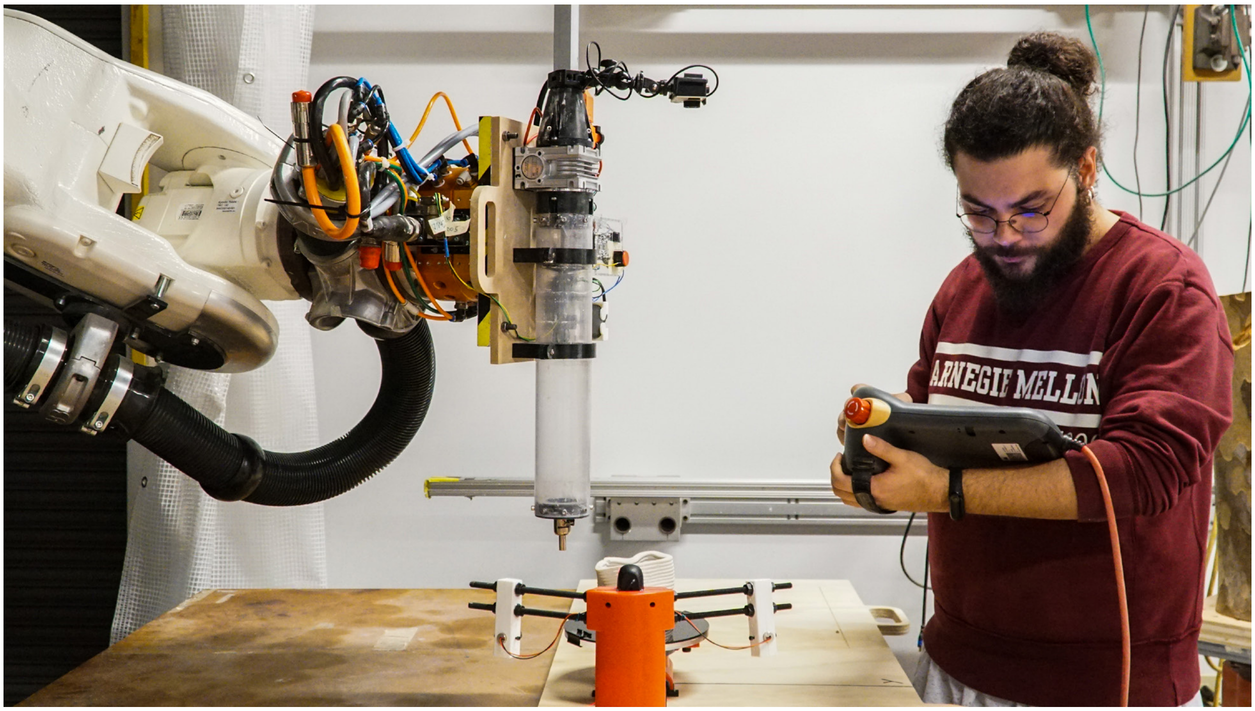

CAM as a Tool for Creative Expression:
Informing Digital Fabrication through Human Interaction

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Abstract

Although design as a profession often deals with material artifacts in various scales, the role of the designer has long been defined to be highly conceptual and immaterial. This distinct definition constitutes the basis for today's design workflow, in which designers are mainly concerned with the representation of the design through drawing and not so much with its materialization through making. Even though the introduction of computer-aided systems enabled faster and more accurate fabrication and representation tools, these systems are far from capturing non-linear and complex design workflow, and the fundamental model of interaction remained the same, merely replicating a more capable drafting board. Building upon precedents in adaptive and interactive fabrication methods, this thesis proposes a design-fabrication workflow where users can actively manipulate the fabricated artifact within design-fabrication workflow. This geometric manipulation can be captured using computer-vision based feedback loop to inform digital representation. By introducing a feedback loop, the proposed workflow captures design intentions introduced by the user using basic geometric decomposition and reconstruction algorithms. Using the updated digital representation, the proposed system can adapt and extrapolate future tool paths to continue fabrication and offers a design hypothesis for the user to evaluate, presenting a range of geometrical potentials. By doing so, this thesis argues that active engagement with materials can enhance creative freedom and inform design decisions, and that creative human agency can coexist along deterministic machines to facilitate creative exploration through making.

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To my mom, Serpil Çapunaman,

and my dad, Yücel Çapunaman.

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1 Introduction

1.1 What is at stake?

Even though design as a profession often deal with material artifacts in various scales, the role of the designer has been long defined to be highly conceptual and immaterial. The distinct dichotomy between mind and body, crystallized in the Renaissance era by Leon Alberti, helped shape the basis for most of the contemporary design workflows which we know today and where the primary concern of designers is the fabrication of the representation (Carpo and Davidson 2011). Based upon Aristotle's hylomorphic ontological understanding of materiality, this definition of the role of designers has been undermining the materialization in the design process, assuming that materials are inert recipients of form. As we are professionals who deal with material artifacts, this alienation from the matter itself creates a gap between our understanding of materials and imposed forms, which in turn constitutes a challenge to computer-aided design workflows.

The above definition of the role of designers and the *hylomorphic* model of material causality has influenced the progression of new technologies emerging in the field of design (DeLanda 2001). Following the successful research efforts in automating the fabrication process starting from the 1940s, Computer-Aided Manufacturing (CAM) and Design (CAD) tools focused on liberating designers from arduous tasks of design, echoing Albertian definition of *skilled craftsmen* through the idea of computational tools as *perfect slaves* (Cardoso Llach 2015). Even though such efforts enabled faster and more accurate fabrication, CAM tool implementations are deterministic, minimizing ambiguity and discoveries that inform design decisions, and highly generic, failing to capture vast possibilities of computation in design. What initially started as an aspiration to develop a collaborative partner to a human agent, soon was proven not able to capture and codify the informal and often subjective design process (Negroponte 1975). Further studies following the initial success of such systems shifted the course of Computer-Aided Design (CAD) and Manufacturing (CAM) from creative endeavors to representation-oriented implementations (Cardoso Llach 2015). Design as an increasingly digital practice, loosening its ties with materiality with the introduction of highly engineered materials, neglecting the need for building material knowledge. Even though non-linear nature of design workflow intrinsically allows for designs to evolve and be refined through the process, streamlined processing of data within these computer-aided systems, from digital representations, to intermediary machine-codes, to digital fabrication tools and to material limits the users understanding of the potentials and shortcomings of the tools available to them (Cardoso Llach, Bidgoli, and Darbari 2017). Within the scope of Computer-Aided Design and Manufacturing tools, this thesis starts with examining influential milestones within the history of design and elaborate on how these paradigm shifts affected the subsequent developments in the field of Computational Design.

1.2 Why is it important?

In today's context, the majority of computer-aided systems fail to match up to the nonlinear process of design and to bridge the gap between idealized digital representation and physical artifact. Many fields of design across different scales are increasingly adopting these tools. However, how materials are implemented into these systems cannot go any further than a mere visual representation of graphical texture. Furthermore, due to intrinsic highly structured algorithms that these tools employ in their implementations, designers are often required to design with the computational constraints in mind and pause the design process in its linear processing of information to produce a physical representation of the design idea.

Moreover, the goal of developing a streamlined system that aims to encapsulate different stages of design poses another level of limitation. Such computer-aided systems that allow the user to process a design idea from representation to fabrication, often fail to capture the complexity of the design process throughout the different phases of the design workflow. The approach to developing a single system to address varying levels of complex tasks undermines different roles of designers within these workflows and limits the opportunity to discover inherent potentials and limitations of the tools employed in the design workflow. These inherent implementation problems of computer-aided systems implicitly constrain the design space without users, especially non-experts, realizing the consequences.

This thesis addresses two significant drawbacks of contemporary Computer-Aided system implementations within the scope of creative and exploratory inquiries, illustrated in Figure 1. The first one is the problem of (a) *unidirectional processing of information* within these computational pipelines. Especially Computer-Aided Manufacturing tools heavily rely on pre-processing of algorithms and limit users exploring the design space, due to lack of human-machine interaction after parameters are set and necessary computations are carried out. This problem results in inflexibility to reflect and iterate on ideas quickly within the fabrication process and increasingly excludes the human agent from the process altogether. Moreover, contemporary computer-aided systems often fail to adapt to complex design problems, which constitutes the second major drawback of these systems. Although implemented algorithms provide robust methods for fabrication of the artifact suited for either additive or subtractive manufacturing, these methods are often (b*) generic solutions to complex geometries*. The implemented algorithms are optimized for the fabrication machinery instead of appropriating fabrication method specifically to the designed artifact, which limits types of geometries that can be fabricated by specific computer-aided systems. As tools used daily by design practitioners, these shortcomings are essential in defining the role of the contemporary designer in the age of digital tools. This thesis directs the question of "How can digital design-fabrication workflow be informed to facilitate creative exploration through embodied interaction?" to the contemporary computer-aided systems.

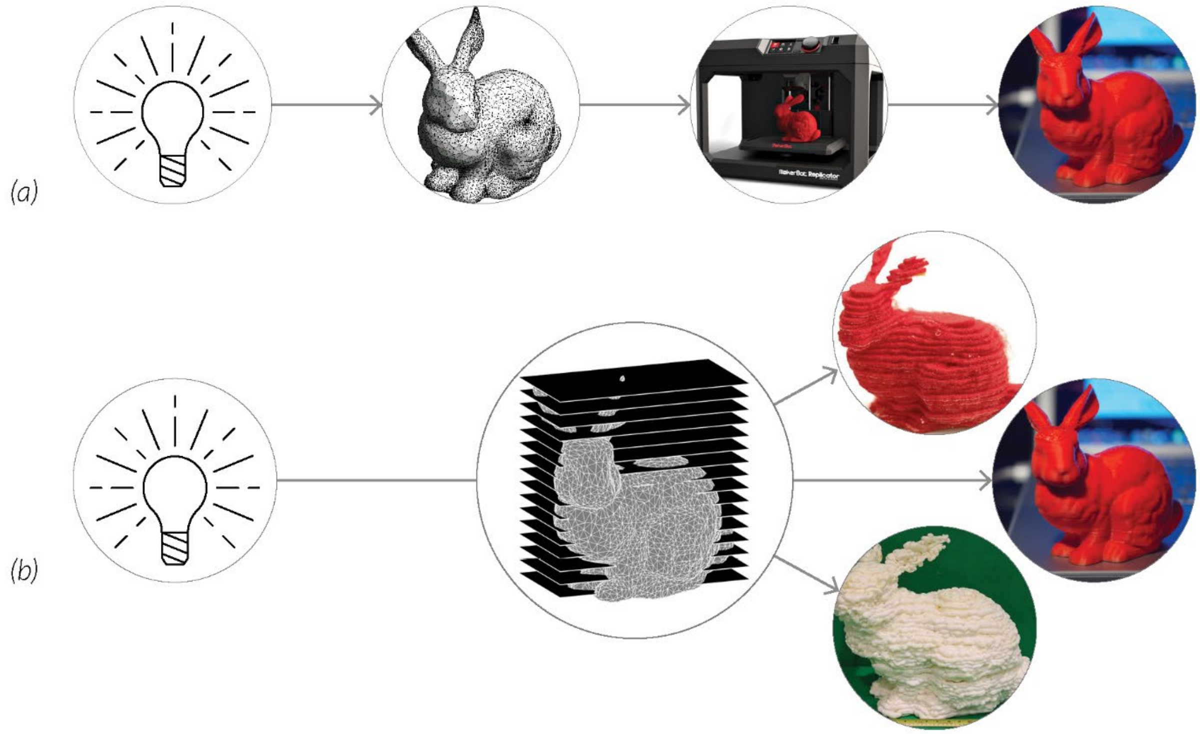

Figure 1. Shortcomings of Computer-Aided systems discussed within the scope of this thesis. (a) linear processing of information, (b) generic, cookie-cutter solutions.

1.3 What is proposed?

This thesis proposes an interactive and adaptive design-fabrication workflow and its basic implementation where users can actively manipulate the object at any given moment during the fabrication process. Utilizing the turn-taking approach, in which human and machine agents take turns in executing tasks, to facilitate interaction between human and machine agents, the proposed experimental setup offers insights into how Computer-Aided tools can afford creative exploration. Throughout the proposed design-fabrication workflow, human and machine agents take different roles with varying levels of contribution to the design and fabrication of the artifact. Through this turn-taking approach, this thesis aims to explore computer-aided systems beyond as sole algorithm executers and instead as flexible facilitators of digital fabrication, capable of incorporating changes in the artifact and adapting accordingly throughout the process.

Within the scope of this thesis, a mechanical paste extrusion system is implemented to enable numerically controlled fabrication, materializing digital representation into a physical artifact. Similarly, Laser-Stripe Triangulation Scanning technique is used to capture the physical artifact being fabricated to inform digital representation. By capturing geometrical information from the physical artifact, this system conveys design intentions introduced by the user through hands-on physical interaction, using primary geometric decomposition and reconstruction algorithms. Using the updated digital representation, the machine agent can adapt and extrapolate future tool paths to continue fabrication and offers a design hypothesis which can be evaluated and tuned by the user, presenting a range of geometrical potentials. In terms of the model of interaction. This reciprocal transfer of information between human and machine agents through the physical artifact informs digital representation throughout the design-fabrication process. This thesis argues that introducing systems detailed above into CAD and CAM workflows provides active engagement opportunities with materials which can enhance creative freedom and inform design decisions, and that creative human agency can coexist along deterministic machines to facilitate creative exploration through making.

The first chapter of this thesis provides the theoretical framework on the historical and contemporary discourse surrounding the role of designers, computers, and materiality within the design process. The second chapter introduces and reviews relevant precedents addressing the questions of interactive and adaptive fabrication from different fields such as Human-Computer Interaction, Architectural Robotics, and Computational Design. The third chapter introduces the hypothesis, describes the hardware and software development carried out for the experimental setup and details proposed workflow. The fourth chapter presents the results observed throughout the testing of the proposed workflow with the experimental setup, discussing the validity of the proposed experimental setup. The final chapter offers some conclusions drawn from the experiments, delineates limitations of the experimental setup and presents potential future improvements that can resolve some of the limitations faced in this thesis.

1.4 Theoretical Framework

1.4.1 Separation of the Mind and the Body

Early examples of creative individuals, architects, often manifested their ideas through bodily interactions with materials. The word origin for "Architect" can be traced back to ancient Greece, referring to the *master/principal* (*Archi-*) *builder/craftsman* (*-tekton*). These master builders were integral to both design and making when manual and intellectual labor were inseparable. They were amongst other builders in the construction site, guiding the construction on every step (Harvey 1974). Their presence in the construction site was very critical because they were not only highly skilled in materializing their ideas, but also verbal communication and hands-on demonstrations were the most effective medium for conveying their design ideas. This workflow allowed master builders to improvise and improve on the artifact during the construction phase, learning about the material and process through the act of making and most importantly have significant autonomy over the objects of their design.

