and textual information. Our user study showed that a blind user can independently 3D prints the overlay and attaches tactile buttons onto the original appliances.

Everyday Objects with Uncertainty

The primary challenge in augmenting the real world stems to its uncertainties. The individual has different constraints in their unique objects and finds various needs. Despite the precision and speed of computational tools, they do not project original specifications onto the digital design tools. Based on our studies to understand uncertainty issues in measurements to identify the physical dimension of an augmentation target, I defined a series of design principles and a parametric tool that addresses uncertainties from measurements in adaptations [3]. Users who want to solve challenges relating to things they own do not need to discard the current solution, or discard a newly printed adaptation in wrong size or distorted dimension because of various uncertainties, they only need to tweak small parts to adjust to a new solution at once.

ASSIGNING INTELLIGENCE TO FABRICATION MACHINE

From previous research, I have learned that a virtual model made in a digital design tool creates a gap with a manufactured artifact. Unlike conventional creative processes, where the physical creation process is the design action itself (i.e. ceramic throwing, sculpting, etc.), the production phase is detached from the design phase in current digital fabrication [4]. Once the fabrication machine starts the physical creation, a designer often loses his control to change, revoke, or modify the process when an unexpected event happenes. To interpolate the gap, the human, as a designer, and digital fabrication machines must exchange their work-in-progress concurrently, communicating with each other seamlessly, allowing for both to be a designer and a producer at the same time during the gradual production.

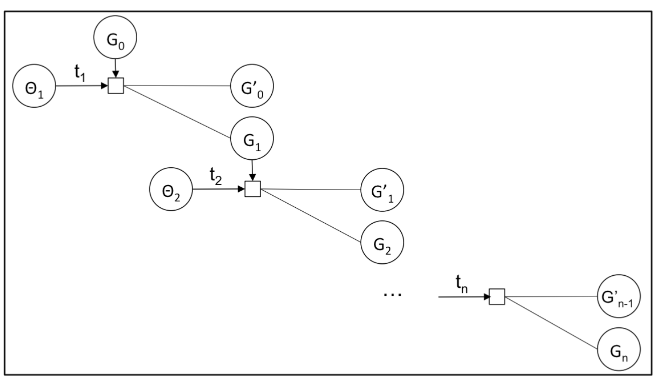

Figure 3. A state of manufacturing is characterized by the number of interventions (Θ_n), and the timing of each intervention (t_n). The system takes the previous state and outputs the combinations of parts already printed (G'_{n-1}) and subsequent parts to be expected to be printed (G_n). At current time t the final outcome is formed by $G'_{n-1} + G_n$ if there is no more events.

Current fabrication machines are passive, an inactive manufacturing machine, executing commands sent to CAM tools. To fully accomplish a collaborative, bidirectional, incremental fabrication pipeline, a designer and a machine should be aware of the current state of the model, which non-linear events occurred, and what effect is created from the intervention at that moment. Facilitating a human to do what s/he does well as well as a machine to do what it does better, leads the fluid turn-taking during this collaboration. The first step is assigning a machine intelligence to understand a physical action as a co-worker. It requires a function that projects human's design activities translated into parameters for machine computation. The function enables designers to apply on-the-fly design actions emerged from an initial design thinking at any arbitrary time, incrementally infusing changed design choices and new discoveries into the physical fabrication process.

My ongoing research focuses on developing a formalism that abstracts handcraft practice in mathematical form, interpreting it as input into a machine's operation to generate command to execute. Developed with a finite state machine (FSM) that projects this principle, an algorithm controls the machine commands in two division, pre-manufactured and to-be-manufactured parts of model. The latter is open for ad-hoc input event at current time t, to reflect changes.