The idea of master builder started to be devalued towards the Renaissance era. With the invention of perspectival representation shifting the focus more and more on representation (Pallasmaa 2013), the designer's role was destined to be redefined. The word *design* carries hints of this shift in our understanding of the role of designers, as the origin of the word can be traced back to the Italian word *disegno*, which means drawing. The transfer of design idea through drawings enabled tedious manual labor to be isolated from the design process itself. Furthermore, structured representational mediums allowed identical reproductions of many artifacts with higher precision (Carpo and Davidson 2011). The need for the master builder to oversee the construction to convey their design ideas was no longer valid, replacing master builders with drawings. This resulted in a new definition of designer, one who "represented their ideas for three-dimensional forms with drawings accurate enough to be executed subsequently by workmen." (Gürsoy and Özkar 2015, p. 30)

In the light this development, one of the most important figures of the era, Leon Alberti, proposed that “architecture was a concern of the mind” (Ingold 2010, p. 93), valuing immaterial labor of designing over arduous material labor. Alberti redefined the architectural design process into two distinct stages; *lineaments* and *structure* (Lang 1965). *Lineaments*, as described by Alberti, are a combination of geometrically well-defined and highly abstracted line and angle representations of the building. S*tructure*, on the other hand, refers to the construction of the building, imagined being handled by a skilled craftsman. This dichotomy constitutes a significant shift in the perception of the role of designers, where designers were alienated from materiality, resonating with the Western cultural perspective that values the mind over the body. Through his definitions of *lineaments* and *structure*, Alberti circumscribed a deterministic and more controlled approach to architectural design, eliminating ambiguity in the process of making beyond lineaments. What once was an improvisational translation of idea in mind to the matter on the field, became a well-defined and deterministic workflow.

Regarding his definition of lineaments, Alberti claims that “It is quite possible to project whole forms in mind without any recourse to the material, by designating and determining a fixed orientation and conjunction for the various lines and angles“ (Alberti 1988, p. 7). By defining the boundaries of design within the realm of the mind, he separates immaterial lineaments from the material structure. His abstracted representations of buildings became a vehicle to convey highly abstract concepts into physical artifacts that in return offer greater control and precision over the built artifact (Carpo and Davidson 2011) for the cost of losing emergent and rich ambiguity within the act of making.

Along with his approach to design as a concern of the mind, Alberti heavily echoes Aristotle’s deterministic imposition of form over matter, *hylomorphism*. His description of the design process from immaterial idea to the artifact implies a linear progression throughout. This proposed linear progression in design process heavily relies on the ontological understanding which values form over matter and assumes that matter is only the recipient of form, not capable of informing the form in any way. In combination with the proposition that design is an intellectual and immaterial activity, *hylomorphic* ontology, which entirely neglects materials' innate potential to be shaped, solely defines the role of the designer as form creators, definitively separating the act of designing and making from one another. Even though the role of designer described by Alberti changed in practice over time, this description constituted the foundation of contemporary design workflow significantly as it is evident from the lack of material integration in the design process and a heavy focus on representation.

1.4.2 The Mind, the Body and the Machine

With the advancements in computational technologies in the 1940s and onwards, computers became the topic of interest in the field fabrication and design. The shift in design medium from physical geometrical representation to structured digital representation required the development of various tools and algorithms to facilitate Computer-Aided Design and Manufacturing. This section detailing critical milestones in the history of computer-aided systems is based on meticulous documentation published by Daniel Cardoso Llach in his book, titled *Builders of the Vision: Software and the Imagination of Design* (Cardoso Llach 2015).

Contrary to popular belief, as noted by Cardoso Llach, the origin of Computer-Aided Design tools was closely interlinked with problems of materialization and was developed to ease encoding of Computer-Aided Manufacturing systems with the help of discrete digital representations (Cardoso Llach 2015). As a wartime effort to cut down fabrication costs and time these researchers at the Massachusetts Institute of Technology (MIT) were among the key proponents of the idea to automate machine tools to replace the human element in fabrication. The complexity of such a challenging task required the development of many crucial hardware and software components starting with the development of Computer Numeric Control (CNC) machines and codification of geometries for fabrication and followed by the theorization of mathematical representation of geometries in computational tools. Early discussion on this topic revolved around defining the role of the computer, Douglas Ross advocating for full automation of design and Steve Coons imagining computers as partners (Cardoso Llach

2015). Early attempts to fully automate design process failed as the attempts "to conceptualize and codify design into a single general routine proved less than definitive."(Cardoso Llach, 2015, p. 62), acknowledging the human factor in the design process.

Figure 2. Ivan Sutherland using Sketchpad, one of the earliest Computer-Aided Design system. Reprinted from Builders of the Vision (p.50), by D. Cardoso Llach.

Similar to Alberti's concept of *lineaments*, researchers envisioned Computer-Aided design tools to enhance human designers' capability to elaborate blueprints and define shapes in response to the need to codify geometries for fabrication purposes, which are highly abstracted and geometrically well defined. Echoing Albertian separation of mind and body, Steve Coons imagined computers as "perfect slaves capable of performing the dirty work of dealing with materials, whereas the designer or artist is free to concentrate fully in the creative act." (Cardoso Llach 2015, p. 64). As Cardoso Llach observes, with an assumption that materials are "passive recipients, instead of active participants of design," Coons' *perfect slave* enables a "seamless and automated translation from disembodied ideas into material objects" (Cardoso Llach 2015, p. 64), further delineating the influence of hylomorphic ontological view. With many apparent advantages of precision and efficiency that constituted the reasoning for Albertian separation (Carpo and Davidson 2011), Coons' ideal of *perfect slave* shaped our expectation of the role of computers in design and fabrication workflow, further widening the gap between the mind and body through computers.

1.4.3 Design via Computer-Aided Tools

As computer-aided systems are growingly taking over a wider portion of the workflow from idea, to representation, to the fabrication of physical artifacts, it is not possible to overlook advantages these systems offer to the designers. From precise control over the design representation to the seamless translation from the digital representation to physical artifacts, these tools satisfy the demand for precision and efficiency from various design and engineering fields. However, these tools still embody the distinct separation of the mind and body as these tools were intended by Coons to be *the perfect slave*, freeing designers from arduous tasks of the process.

The assumption in the computational design process that materials are inert recipients of design in mind constitutes a layer of barrier that complicates the incorporation of material knowledge into the design workflow. In his article titled *Philosophies of Design: The Case of Modeling Software*, Manuel DeLanda carefully examines the integration of materiality in CAD software (DeLanda 2001). Starting his observations from the most basic form of CAD, which is solid modeling, he observes that simple Boolean operations commonly used within solid modeling environments inherently embody a *hylomorphic* model, imposing form over *virtual materials.* Today, more complex computational representation of geometric primitives such as curves, surfaces and solids implementations such as Mesh and Non-Uniform-Rational-Bezier-Surfaces (NURBS) based modeling environments are at the disposal of designers. Although these representation techniques open up new potentials in computer-aided systems, It is hard to deny that the *hylomorphic* model of imposing form over matter is still prevalent, 'material' in the context of is still limited to graphical texture representation.

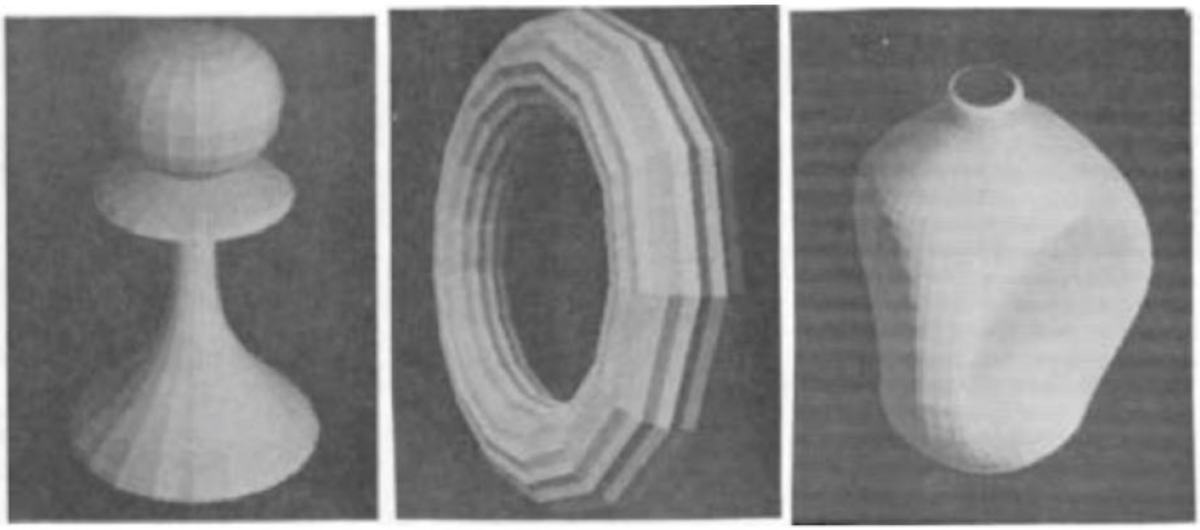

Figure 3: Early discrete representation of geometries. Reprinted from A Solution to the Hidden Surface Problem (p.449), by M. Newell.

Furthermore, another implementation bias in CAD and CAM systems is that often the algorithms integrated into these systems are highly structured, discretizing complex geometries to idealized mathematical representations and excel at linear processing of data due to procedural task execution inherent in computational systems. As a creative field of inquiry, the design process often processes readily available information subjectively. Vladamir Bazjanac, one of the early contributors in Computer-Aided design systems, notes that “few models used by designers in the design process are formal” and “information used in the design process always can be and usually is subjected to personal interpretation.”(Bazjanac 1975, p. 22) To demonstrate the challenges of codifying such informal models employed by designers, Bazjanac introduces an experimental setup, comparing results of two design proposals in response to the same design brief, one designed by human subjects and the other designed with the help of *Building Optimization Program* (BOP), developed by Skidmore, Owings and Merrill architecture company in 1971. As a result of this experiment, Bazjanac explains that both designs have exhibited desired characteristics as well as similar shortcomings in their proposals. However, he points out a critical outcome of this experiment which is that “BOP in fact limited the solution space to only one morphological type and discouraged exploration of any innovative ideas."(Bazjanac 1975, p. 23) Even though contemporary tools are more advanced compared to the algorithm developed back in the 1970s, it is clear that linear information processing model of computational systems lack the flexibility for design exploration and often limit the designer due to its highly structured representation model. Similar findings were also pointed out in later chapters by Nicholas Negroponte in his reflection to initial design task experimentations with Sketchpad system (Negroponte 1975).

In the light of such reflections on Computer-Aided Design tools, it is safe to say that discrete and deterministic nature of these implementations often fails to capture the exploratory nature of design-fabrication processes. Even though computational methods available in the field of design can provide a very rich and ambiguous design space, CAD and CAM implementations aiming to codify the complexity of the design process and different roles of designers throughout the workflow, and to streamline these systems to automate substantial chunk of design often narrows down the design space considerably, in some cases even down to one 'optimized' solution. In his thesis, Diego Pinochet categorizes the fundamental problems of these tools as the *generic operations* for non-generic and exploratory applications in the field of design, the *black-boxed implementations* that limit intervention to these algorithms to minimal levels, and the *creative gap* caused by linear processing of information inherent to computational systems (Pinochet Puentes 2015). In addition to these, abstract materiality hinted in these systems through visual 'textures' and highly streamlined nature of these systems which enforces discretization of information at each exchange between systems (eg. converting NURBS surface to a Mesh, slicing a Mesh to obtain polyline tool paths and codification of polyline tool paths into 3D coordinates) further constrain the design space. As these systems shifted the main focus of computer-aided systems primarily to representation and lately optimization, contemporary computer-aided systems are contradicting with the initial vision of supporting users of such systems in navigating and expanding design space through allocating arduous tasks to the machine.

1.4.4 Design Informed by Making

Within the widely accepted linear and discrete progression from form to matter introduced earlier, or *workmanship of certainty* as David Pye calls it, "the quality of the result is exactly predetermined before a single salable thing is made."(Pye 1978, p. 20) In other words, this process forces forms over matter. Within today's world of mass-production, the workmanship of certainty is necessary and valuable. It is hard to neglect the importance of workmanship of certainty which enables faster and economical fabrication as well as the accurate transfer of information. Since this workflow follows the *hylomorphic* ontology, inquiries into design problems are limited in incorporating material knowledge gained from the playful nature of making. In parallel to the creative and playful nature of making, David Pye puts forward an opposing approach on how we make things, namely *workmanship of risk* (Pye 1978). Different than workmanship of certainty, in the workmanship of risk "the quality of the result is not predetermined, but depends on the judgment, dexterity, and care which the maker exercises as he works" (Pye 1978, p. 20). Aside from aesthetic qualities of both types of workmanship defined by David Pye, the workmanship of risk embraces potentials of the process and materials. It allows other bodily interactions with the material world than highly prioritized *seeing* and *hearing*, opening up discoveries through uncertainties in the process. Similarly, DeLanda describes this conversational and open-ended process by defining the act of making as "acting more as triggers for spontaneous behavior and as facilitators of spontaneous processes than as commanders imposing their desires from above" (DeLanda 2001, p. 135). As a result of such conversational making process, final artifacts cherish these uncertainties.

Despite allowing for momentary creative discoveries on the representation level, the *workmanship of certainty* limits material uncertainties to a bare minimum. Diego Pinochet in his paper observes that "A designer cannot touch, feel or interact directly with the objects he creates; this moment of sensing, feeling and discovery is lost," referring to the representation dominated and unidirectional interaction workflow (Pinochet Puentes 2015, p. 14). Due to its top-down approach imposing form on the matter, Albertian model of design workflow does not allow feeding back insights gained through active engagement with materials and fabrication process easily. This approach to design workflow often executes the materialization on very late, if any, into the design process.

Contrary to the definitive approach in the *hylomorphic* model, a more "reciprocal way of making," as Pinochet refers to (Pinochet Puentes 2015, p. 15), would enhance the design process, incorporating these insights and explorations back into ideation phase. Pinochet's proposed model would allow designers to negotiate their ideas with material capabilities as well as fabrication limitations. In addition to utilizing insights gained in the design process, this nonlinear conversation would create a suitable ground for designers to discover new spatial relationships. Similar to how Stiny's computational theory of shapes exploits the uncertainty in the perception of shapes, to enable observers to recognize different shapes at each iteration (Stiny 2006), this nonlinear workflow could provide an opportunity to iterate on the design idea recursively.

Even though *hylomorphic* ontology suggests linear progression of the design process, Donald Schon defines designers behavior as a sequence of "seeing, drawing, seeing," (Schon 1992, p. 133) highlighting a reciprocal interaction throughout the design process in which discoveries and ambiguities inform design decisions. Schon observes that embodied the nature of design constitutes a fundamental challenge for computer systems. As sensorially deprived entities, computers are not capable of facilitating such embodied workflow. Instead, these systems excel at linear processing of information, which renders any attempt to intervene between stages of the design process impossible. Furthermore, in their 1983 article titled *Learning as Reflective Conversation with Materials: Notes from Work in Progress* Schon and Bamberger note that making, which is widely accepted to be cognitive and material, "involves coming to see in new ways." (Bamberger Schon 1983, p.68) During their experiments in which participants were engaged in the act making, they observed that subjects were "engaged in on-the-spot experimenting in response to the new phenomena they were discovering" and "conversing with their material." (Bamberger and Schon 1983, p.69) They argue for *knowledge-in-action*, as referred by the authors, in the process of making.

The context outlined above provides insights into how momentary discoveries can inform the understanding of a design problem through the act of making. This perspective on the role of making in design illustrates how engaging in a conversation with materials can enrich the understanding of the design problem and deliver understandings that are hard to gain through other means of communication. Contextual framework obtained from the body of work presented previously is essential in positioning this research within the broader context and defining the necessary implementations to facilitate the desired mode of human-machine dialogue.

1.4.5 New Materiality

Crystalized into the design process first by Alberti and echoed later by computational design visionaries such as Coons, Aristotle's *hylomorphic* model of creation still remains as an influential model of material causality, which intrinsically assumes that materials are inert recipients of the imposed form. This inert nature of materials proposed by the *hylomorphic* model can be seen today in how CAD and CAM systems represent material. In many examples, implementations of materials in these tools are either for visual purposes only or follow one predefined model of material behavior and are often represented by primitive geometries and neglect any intrinsic properties. This section further details the paradigm shift in our understanding of materiality based on the body of work published by Manuel DeLanda (DeLanda 2001, 2015).

This high level of material abstraction is far from reflecting the troubles of materiality. Organic and irregular materials, *anisotropic*, have been long known to cause problems for construction but even highly engineered and homogenized materials, *isotropic*, are not able to perform up to idealized representations. However a new model, namely new materiality, that transcends *hylomorphic* model of creation have been theorized starting from the late 1990s. Manuel DeLanda, one of the advocates of new materiality, reasons with this high level of discretization of materiality, noting that "the complex behavior of materials has been typically neglected and reduced to simple, routine properties." (DeLanda 2001, p. 133) Moreover, DeLanda exemplifies the paradigm shift regarding materiality by illustrating how science approached the discretization of materials: “The physics developed by Newton stripped materials of all their complexity and reduced them to "mass", while the chemistry which developed a century and a half later, dealt only with the simplest chemical properties and interactions” (DeLanda 2001, p. 133)

DeLanda, in return, proposes that materiality is more complicated than linear reasoning that Aristotle proposes. He claims that in addition to external forces’ capacity to effect, materials also have a capacity to be affected that defines their behavior (DeLanda 2015). This concept of material as an entity with inherent characteristics to be affected presents the opportunity to go beyond deterministic approach to materiality, hinting at a conversational making process in which materials can inform tools, techniques as well as design decisions and forms. This conversational materiality presents a valuable opportunity for designers to consider materials beyond textures and visual cues.

1.4.6 Human-Machine Collaboration in Today’s Context

As previously mentioned, the role of the designer is shifting gradually to a digital practitioner with the wide availability of computer-aided systems that can perform intensive computational tasks with ever-increasing computational power embedded in user-grade computer systems. This paradigm shift towards a digital practitioner inexplicitly requires a change in the vocabulary of these digital practitioners. As both CAD and CAM systems are becoming standard tools for designers, adapting to highly structured representation format that is imposed by these tools is integral to the digital design and fabrication process. Contrary to popular belief, these tools still are not capable of simulating complex design tasks as simulated in digital environments even though these tools are implemented to work seamlessly and offer high precision and accuracy. In their paper titled *Assisted automation: Three learning experiences in architectural robotics*, Cardoso Llach et al. offer a new perspective contrary to the trend of seamless implementations, on how ‘seamful’ interactions within the design-fabrication workflow can inform designers (Cardoso Llach, Bidgoli, and Darbari 2017). They point out the importance of human-machine dialogue in developing an understanding of the tool and the technique within the context of design education. As also noted by Cardoso Llach, the human-machine dialogue has been at the very essence of early vision for computer-aided systems (Cardoso Llach 2015).

Today the topic of human-computer interaction/dialogue is more relevant than it has ever been before. Scholars from different fields such as Cognitive Science, Computer Science, Human-Computer Interaction are building a new body of work on facilitating human-machine dialogue in creative scenarios (Suchman 2007; Candy and Edmonds 2002; Lubart 2005; Kantosalo and Toivonen 2016). Other than applied research exploring different means of interaction models detailed in the next section, many researchers are working towards formulating these interactions within creative scenarios. Even though a large body of work interested in the same area existed before, in their 2002 publication, Candy and Edmonds introduce the concept of *co-creativity*, mainly concerned to develop an extensive understanding of how agents in creative workflows participate and what types of roles machines can take on within such workflows (Candy and Edmonds 2002). Through their research, authors aim to delineate potential areas where computational intervention may support creative work handled by human agents, through three different case studies with varying complexity of creative tasks.

Though not definitive and tested extensively, in his paper Lubart classifies four different types of roles that computers can take over within a creative process; computer as a *Nanny*, computer as a *Pen-Pal*, computer as a *Coach*, and computer as a *Colleague* (Lubart 2005). Ranging from executing routine tasks we all are accustomed to, such as auto-saving and information presentation, to computers giving advice to the users or even contributing to the dialogue with new ideas, Lubart classifies different levels of computationally and socially complex challenges. Building upon Lubart's role definitions of computers in the creative process, Kantosalo and Toivonen analyze human-machine interaction on both system and agent level for their fitness for *co-creative* scenarios (Kantosalo and Toivonen 2016). Authors introduce *complete* and incomplete agents alongside *task-divided* and *alternating* systems. Since these descriptions on both agent and system level are highly interlinked they define *task divided* co-creativity as "co-creativity in which the co-creative partners take turns in creating a new concept satisfying the requirements of both parties" and claim that only complete systems, which are capable of defining their own concepts, can participate in such an interaction. On the other hand, authors propose that *incomplete* agents that lack the ability to define their own concept can contribute to *task-divided* systems, which is defined as "co-creativity in which the co-creative partners take specific roles within the co-creative process, producing new concepts satisfying the requirements of one party." (Kantosalo and Toivonen 2016)

If we were to categorize contemporary Computer-Aided Design and Manufacturing systems within these definitions, it is safe to say that all of the systems commercially available to end users operate in currently operate in *task-divided* modes of interaction with varying levels of complex roles these tools take on within the systems. In the light of the body of work exemplified above, we can conclude that contemporary computer-aided systems heavily rely on carefully orchestrated algorithms and computational constraints to operate. Though the available computational power is increasing exponentially, these systems are nowhere near providing "seamless" design workflow or encoding complex process of designing envisioned from the beginning of Computer-Aided era, and still, require manual interventions.

2 Background

There has been growing interest in facilitating conversational fabrication scenarios in Human-Computer Interaction, Architectural Robotics, and Computational Design fields. Current literature focuses on exploring novel interaction methods for real-time fabrication of physical artifacts through different means of interaction interfaces ranging from augmented reality assisted fabrication to integrate sensory feedback to inform the digital representation of the artifact. Precedents below often preserve unidirectional nature of current digital fabrication systems or and neglect potentials of hands-on exploration through material engagement but propose novel models of interaction with Computer-Aided Manufacturing and Design tools.

2.1 Real-Time Fabrication Through Interaction

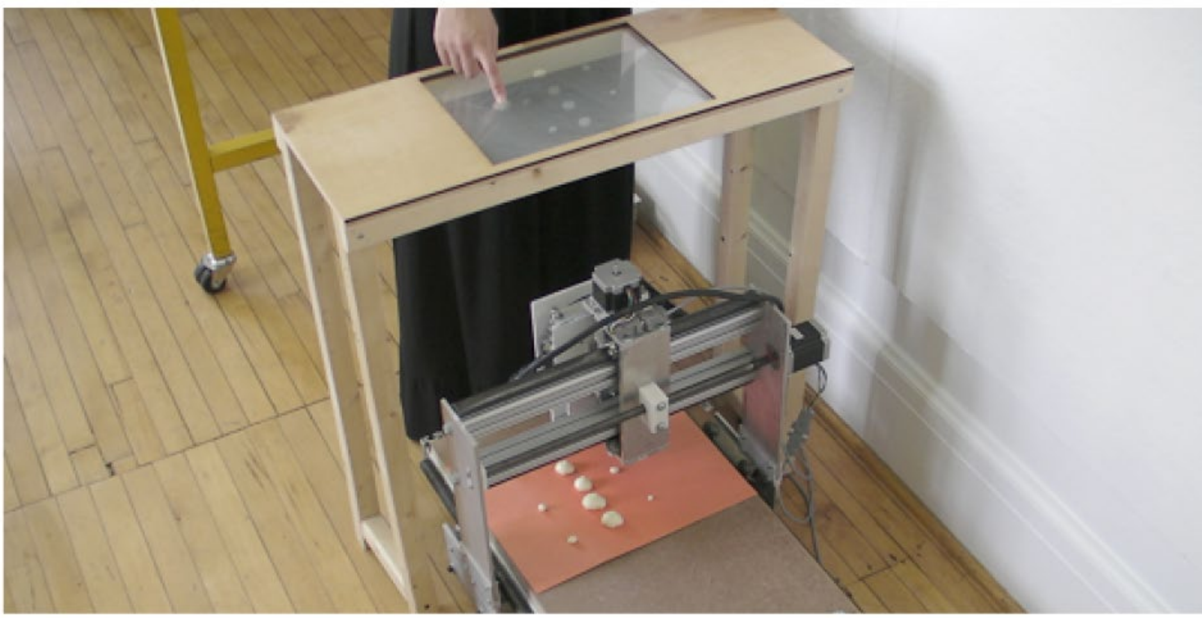

Figure 4. Fabrication using touch input from the user. Reprinted from Interactive Fabrication: New Interfaces for Digital Fabrication (p.80), by Willis et al.

Often cited for coining the notion of interactive fabrication, researchers in Carnegie Mellon University propose an alternative interaction method for controlling digital fabrication tools (Willis et al. 2011). In their paper, authors present three fabrication workflows that incorporate real-time user input to inform the CAM system and aim to close the divide between designer and digital tools through incorporating various means of digital interfaces and sensors to support embodied real-time interaction and fabrication.

Even though prototypes exemplified here are far away from replacing current GUI implementations in computer-aided systems, they successfully speculate how interaction with CAD tools can be controlled and informed through different means of digital interactive mediums such as capacitive touch screens. The exploration into different mediums of interaction enables users to gain increased control over the fabrication process. Nonetheless, this research is vital in exploring how fabrication can be integrated within the design process as the proposed systems are in no way or shape pre-programmed and rely on real-time data to carry out the fabrication task.

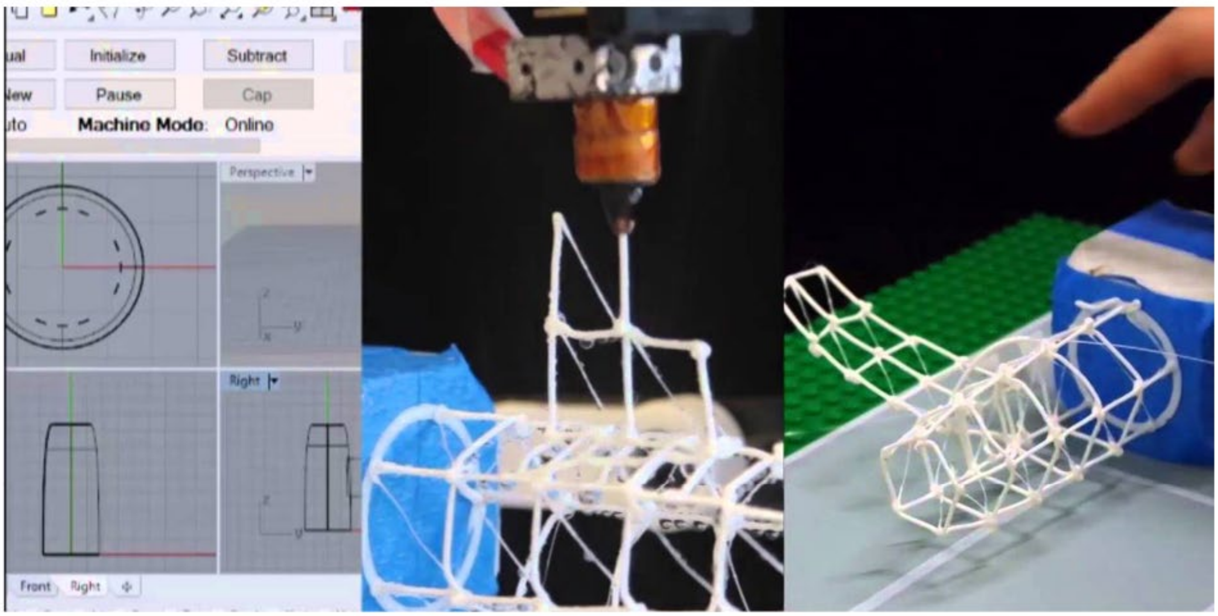

Figure 5.On-The-Fly Print demonstration. Adapted from On-The-Fly Print: Incremental Printing While Modelling (p.801), by Peng et al.

Another precedent that challenged the idea of real-time fabrication and modification of the digitally designed artifact is presented in the paper titled “On-The-Fly Print: Incremental Printing While Modelling”(Peng et al. 2016). Authors develop a real-time design-fabrication workflow in which a robotic arm utilizes Fused Deposition Modeling (FDM) technique to fabricate an artifact in low fidelity wire mesh form to decrease fabrication time to create more fluent interaction as the digital representation is being designed in Computer-Aided design environment. This body of research also allows previously printed parts of the artifact to be edited with subtractive manufacturing methods. Through their research, authors propose an intermediary workflow between digital and hands-on fabrication methods. Even though this project proposes a novel workflow to fabricate artifacts through live communication protocols with an industrial robotic arm, the interaction is limited to digital manipulation through more conventional interfaces to CAD systems for the most part.

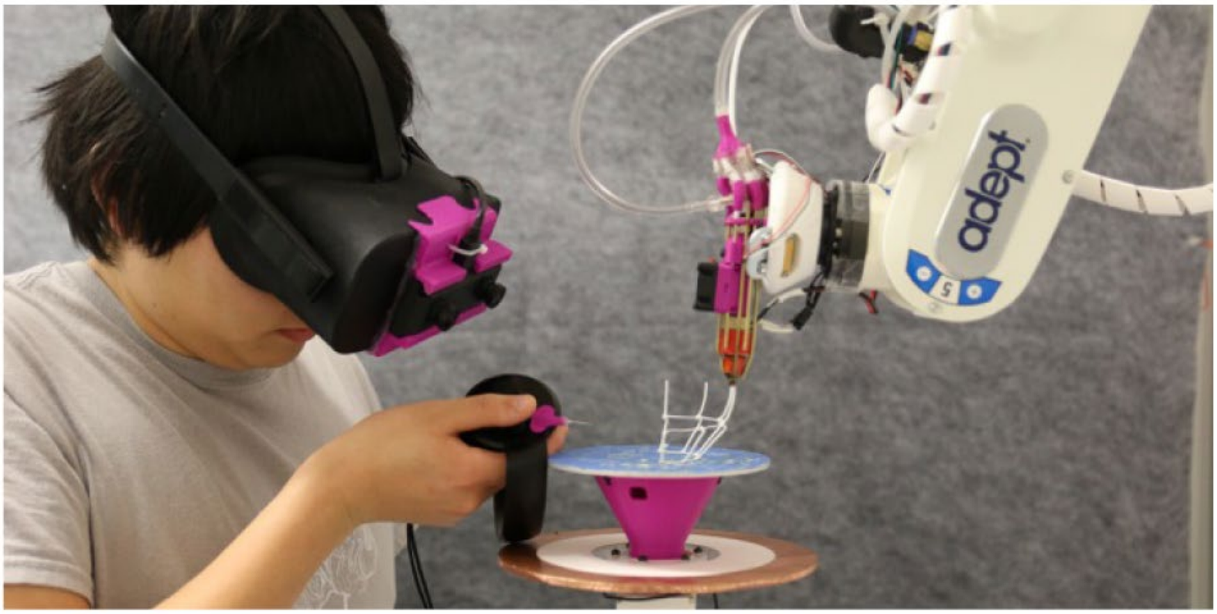

Figure 6. Real-Time fabrication demonstration using RoMA. Reprinted from RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer (p.1), by Peng et al.