Figure 2 shows the state transition based on the human's direct physical input, changing the final shape of the fabrication outcome. In this state machine, the digital fabrication machine is not a passive command executor, but becomes an intelligent machine listening to external events until the execution command (G_n) queue at current time t is empty, to process for the next manufacturing. When external event Θ at time t is projected as input, the state machine updates jobs remaining in a task queue, regenerating commands to be executed after time t_n to reflect changes. At a time t_n, when the nth event occurred by a designer, an expected outcome is made up of machine commands that execute G'_{n-1} (already printed part of model) and G_n (newly generated by physical input Θ). If there is no more design action occurs at current time, the combination of machine execution commands ($G'_{n-1} + G_n$) will form a final outcome. On the other hand, when an additional event occurs after time t, the task remaining in a job queue (G_n) is repeatedly divided into several different phases, forming an incremental outcome relying on the event.

By encapsulating physical dynamics and humans' design actions into the numeric form, machines can understand human interaction as an input that needs to be processed in a computation. Real-time input, abstracted in mathematical form, is later transferred to the manipulation language. By doing so, a machine can handle human interventions aimed at applying their design action to the current state, generating the next commands to be executed in a job queue, excepting what has been already been produced.

Creating a Communication Channel

This formalism and the finite state machine model catalyzes the collaboration during the entire fabrication pipeline between humans and fabrication machines, since a human can always interrupt a production and adapt their ongoing design actions by the help of machines. A machine processes an event during this interruption to apply changes to the emerging outcome. Defining the finite state machine for a modern fabrication machine and identifying the algorithm to explain the transition function between the states opens a communication channel between human and machine. It is the first attempt to augment machine capabilities to realize human intention and behavior, in real-time. Assigning intelligence to a fabrication machine in order to handle the virtual model and physical actions in computation turns this machine into a proactive collaborator from just a passive piece of machinery.

In addition, a machine equipped with the intelligence to handle humans' design action as computational input enables researchers to explore a design space of the fabrication technology. Researchers will be able to design various interaction techniques and find new applications by differentiating the type of physical input Θ and by implementing techniques that a fabrication machine can understand this Θ to extend machines' capability, using modern technology (i.e. computer vision, sensor network, crowdsourcing platforms).

AUGMENTATION IN-THE-WILD

Based on previous findings, I will focus on pushing the boundaries of the fabrication in the future. My ongoing research defined a new fabrication pipeline such that the input is not definite at the design time, but rather incremental, continuously affecting the model manufactured by a digital fabrication machine. The finite state machine model proposes an interaction loop that changes the provisional outcome at the moment. Now, a machine is ready to handle unpredictable, ambient input from nature, augmenting nature by fabrication.

Figure 4. Incremental fabrication enables designers also to augment nature with its ambiguous, unpredictable natural inputs. For example solar energy, birds' nesting behavior, growing pattern of grass, the direction of wind, etc., change over time. *Images retrieved from Thingiverse & Instructables

Nature as Input to Transition Function

I hope to develop the framework to extend the fabrication for creating augmentations with nature input. We not only live with the existing artificial objects, but also live in/with nature. Organic inputs from nature are ambiguous, nearly impossible to predict at the initial design time. For example, solar energy and the thickness of the tree (figure 4) will gradually change over time, and the requirements for these nature deployed objects' designs might need to be adjusted. Ambiguity is innate in all of nature, and humans' design actions also change the final outcome in the moment. My goal is to define a computational tool that (1) takes natural input as an discrete/continuous event Θ_1 at any arbitrary time t, (2) provides an interface with humans to make design decisions $_2$, and (3) produces the next augmentation module for incremental fabrication according to the analysis of redefined requirements, ongoing constraints, and deployed parts.

Fabrication at Scale

Incremental fabrication allows fabrication at scale, by adapting gradual input whenever event occurs. Future fabrication would not complete at once. Humans' on-going design should be supported by an optimal solution generated by the computation. At present, the primary goal of advances in the fabrication technology is to reduce the size of machines, which makes fabricating objects in scale hard. Users desire to build objects to scale, necessarily gradual, fusing common materials and existing objects on-site. Intelligent computation can aid this process by generating a proxy, which stays during the assembly process as a scaffold. A computational algorithm will generate the proxy structure with ad-hoc material attachments, reducing potential negative impacts when attached. The computation will facilitate constructions of the best form, best interaction models between components, required force, etc., that are all embedded in target design. Users will be able to fabricate large-scale constructions over time that are aesthetically appealing, functional, and mechanically stable.

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