In a more recent paper, authors from the same research group present *RoMA* (Peng et al. 2018) an incremental improvement over their previous work, *On-The-Fly Print*, which integrates Augmented Reality (AR) setup to further improve the model of interaction with the proposed Computer-Aided Design workflow. In addition to previously mentioned improvements over contemporary CAM tools that utilize FDM fabrication method, this research allows designers to integrate real-world constraints in their design process through the AR system and allow them to work side by side with a robotic arm to both incorporate affordances of the tool and creative expression of the user. Although *RoMA* significantly improves the model of interaction, similar to *On-The-Fly Print* it neglects potentials of bodily interaction with the artifact. Contrary to the previous version presented in *On-The-Fly Print*, in this paper, researchers also did not incorporate subtractive manipulation of the artifact. Overall, since the intervention is limited to the digital realm in both *RoMA* and *On-The-Fly Print*, both of these precedents are not able to overcome the deterministic nature of such fabrication systems.

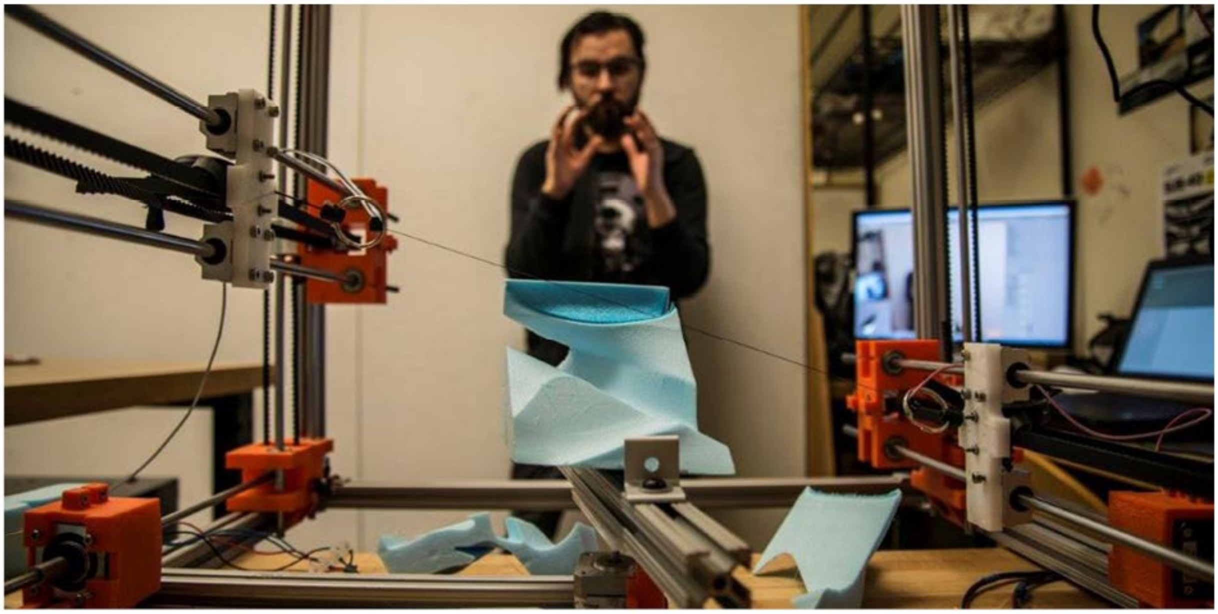

Figure 7. Demonstration of real-time interaction with the system. Reprinted from Making Gestures: Design and Fabrication Through Real Time Human Computer Interaction (p.78), by D. Pinochet Puentes.

Within a design context that is highly dominated by disembodied *hylomorphic* model creation, Diego Pinochet challenges this divide through his thesis titled *Making Gestures: Design and fabrication through real-time human-computer interaction* (Pinochet Puentes 2015). He defines the problems of contemporary CAM and CAD tools to be black-boxed and generic, limiting creative freedom that design requires. In response to this assertation, he proposes an interactive design-fabrication workflow for hot-wire cutting of foam blocks. In his experimental setup, he prioritizes the use of bodily gestures to operate the tool asserting that it "add[s] a new dimension of design and making present in analog design into the digital design process by capturing the real-time contingency between designers intentions, tools, and materials behavior promoting the improvisational aspects of design."(Pinochet Puentes, 2015, p. 78) Even though this precedent achieves the set goal of facilitating momentary findings that inform design decisions, the experimental setup is limited within the digital interface of Kinect camera, and the developed workflow still behaves like Coons' *perfect slave*.

2.2 Establishing Sensor Feedback

Figure 8. Demonstration of real-time hand milling of an artifact. Reprinted from FreeD: A Freehand Digital Sculpting Tool, by A. Zoran and J. Paradiso.

In their paper titled "FreeD: A Freehand Digital Sculpting Tool," Amit Zoran and Joseph Paradiso propose a real-time subtractive manufacturing tool, namely FreeD, that is guided by CAD representation of the desired geometry (Zoran and Paradiso 2013). Different than how current fabrication tools completely automate the act of making, authors use CAD data only to guide the user. The tool enables creative expression of the user by not enforcing deterministic tool paths to inform how the artifact is carved out as long as the user doesn't come dangerously close to risk desired object's integrity. Authors of this research compare this proposed fabrication workflow to violin makers' use of templates. Through free gestural control of the tool, authors enable computer-aided systems to act as a template to fabricate controlled but unique artifacts and provide greater autonomy over the fabricated artifact.

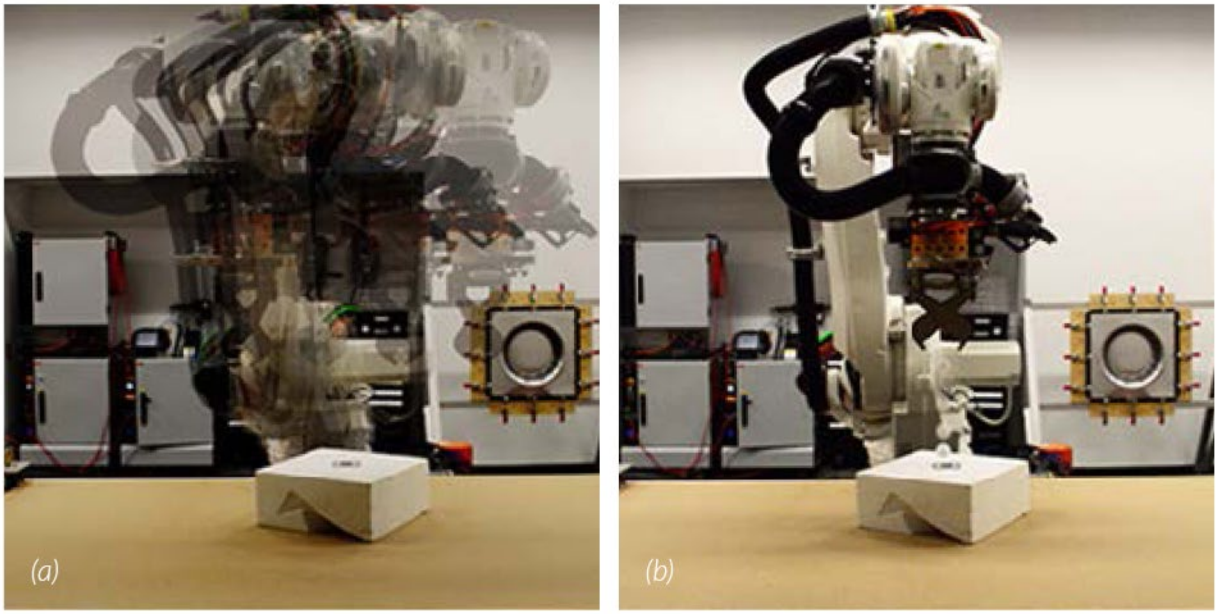

Figure 9. Demonstration of context awareness of the machine agent, (a) machine capturing the artifact, (b) and dropping a ball through the hole. Reprinted from Seeing is Doing: Synthetic Tools for Robotically Augmented Fabrication in High-Skill Domains (p.415), by Bard et al.

Another research on augmenting fabrication tool with sensory systems by Bard et al. exemplifies how the digital representation of matter can be informed through a series of case studies (Bard et al. 2014). These case studies utilize different computational approaches such as low-fidelity force feedback and motion capture systems as well as Computer-Vision algorithms. Authors suggest incorporation of sensory feedback systems to augment fabrication tools to facilitate *adaptive fabrication*, which is described as "a responsive construction approach that allows a task to update based on data received from external sensors and events" (Bard et al. 2014). Aside from proposing a bottom-up approach to complex fabrication tasks, *adaptive fabrication* offers promising results in informing the digital representation of the matter engaged. These custom tools developed by the authors inform the whole system with contextual awareness and allow digital representation to be synchronized with data collected from physical matter, capturing the material properties better than the idealized representation of the matter in CAD systems. Authors aim to enable adaptive toolpath generation based on the current state of the matter engaged by the fabrication system through these feedback mechanisms presented in their paper, presenting an alternative bottom-up approach to how contemporary CAM systems operate.

2.3 Facilitating Creative Exploration

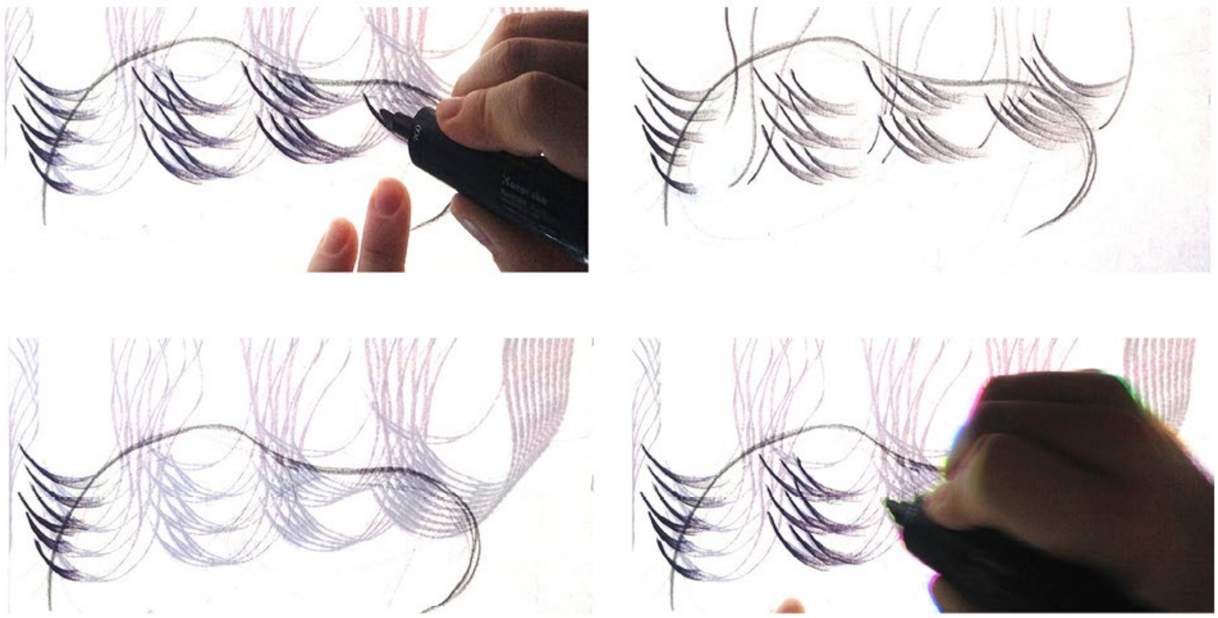

Figure 10. Demonstration of creative suggestions proposed by the machine. Reprinted from A Place for Computing Visual Meaning: the Broadened Drawing-scape (p.99), by O. Gun.

Different from the precedents detailed in previous sections, Onur Yüce Gün's research explores how computational systems can play a role in informing design decisions throughout the creative process (Gün 2016). In his attempt to situate computational systems within the creative visual process, the author employs simple computational algorithms such as *translation* and *arraying*, in order to inform users with potential visual cues. Using a simple image capturing device and a projector, Gün's setup can capture and process the two-dimensional drawings and present visual hypotheses which user can decide to incorporate in their drawing if they choose to. Even though this particular research does not address the issues of materiality, it provides crucial insights into how computational tools can be used in tandem with a creative human agent to enable informed design decision.

3

CAM as a Tool for Creative Expression

3.1 Hypothesis

As discussed in the previous chapter extensively, contemporary computer-aided systems lack the capacity to capture the complex, nonlinear and informal design workflow. This poses a fundamental challenge for these systems to bridge the gap between our understanding of materials and imposed forms. Much of the contemporary discourse still heavily focused on the ideal representation of ideas and automation of these tools.

Through this thesis, I argue that contrary to the goal of freeing designers from arduous tasks in the design workflow, active engagement with materials can enhance creative freedom and inform design decisions. Moreover, I assert that creative human agency can coexist along deterministic machines to facilitate creative exploration through making.

My Hypothesis in this thesis is that incorporation of interactive and adaptive frameworks in design-fabrication workflows can enable situated knowledge gained through material interaction to inform design decisions, facilitate hands-on creative exploration within digital fabrication workflow and allow non-expert users to engage in complex design and fabrication problems.

3.2 Experimental Setup Overview

Building upon these investigations into *interactive* and *adaptive fabrication,* detailed in the previous chapter, this research proposes a design-fabrication workflow informed by computer-vision setup not only to enable direct and increased control over the fabrication process but also to facilitate a creative conversation between human and machine agents. This proposed workflow aims to augment the machine agent that is executing the tasks related to a digital representation of the artifact by introducing a computer-vision setup and give human agent more significant authorship over the artifact by facilitating direct manipulation of the artifact through the real-time computation of tool paths for the fabrication system.

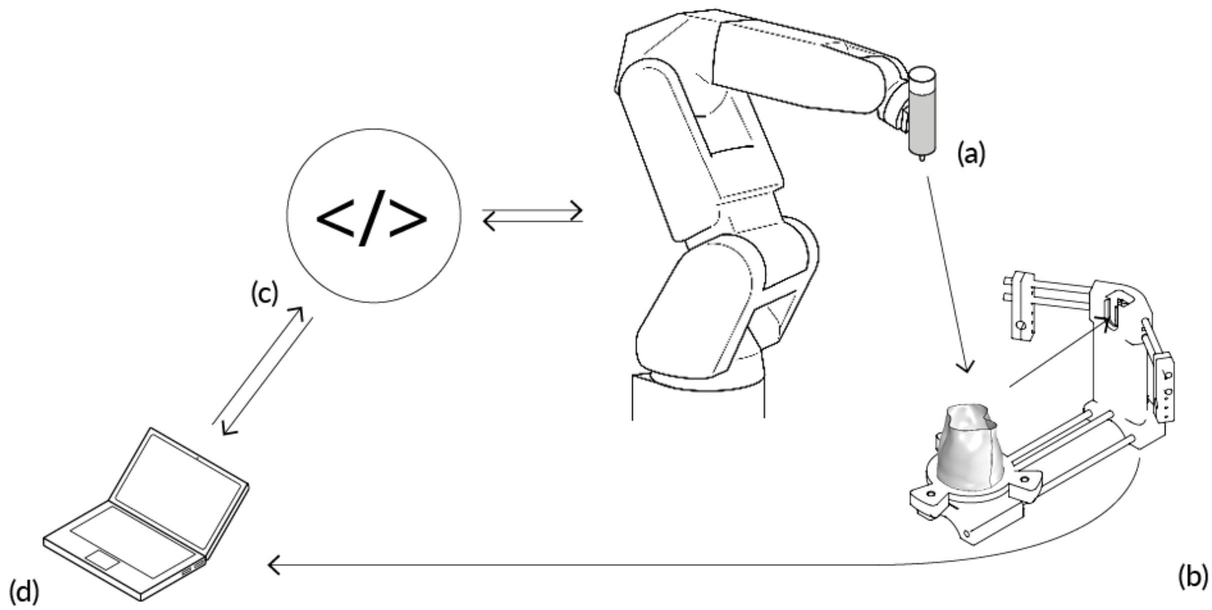

Figure 11. Subsystems of the proposed experimental setup: (a) Mechanical Paste Extruder, (b) Laser-Stripe Triangulation setup, (c) Live Communication Protocol, (d) Geometric Processing algorithms and the Application.

This proposed workflow is mainly composed of five subsystems, illustrated in Figure 11, namely (a) a mechanical paste extruder to facilitate the fabrication of the object, (b) a Laser-Stripe triangulation scanning setup to update of the digital representation of the artifact. In addition to these mostly hardware implementations, I have implemented (c) a live communication protocol which operates the fabrication mechanism, (d) a Grasshopper for Rhinoceros 6 based IronPython script that performs tasks such as geometric reconstruction and tool path generation and (d) a Python-based application to control the turn-taking and handle data flow between other subsystems. In the implemented experimental setup, I have built these hardware setups upon open-source hardware and software projects shared in the public domain. Although, basis for such implementations significantly utilized the existing body of codes and 3D CAD files, appropriating these subsystems to the experimental setup inherently required hardware and software development and testing cycles to ensure that each subsystem is capable of executing tasks requested by other subsystems and operate in a low tolerance window, which is detailed later in this chapter.

3.3 Proposed Model of Interaction

The theoretical framework of the model of interaction for the proposed design-fabrication workflow and role of the machine within the workflow are built upon precedents introduced in the background chapter, formulating system and agent level requirements. Within the framework described in the papers by Kantosalo and Toivonen, and Lubart (Kantosalo and Toivonen 2016; Lubart 2005) this thesis propose a computational system that can be classified as a basic version of Lubart's *computer as coach* description. In parallel with this classification, the current setup offers design hypotheses derived from the digitally reconstructed geometry of the artifact, which can be tuned by the users, presenting a range of geometrical potentials. In terms of the model of interaction in system level, current implementation of the workflow can be classified as a *task-divided co-creativity*, where both human and machine agents take on specific tasks within the design-fabrication process. Through these definitions of the model of interaction and the role of the machine in the workflow, we can infer that the system is an *incomplete* system within Kantoloso and Toivonen's definition since this implementation heavily relies on carefully orchestrated protocols and algorithms to perform. Furthermore, it is not capable of putting forward a design requirement for the artifact to be satisfied by both parties participating in the design-fabrication process.

Complementing the aim of this thesis to facilitate embodied material interaction, the physical artifact plays a crucial role as an interface between subsystems and a medium for transferring information. As an artifact engaged by both fabrication and computational subsystem as well as the user, the physical artifact is envisioned both as the intermediary interface medium that transfers the design intentions imposed by the user and as the outcome of the process. The deliberate decision of not integrating commonly used interfaces such as a monitor except a brief window when the visual design hypothesis is presented to the user supports the intention to take the proposed workflow out of the computer into the physical realm. The artifact as the primary medium for interaction can capture the design intention introduced by the human agent through hands-on manipulation and constitute the foundation upon which machine agent can impose the design hypothesis through extrapolating the geometry.

Figure 12. Keypad customized for the proposed workflow.

In addition to using the artifact as the primary medium to transfer information between implemented subsystems, I have integrated a wireless keypad into the workflow. The role of this keypad within the proposed workflow is mainly to address potential safety issues that can arise due to real-time control of the industrial robotic arm. If the user chooses to, the proposed workflow can easily be appropriated to work only through interaction with the physical artifact as a medium, but such workflow would heavily rely on discrete automation, limiting the control over the process. The proposed experimental setup incorporates the keypad in order to circumvent potential hazardous movements of the industrial robotic arm which may pose a threat to the user. This keypad enforces a confirmation protocol on the human agent to avoid any task to be executed without the conscious decision of the user. Through these interaction implementations, this thesis aims to introduce deliberate "seams" within the design-fabrication workflow to help users to develop a better understanding of the tools, encourage creative exploration through hands-on interaction with materials and allow for the reciprocal exchange of information and intent.

3.4 Proposed Computational Workflow

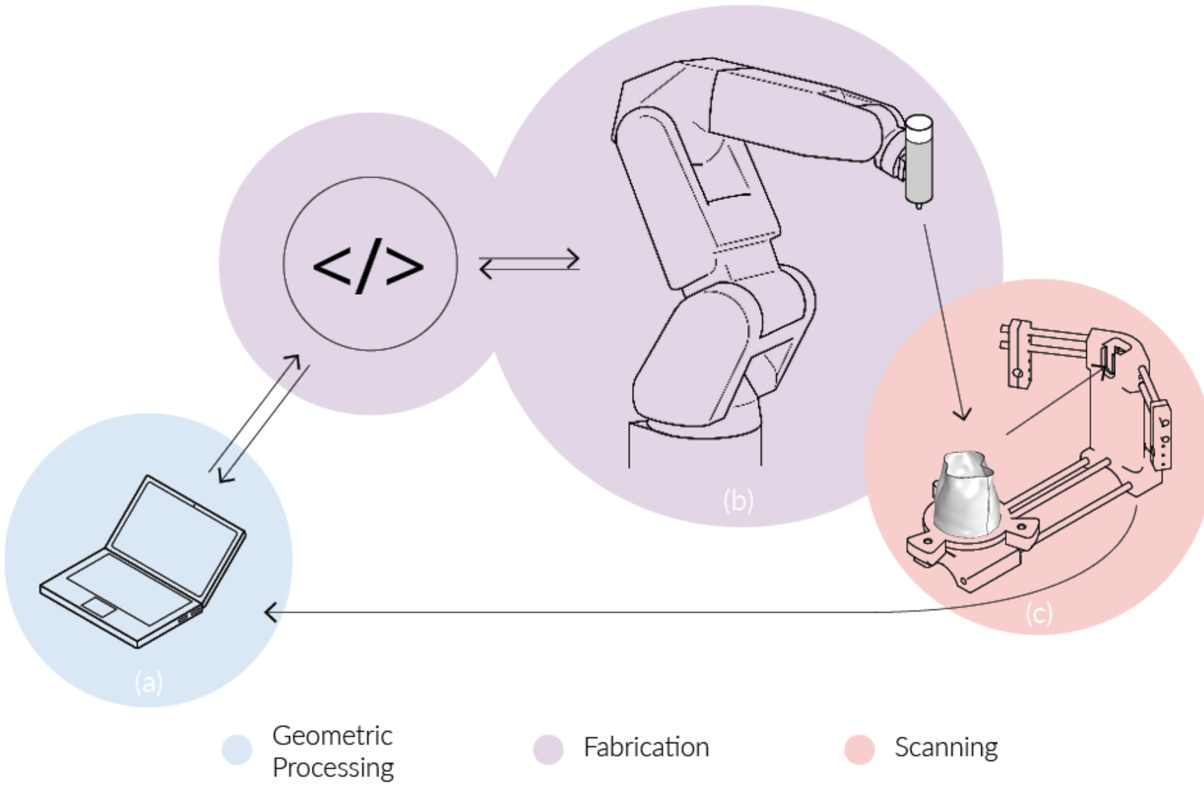

Figure 13. Different computational stages of the proposed workflow: (a) Geometric Processing, (b) Fabrication, (c) Scanning.

As briefly introduced in section 3.1, this thesis proposes an alternative design-fabrication workflow to facilitate creative exploration within computer-aided systems and enable human-machine dialogue in creative scenarios. The envisioned reciprocal interaction model for this experimental setup mainly consists of 3 main computational stages; (a) *geometric processing,* (b) *fabrication,* (c) *scanning.* These systems are illustrated with blue, purple and red colors respectively in Figure 13. Using the Python 3.6 application detailed later in this chapter, the proposed workflow can coordinate the transfer of information between these different stages during the design-fabrication process and allow user inputs to pause, stop or resume these tasks.

The workflow is initiated with user-defined geometry. In the initial *geometric processing* stage, the toolpath generation algorithm is deployed to generate an XYZ file containing target points for each layer sliced using the input geometry. Once the toolpath is ready, the application establishes a connection with *Machina-Bridge*, real-time communication protocol. Following user input through the keypad introduced earlier, the user initiates the *fabrication* stage. Target points of the toolpath are sent layer by layer, and the fabrication process is carried out until all layers are fabricated or the user pauses the fabrication process at the end of a full layer fabrication any time after a certain number of layers are fabricated to ensure sufficient amount of material is deposited for the user to modify. Within the scope of the experimental setup detailed in this thesis, the fabrication process is carried out until the fabricated artifact reaches 75mm in Z-height or 30 layers with 2.5mm layer height. Throughout the process, users can safely engage with the end-of-arm tool to tune the extrusion rate to accommodate layer adhesion and fabrication imperfections caused by factors such as air pockets present in the material.

Once these conditions are met, the fabrication process is paused, and the industrial robotic arm moves away from the artifact for the user to carry out physical deformation. Users are not primarily restrained to any particular geometry, but as discussed in detail in later chapters, best scanning results are obtained when the deviation in the surface curvatures are gradual. Extreme geometrical deformations can result in false-positive geometrical reconstructions that do not capture the actual geometry of the artifact. Furthermore, due to the physical limitations of the experimental setup detailed in this thesis, the artifact is limited to a build volume of 200 x 200 x 205 mm. The implemented Laser-Triangulation setup either cannot capture any geometry outside of this volume.

During the physical deformation process, the implemented workflow waits for user's input to proceed. Using the keypad, the user can initiate the *scanning* stage and the application transfers data to geometric processing algorithms to process the scan data to reconstruct the artifact digitally and proposes a design hypothesis using extracted geometrical data from the scan data. Using keypad inputs, the user can tune the parameter for manipulating the design hypothesis and confirm the geometry to initiate the toolpath generation of extrapolated layers.

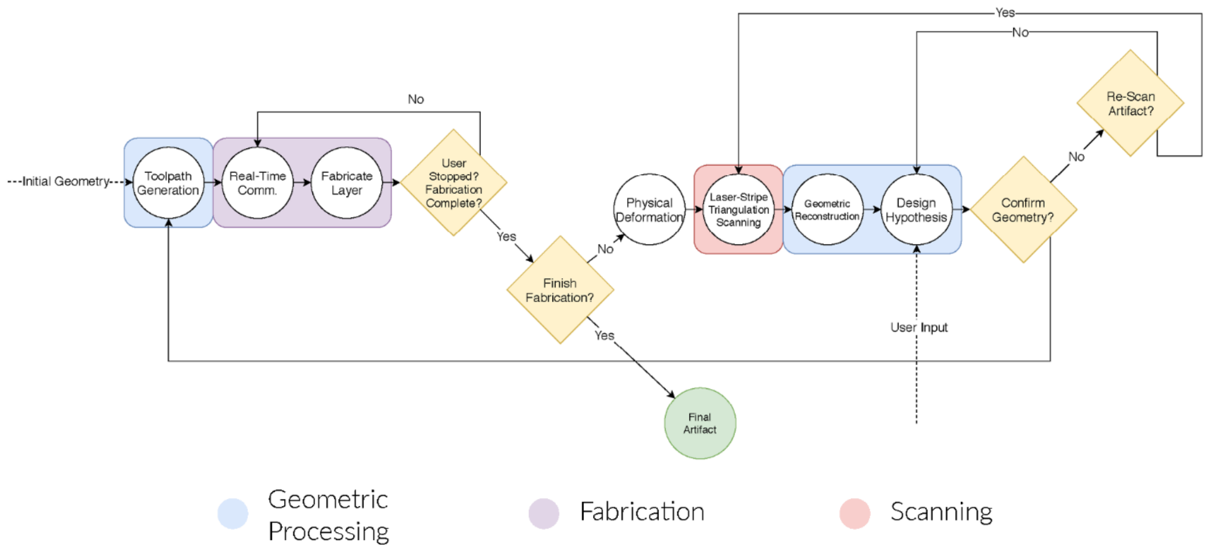

Figure 14. Proposed system flowchart.

As can be seen in Figure 14, following the generation of the toolpath for the extrapolated geometry the workflow transitions back into the *fabrication* stage. The proposed workflow can be terminated by the user after the fabrication of a full layer. If the user does not wish to go any further with other stages, the user can end the process using keypad inputs. Although still malleable, the fabricated artifact can be removed from the setup or can be further processed by the user to achieve the desired surface finish using additional tools.

3.5 Hardware Development

The proposed design and fabrication workflow heavily relies on its subsystems to work synchronously within a low tolerance window. The hardware development of two subsystems, mechanical extruder and Laser-Stripe triangulation setup play a crucial role in how this proposed workflow performs. For this reason, these hardware development cycles have been significant in both pinpointing the limitations and potentials of these systems as well as improving the system to meet the desired low tolerance window.

3.5.1 Mechanical Paste Extruder Setup

Within the scope of developing an end-of-arm tool for facilitating the fabrication of the artifact, two main constraints informed the implementation details. These constraints are (1) the need for the fabricated object to be deformable during the physical intervention stage and (2) the precise control over material deposition rate to accommodate higher speeds that the driving mechanism, ABB 6640 industrial robotic arm, is capable.

Additive manufacturing as a manufacturing technique gaining popularity amongst hobbyists, makers, and designers, provide many forms of open sourced projects utilizing different means of depositing materials in a precise and controllable fashion. Even though plastic filament deposition manufacturing that utilizes melted plastic deposition is the most common method used for additive manufacturing, a growing number of enthusiasts are challenging different materials and mechanical assemblies. This growing interest in additive manufacturing techniques provides numerous highly customizable reference setups for hardware assemblies that are capable of depositing a wide range of materials ranging from paste materials to metals.

In order to facilitate an easy physical manipulation within the proposed workflow, potential deposition assemblies were narrowed down to accommodate porcelain clay, as this material can easily be deformed without the need of additional tools and which inherently have a longer window for physical manipulation. In light of the material constraints established to accommodate the workflow, two potential extrusion assemblies that can be implemented were pneumatic and mechanical systems. Pneumatic systems are composed of a chamber that extrudes paste-like materials by introducing high pressured air. Even though many of these pneumatically driven systems offer cost-effective setups and a vast range of customizability, I have abandoned this technique as such systems provide very little control over extrusion rate and potential air pockets introduced in the process of filling up the chamber can cause irreversible damage to the fabricated artifact.

Mechanical ram extruders, on the other hand, are driven by a stepper motor that actuates a plunger that displaces material in a more controllable fashion. By implementing a robust control with a stepper driver to control the motor speed, this system can be adapted to precisely control rate of extrusion. Moreover, since stepper motors offer precise rotation encoding up to 0.45-degree resolution, with some basic calculations extrusion rate can be calculated down to less than a cubic centimeter accuracy. Lastly, since the control of mechanical ram extruder setup is programmed over digital microcontrollers, integration of a signal system between the industrial robotic arm and the end-of-arm tool is possible, allowing for binary control of on-off states.

3.5.1.1 Mechanical Assembly

As briefly mentioned before, many communities that explore different deposition techniques offer meticulously documented open-source hardware projects to help give others interested in the area a ground to build upon. In this research, designed and constructed mechanical assembly for clay deposition was based on similar open-source hardware documentation published by Bryan Cera (Cera 2018).

Cera's particular project that constitutes the basis for the version used in this research is very well documented. Nevertheless, many aspects of the mechanism were appropriated here according to the availability of the hardware as well as the limitations and requirements of the proposed workflow. These modifications range from increasing the capacity of clay that this mechanism can hold to limiting the range of extrusion speed to a suitable range for fabrication with an industrial robotic arm.

One of the first changes I have made to the mechanical design was on the material capacity. The original hardware was designed with material capacity at around 700ml of material as it was initially designed to be used with a thin nozzle to extrude minimal amounts of materials in the fabrication of highly detailed models. This capacity was increased to 1.5 Liter to enable potential scaling of fabrication if necessary as well as to ensure a sufficient amount of material is always ready to be extruded during the fabrication cycle. Since the base hardware design is modular, extending the PVC tube was sufficient to achieve a larger capacity.

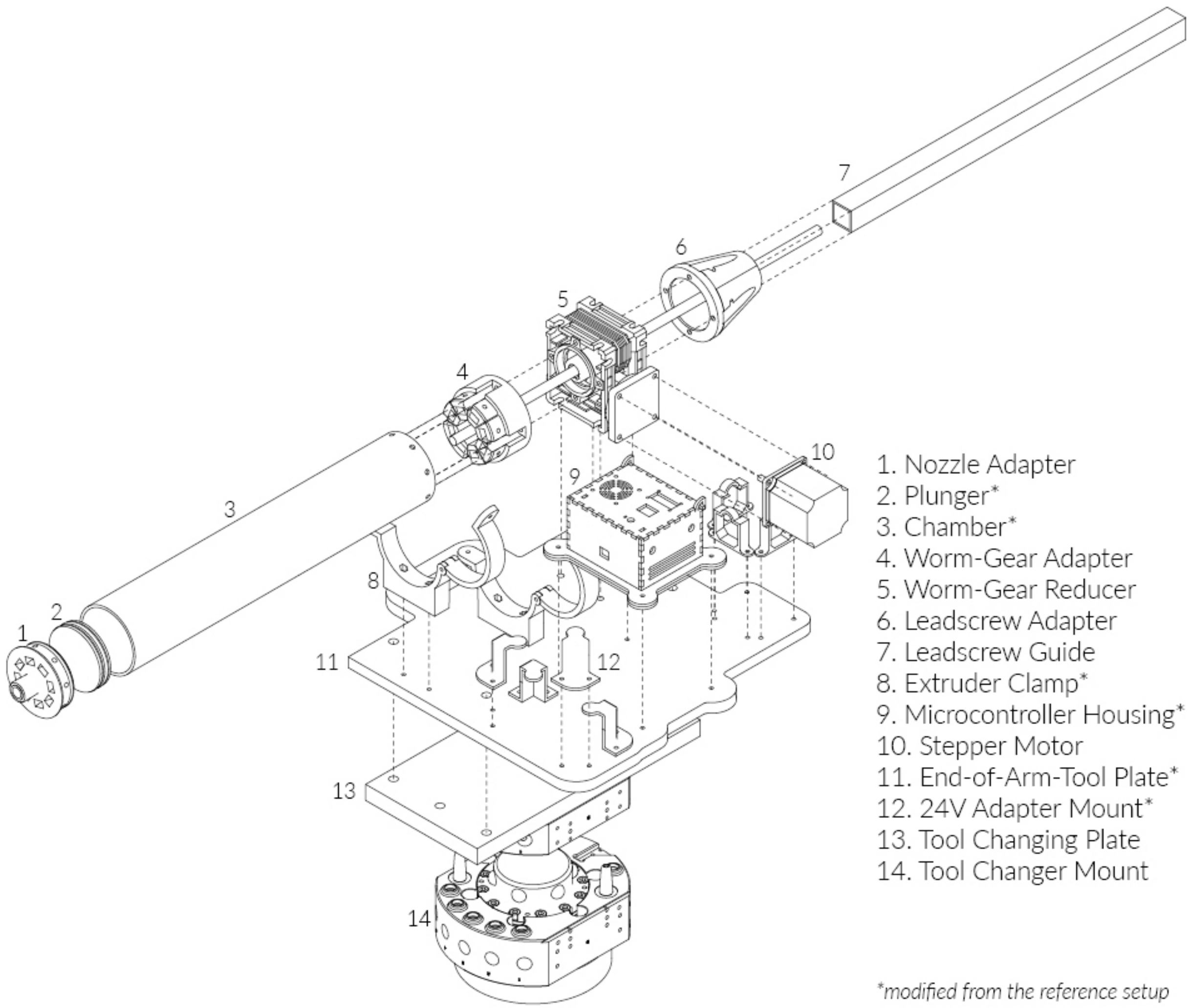

Figure 15. Developed hardware implementation.

Similarly, due to the change in the operating mechanism that is used alongside the extruder from the gantry system to an industrial robotic arm, the rate of extrusion was not sufficient to accommodate higher speeds that a robotic arm can reach during fabrication. In order to fully utilize inherent advantages of a robotic arm and allow for faster prototyping with larger layer height values, I have selected the worm gear speed reducer at 20:1 ratio instead of 30:1 ratio used in the reference setup. The implementation of the lower gear ratio allowed for faster extrusion rate and provided flexibility with the range of appropriate layer height. Even though this change in the mechanical assembly reduced the applied force on the plunger, the range of operation was adequate.

Aside from these significant modifications to the extruder setup, I have also modified the majority of the 3D printed parts to accommodate different dimensions of available hardware and rapid prototyping tools. Moreover, some of these parts were appropriated to ensure stable operation during fabrication. These modifications are marked in Figure 15 above.

3.5.1.2 Microcontroller Circuitry

Following the initial prototype of the mechanical assembly, the other area of focus in the development of the mechanical paste extruder was the digital interface for extrusion control. Initially, I have decided on critical control parameters and required interfaces for robust operation of the developed tool. These parameters were the rate of extrusion to enable necessary adaptation for different fabrication parameters, the direction of motion to help material loading process, digital input from the industrial robotic arm to control the on-off state of the extrusion mechanism and power interface for the microcontroller and the NEMA 23 motor. I have implemented these control parameters and power interfaces on software and hardware level using an ATMega328P based Arduino microcontroller different electronics components such as a potentiometer, a binary switch, and a relay to interface with the user and the robotic arm. I have implemented the control of the rate of extrusion using a potentiometer which linearly maps the value read on the potentiometer to the working range of the stepper motor used in the reference setup to give users adequate control. Similarly, I have integrated a binary switch into the circuitry to enable the control of the ram movement direction. This feature was especially important when the chamber needs to be refilled, eliminating the need for disassembly.

Another critical interface implemented in the circuitry was the integration of a relay. Since the industrial robotic arm digital signals operate well beyond the capabilities of a microcontroller, at around 24V, I have introduced a relay system to read the on-off signal through a relay interface without posing any risk of high voltage damage to the microcontroller. Through this circuitry interface, the developed application can control the state of the mechanism by regulating the digital signal through the real-time communication protocol.

Lastly, I have separated the operating power for the stepper motor used in the implemented setup from the main circuitry both powering the stepper motor and a mounted fan to ensure the stepper motor drivers remain in operational temperatures. I have then mounted this circuitry on a custom laser-cut box in order to protect the circuitry from potential harm from dust and splashes.

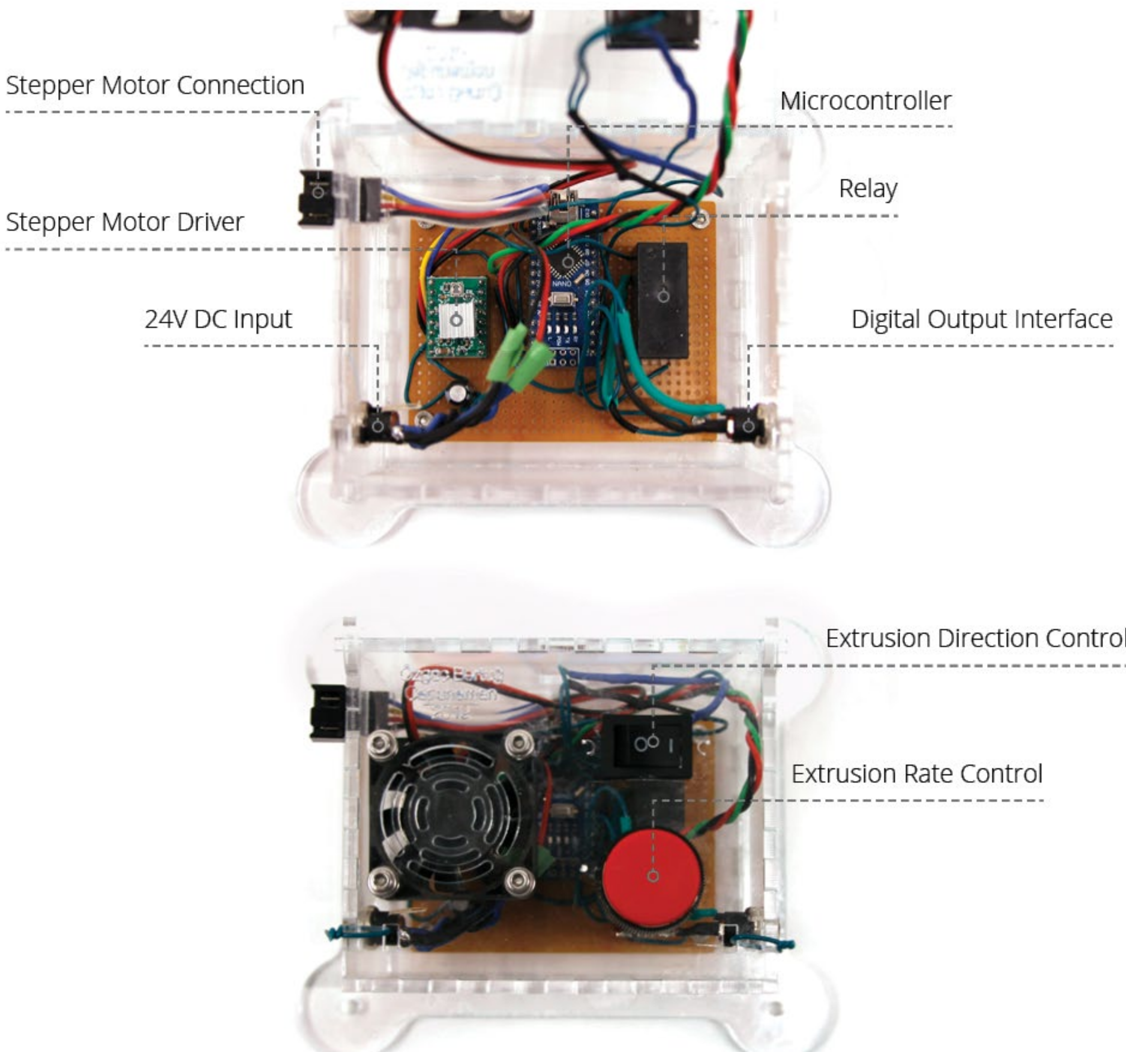

Figure 16. Components of the microcontroller assembly for stepper motor control.

3.5.1.3 End-of-Arm Tool Development

The original open-source hardware setup was intended to be used with a gantry system, which in many cases was not able to carry the load of the tool. For this reason, this reference build was often fixed next to the actual fabrication tool, feeding separate nozzle hardware through a tube. The change of machinery from gantry system to industrial robotic arm, which is rated to carry heavy loads, allowed the extruder to be directly mounted on the robotic arm, performing both as material displacement mechanism as well as extrusion nozzle.

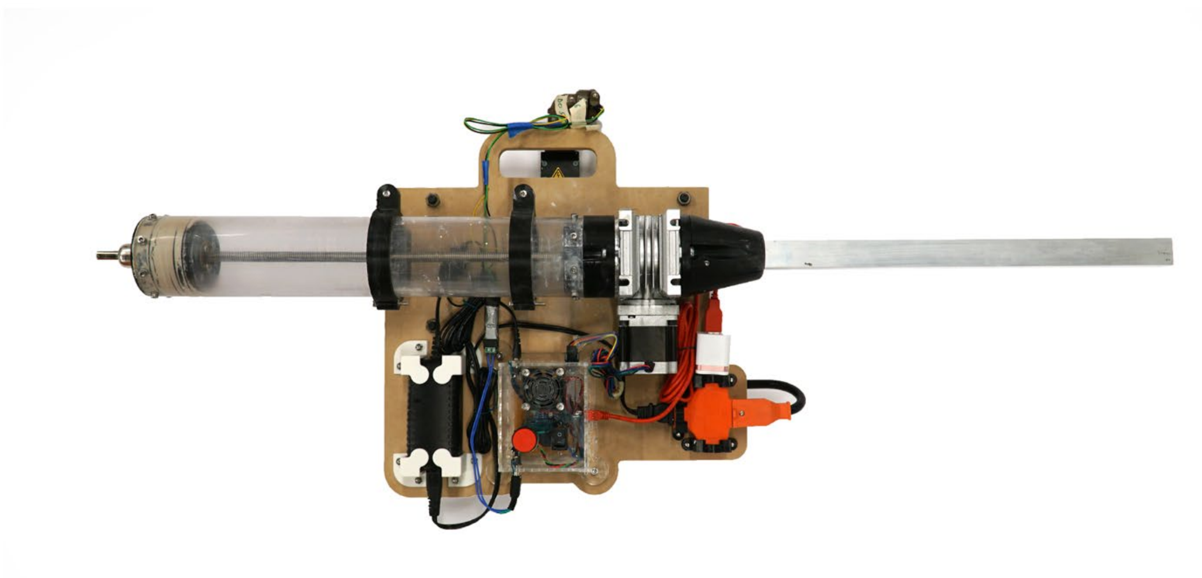

Figure 17. Assembled end-of-arm-tool.

Alongside with physical constraints present in how signal and power outlets are positioned on the ATI plate, this change in how the extruder is used, affected how the end-of-arm tool is designed. I have laid out the end-of-arm-tool with the 110V AC and 24V digital signal outlets available on the robot in mind. The 110V AC outlet is used to power the motor as well as the microcontroller using 24V and 5V adapters respectively. Additionally, I have positioned the center of gravity of the extruder subassembly as close to the Tool Changing Plate's center in order to avoid any potential problems that might emerge due to the misaligned center of gravity.

3.5.1.4 Subsystem Testing

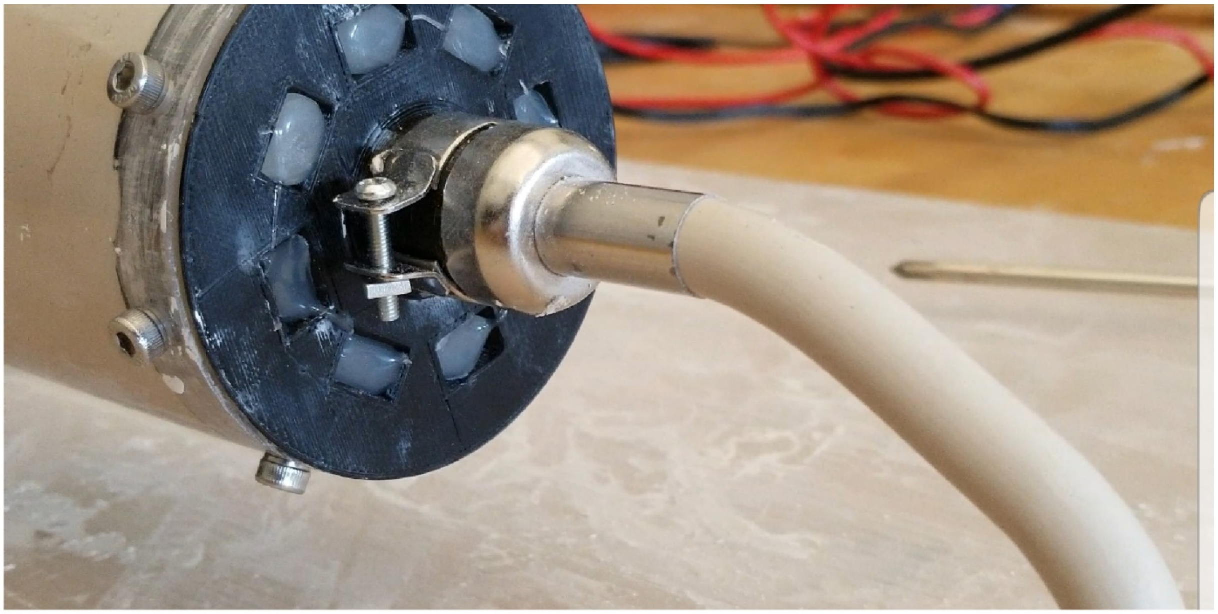

Figure 18. Initial extrusion test.

Following the development of both control circuitry and the mechanical extruder, I have tested these systems on different occasions. Initial tests carried out with clay was aimed at developing a better understanding of the material affordances. The first test focused on how the system behaves and whether the assembly can extrude material as expected. Initially, I have loaded the clay without any addition of water since the clay used in the system, Aneto 3D, is a premixed clay explicitly engineered for additive manufacturing. This test failed due to less than desirable water content, and in multiple runs, the motor was not able to displace any material. Following that, I have mixed the clay with 50 ml water per kilogram of clay to increase viscosity, and this mixture yielded much more promising results as the motor was capable of extruding material through the nozzle. However, when tested for layer adhesion, this mixture yielded mixed results since the extruded clay was not adhering to itself. Lastly, I have loaded the extruder with a clay mixture of original Aneto 3D clay with 100ml water per kilogram of clay used and carried out the same material extrusion test. This specific mixture resulted in relatively easy extrusion of clay. Throughout this test, the motor was capable of extruding at its fastest rate and the extruded material provided much-desired malleability and layer adhesion.

3.5.2 Laser-Stripe Triangulation

The other subsystem that required hardware development was the laser-stripe triangulation scanner. Similar to the additive manufacturing, the increase in popularity of consumer-grade fabrication tools, hardware and software systems for 3D scanning became more attainable by consumers. Currently, there are many different approaches to the digital 3D reconstruction of physical objects including Laser-Stripe Triangulation scanners, photogrammetry, and high-end depth cameras. Even though these tools have different advantages over each other such as higher accuracy, being able to capture the texture and allowing users to digitally reconstruct objects using readily available consumer-grade cameras, due to constraints established by the selected material and fabrication technique laser-stripe triangulation scanning became the appropriate tool for the proposed workflow.

3.5.2.1 Method of 3D Reconstruction

As previously mentioned, multiple tools and hardware for digital 3D reconstruction are commercially available. Within those tools, photogrammetry, depth cameras and Laser-Stripe Triangulation are the most common tools used widely for 3D reconstruction purposes. These three approaches were tested to distinguish the advantages and disadvantages of each system.

The first test on 3D reconstruction was photogrammetry. Just by capturing the object from different angles, an algorithm can estimate a rough point cloud from the artifact. This method heavily relies on distinct visual features on the scanned object to create the point cloud, and the accuracy depends on factors such as how homogeneous the surface is, the number of distinct features and controlled lighting conditions. Since the proposed material and fabrication technique results in a homogeneous and featureless finish, resulting point cloud data often lacked in capturing overall geometry.

Similarly, high-end depth cameras were not able to meet the accuracy tolerance that the proposed workflow inherently requires. In many tests with such a system, the depth camera failed to capture the object accurately since depth sensors are lower in resolution than typical RGB cameras as well as being limited by software limitations that optimize 3D reconstruction for large scale objects and interiors. This limitation resulted in point clouds with an accuracy of the 3D reconstructed object around ~5 mm.

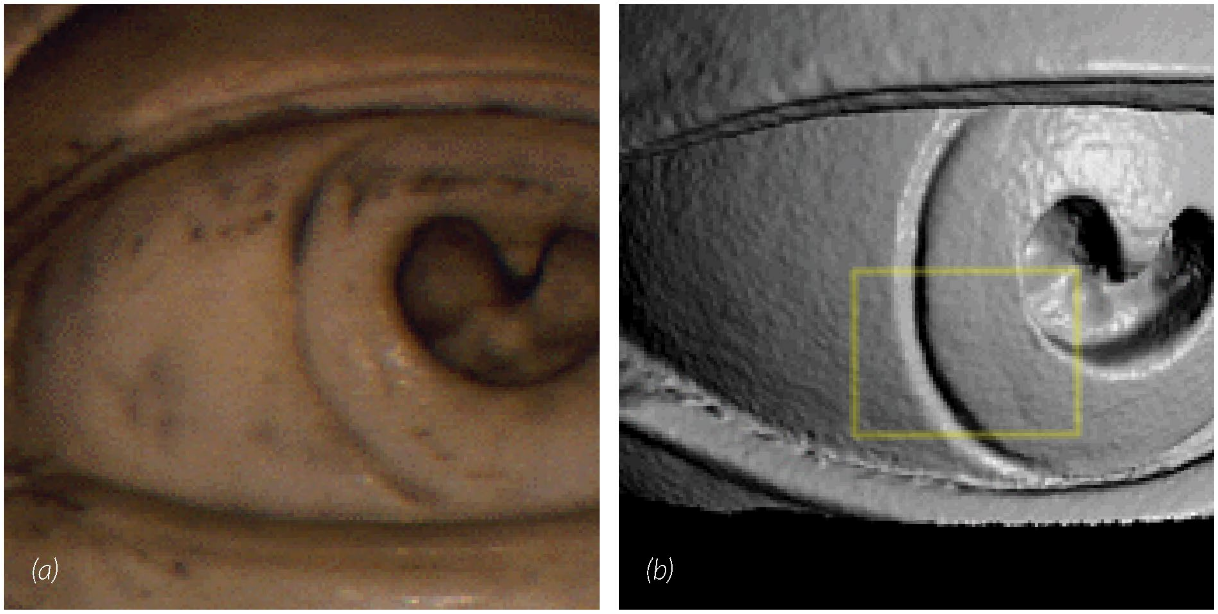

Figure 19. Comparison of (a) physical artifact and (b) reconstructed digital representation. Reprinted from The Digital Michelangelo Project: 3D Scanning of Large Statues, by Levoy et al.

Laser-Stripe Triangulation, however, do not rely on distinct features or sparse depth sensor data to generate a point cloud. This property of the Laser-Stripe Triangulation allowed for the employment of this method in the 3D reconstruction of artifacts with the homogeneous surface finish. One of the most cited applications of this method is *The Digital Michelangelo Project: 3D Scanning of Large Statues*, published by Levoy et al. (Levoy et al. 2000). Although marble poses more complex computational problems due to its material composition that causes subsurface scattering, authors successfully reconstructed numerous sculptures by Michelangelo. As can be seen in Figure 19, this method in combination with high resolution still cameras was able to capture minute details such as Michelangelo's chisel marks. Additionally, Laser-Stripe Triangulation method is known for operating in relatively wider external light levels with the adequate calibration of intrinsic and extrinsic variables, and provide much higher resolution in the reconstructed object. The implemented setup in the scope of this thesis can sample up to

720 points per 0.45-degree rotation in the polar coordinate system. Even though this system limits the potential scaling opportunities to a scan volume of 200 x 200 x 205 mm, considering that the scanned object needs to be within the boundaries of the scanning plate, this method yielded the most promising results in terms of accuracy and low tolerances.

3.5.2.2 Hardware Development

As an example of one of the most accurate 3D scanning setups, laser-stripe triangulation scanners heavily rely on robust hardware implementations and through modifications to its hardware these systems can be appropriated for different use cases. As a commercially available kit, Ciclop 3D scanners are regarded as entry-level hardware, which is capable of scanning small to medium sized objects. Initially, the hardware development intent was to swap the built-in 3D scanning bed with an industrial rotating table to enable larger fabrication area and higher accuracy; I have later discarded this idea as the control of the system through Python interface was not possible due to lack of hardware specific low-level camera drivers which were only built into the standalone application.

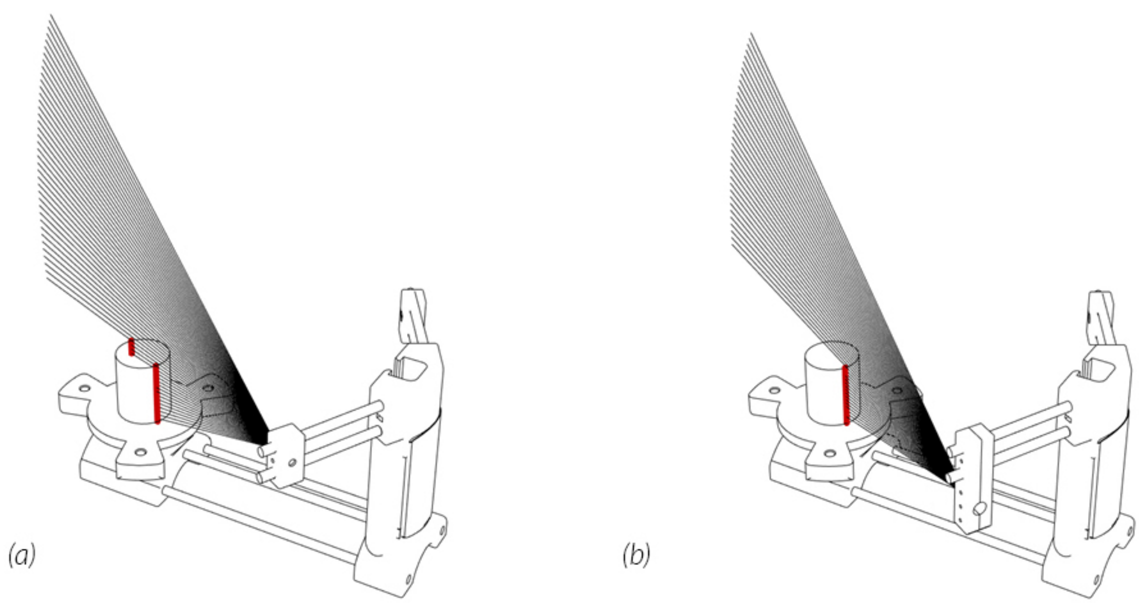

Figure 20. (a) Original laser light source placement, and (b) modified laser light source placement.

Aside from building and tuning the 3D reconstruction subsystem, I have made one significant modification to appropriate the hardware to the proposed workflow. As a commercial kit, linear laser light sources were positioned at the same height as the camera. In many cases, this would not cause any problems because either the scanned object is tall enough to block the light from shining on the back side of the objects or the scanned objects do not have openings to be registered as false positives. As the proposed workflow mainly produces hollow objects, this was an essential problem in how the reconstruction is carried out. For this reason, I have lowered the laser light sources using a custom fitted 3D printed piece to intentionally occlude the light to only shine on the side that is closer to the camera, illustrated in Figure 20 above. This implementation greatly helped with the development of the geometric reconstruction algorithm, eliminating multiple edge cases that need to be considered.

Figure 21. Assembled Laser-Stripe Triangulation Setup.

3.6 Software Development

Following the development of hardware subsystems that are designed to operate in relatively low tolerance, software implementations were carried out to control and regulate essential elements such as 3D scanning, processing of the scan data, toolpath generation, live communication with the industrial robotic arm and coordinate different phases of the proposed workflow.

3.6.1 3D Scanning Setup Control

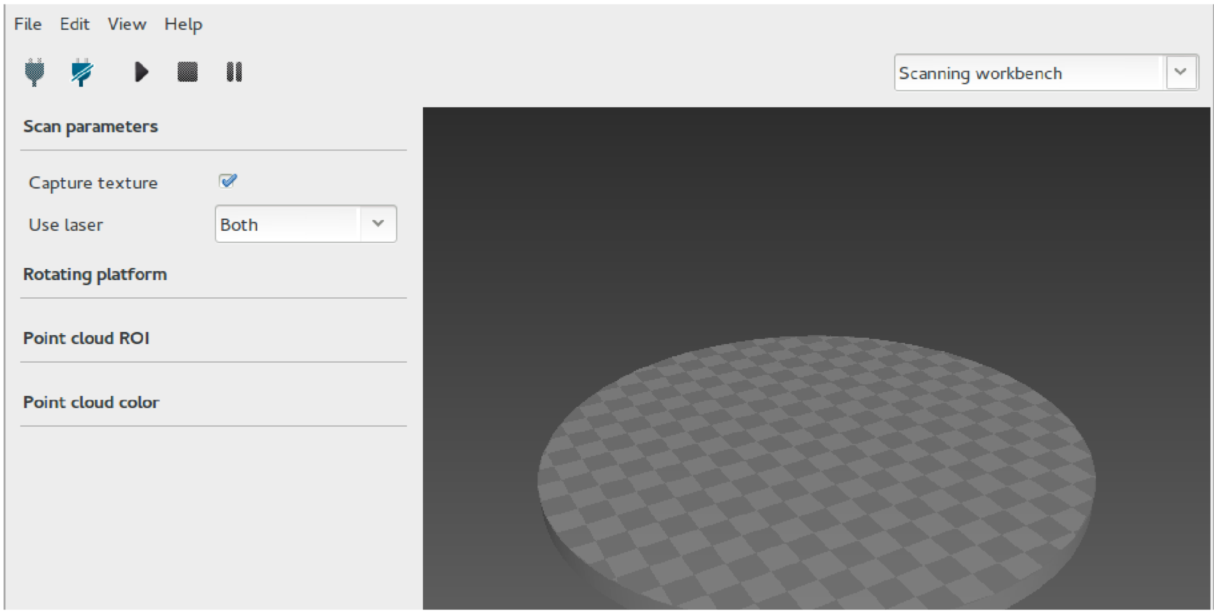

Figure 22. Screenshot from Horus software.

As an open-source software project, Horus is often used with the Ciclop 3D Scanner kit that constitutes the basis of the Computer-Vision feedback setup implemented in this thesis. The software and the algorithms are in the public domain for development and use by other developers (*Horus* [2015] 2019). Even though the source codes for the software is available, the project was discontinued in 2017, which means that full support for new versions of Python, and necessary camera drivers do not exist for development in Windows operating system. During the initial tests, communicating with an onboard microcontroller for controlling the stepper motor and linear laser lights was successful. However, since the version of OpenCV that is specially developed to access low-level onboard camera properties was not available in newer versions of Python programming language, the idea to control and process 3D scanning through Python was not possible. In order to circumvent this problem, I have used the compiled version of graphical user interface software (GUI) for Horus. Since the GUI was pre-compiled, necessary OpenCV version was embedded within the application. Using GUI automating tools such as the pyautogui library, I automated the process of capturing the 3D artifact and controlling hardware parameters.

3.6.2 Geometric Processing and Hypothesis Generation

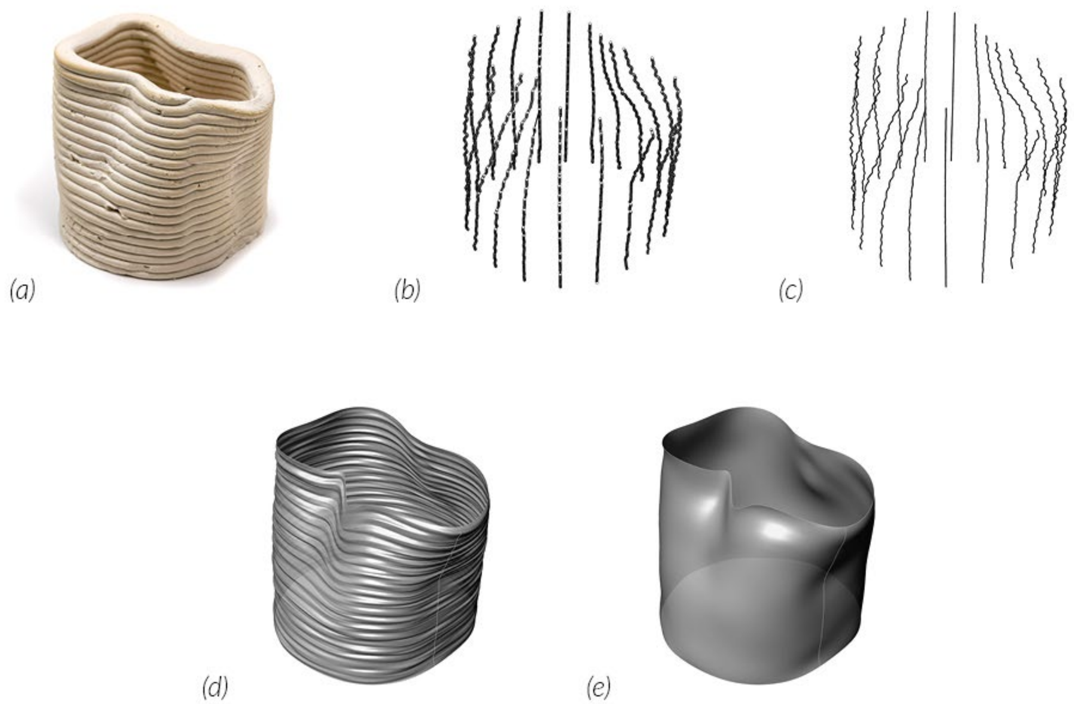

Figure 23. Steps of 3D reconstruction from scan data: (a) physical artifact, (b) point cloud, (c) lines generated from the point cloud, (d) high resolution reconstruction, (e) simplified geometrical reconstruction.

The 3D scanning technique implemented in the proposed workflow inherently processes the artifact into a dense point cloud format. This format is generally suitable for creating mesh surfaces, but since mesh surfaces require vast numbers of point for generating surfaces, the process can often take a very long time. In order to simplify the computation as well as to reduce the time it takes to reconstruct the object digitally, I developed an algorithm which utilizes the NURBS surface definition to reconstruct the surface with fewer sampling using a custom IronPython script in Grasshopper for Rhinoceros 6. In contrast to a standard scanning procedure, the algorithm implemented samples at every 7.5 degrees instead of every 0.45 degrees, which results in low fidelity and relatively accurate representation of the physical artifact as long as the scanned artifact does not contain very minute details on its surface. Since the envisioned interaction generally results in major geometrical features, operating with a 7.5-degree rotation angle was suitable within the scope of the proposed workflow.

Since this technique inherently scans the object a line at a time perpendicular to the scan plane, the algorithm treats each set of samples as section curves and reconstructs a NURBS surface by using these curves as UV curve divisions. These curves are sampled from both lasers placed on left and right side of the camera, providing the flexibility to circumvent any self-occluding geometry by the averaging left and right laser data. These point cloud sections exported by 3D scanning algorithm are then adaptively smoothed by rebuilding these curves with fewer samples according to the maximum Z height sampled from the object in order to eliminate potential noise in the data.

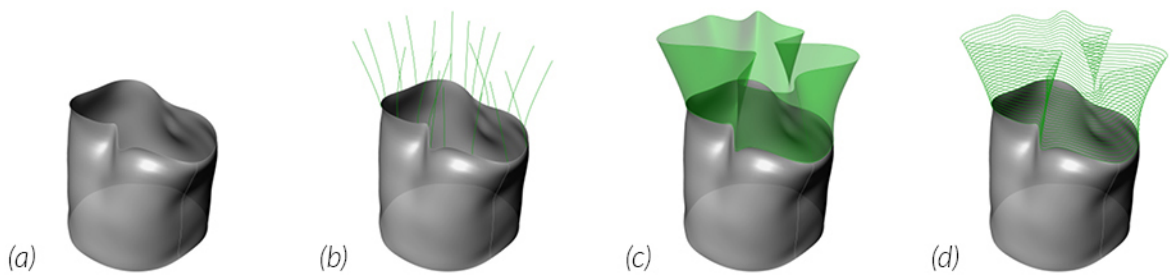

Figure 24. Steps of geometric extrapolation: (a) reconstructed geometry, (b) extended curves, (c) extended surface, (d) generated toolpaths.

Following the reconstruction of the target surface in NURBS definition, the geometric extrapolation algorithm utilizes the surface tangency at the top edge of the reconstructed surface to roughly estimate the geometry for yet to be fabricated layers. This part is extrapolated by extending section lines and reconstructing extrapolated surface using a similar approach to how point cloud is processed. The geometric extrapolation algorithm simply extends the curves obtained from the scan data and generates a surface representation for yet to be fabricated layers.

This algorithm also accommodates for user input to manipulate the generated design hypothesis. As implemented in the proposed experimental setup, the algorithm straightens extrapolated curves to match the World Z vector with a variable parameter. As a user-controlled parameter, this functionality allows users to select the desired curvature of the extrapolated surface. This parameter ranges from 0, meaning that the generated hypothesis is precisely following the reconstructed surface tangency and 1, meaning that the extrapolated surface is a simple extrusion in Z-axis. Once the user confirms the extrapolation of the surface, the algorithm generates the tool paths using the user provided parameters. Since the workflow uses a 6-axis industrial robotic arm as a driving mechanism, the algorithm does not necessarily slice the object as planar curves but instead can accommodate for varying Z height within a particular layer, which enables more complex geometries to be handled and fabricated.

3.6.3 Real-Time Communication Protocol

Another critical component in the functioning of the proposed workflow is the real-time communication protocol. Due to differences in intrinsic programming languages between different industrial robotic arm manufacturers, potential systems that can be implemented in the scope of the proposed experimental were reduced to 2 different libraries, that are capable of working with ABB robots. One of these implementations, OpenABB, supports different coding languages like ROS, Python, and C++, offers the flexibility to integrate custom functions on the industrial robotic arm (*OpenABB* [2012] 2019). Early tests pointed out that implementing OpenABB would require more implementation on development to ensure a stable connection and safe movement of the robot. RobotExMachina on the other hand, developed by Jose Luis Garcia del Castillo(Garcia del Castillo [2018] 2019), offers more convenient interfacing with the industrial robotic arm. Since the developed interface is capable of ensuring safe operation of the robot, stable connection and user-friendly graphical user interface, *Machina-Bridge* significantly helps to find programming mistakes during the development of the experimental setup.

As a library based on .NET programming architecture, in order to integrate it with other algorithms developed in Python 3.6, a Python wrapper developed by Garcia del Castillo and Bidgoli (Garcia del Castillo and Bidgoli [2018] 2019) was used in the development of the real-time communication protocol. The reference Python library used the User Datagram

Protocol (UDP) connection to the intermediary graphical user interface to push desired commands from Python to *Machina Bridge.* Although both *Machina-Bridge* and *Machina-Python* offered promising results, allowing command execution over Python. However, when tested with more complex computational operations required by the proposed workflow, some problems were observed, causing the connection to be interrupted or the industrial robotic arm to move irrationally.

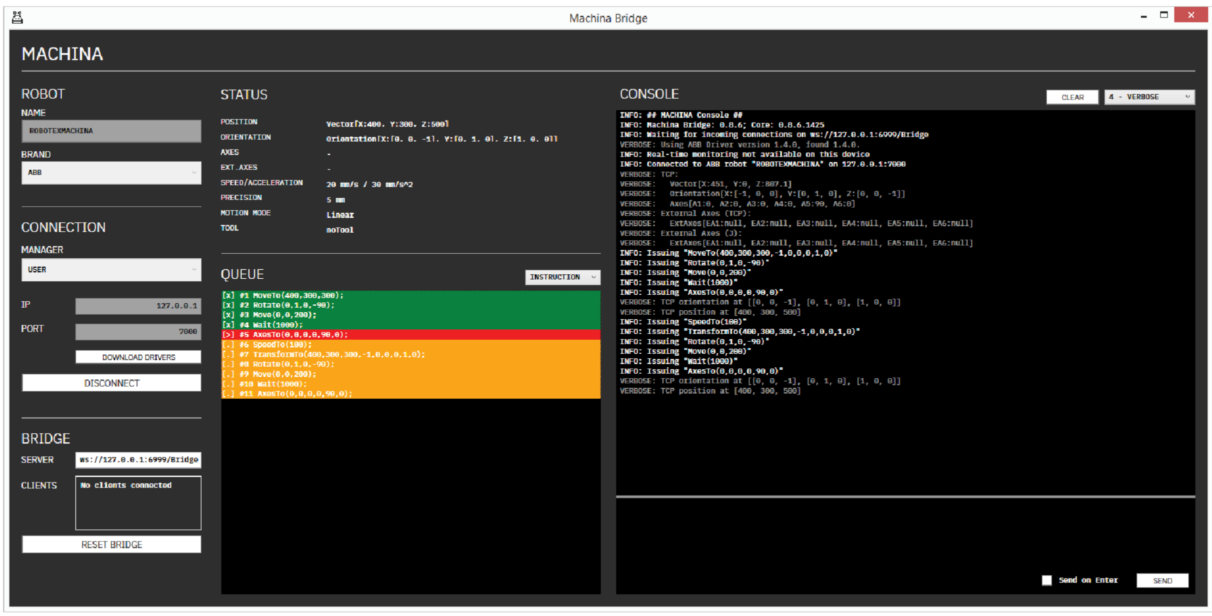

Figure 25. Machina-Bridge screenshot.

This problem was due to how *Machina-Python* is implemented to establish a connection with *Machina-Bridge.* In the original version of the implementation, when a command is pushed *Machina-Python* would establish a connection, send the command over UDP and close the connection. When multiple commands were needed to be pushed, for example when a tool path consisting of 100 target points is sent, these commands would be processed one by one, establishing and closing a connection for each target point. In order to circumvent this problem, I implemented a new version of the library using a first-in-first-out queue data structure to enable queued commands to be pushed as a batch, significantly reducing the number of established connections from *Machina-Python* to *Machina-Bridge.* In addition to the algorithmic fix implemented, I have developed a monitoring algorithm which continuously reads cartesian X, Y, Z coordinates of the Tool

Center Point and computes the distance to a target point to keep track of executed commands on Python implementation.

3.6.4 Software Coordination

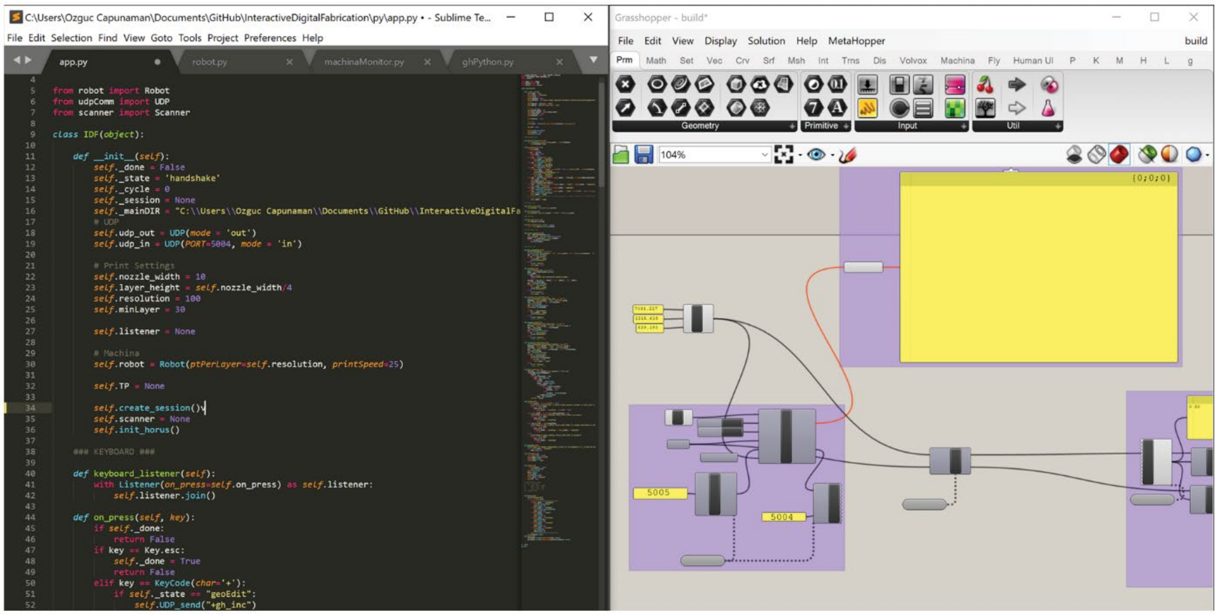

Figure 26. Python application and Grasshopper script developed for the proposed workflow.

Following the implementation of previously mentioned algorithms and protocols, I developed a Python 3.6 based application to coordinate the flow of information between different subsystems as well as to integrate user input through keypad introduced earlier. This application mainly oversees the operations of 3D scanning setup, real-time communication protocol, geometrical algorithms implemented in Grasshopper for Rhinoceros 6 and user inputs. It enables or disables these different subsystems using the different states implemented in the application to prevent unintended actions that can potentially damage the artifact and pose a safety risk for the users.

The application can create a file directory specific to the current workflow session when initiated and perform a handshake with other systems to inform them of the session repository directory to allow all other systems to access the right directory. As previously described, using the pyautogui library, the application can control necessary functionalities of the Laser-Stripe Triangulation setup such as enabling the stepper motor to ensure the artifact stays stationary during the fabrication process. Moreover, the application automates scanning the artifact and saving the scanned data to be used by the geometric reconstruction algorithm. Using a UDP connection established between Python 3.6 and Grasshopper for Rhinoceros 6, the application can push the saved scan data in XYZ format and request tool path, providing necessary parameters required for the task. Once the requested tool path information is provided, the application then can push each layer to *Machina-Bridge* using *Machina-Python* library and continue until fabrication of all layers is complete, or the user sends an input to pause the process.

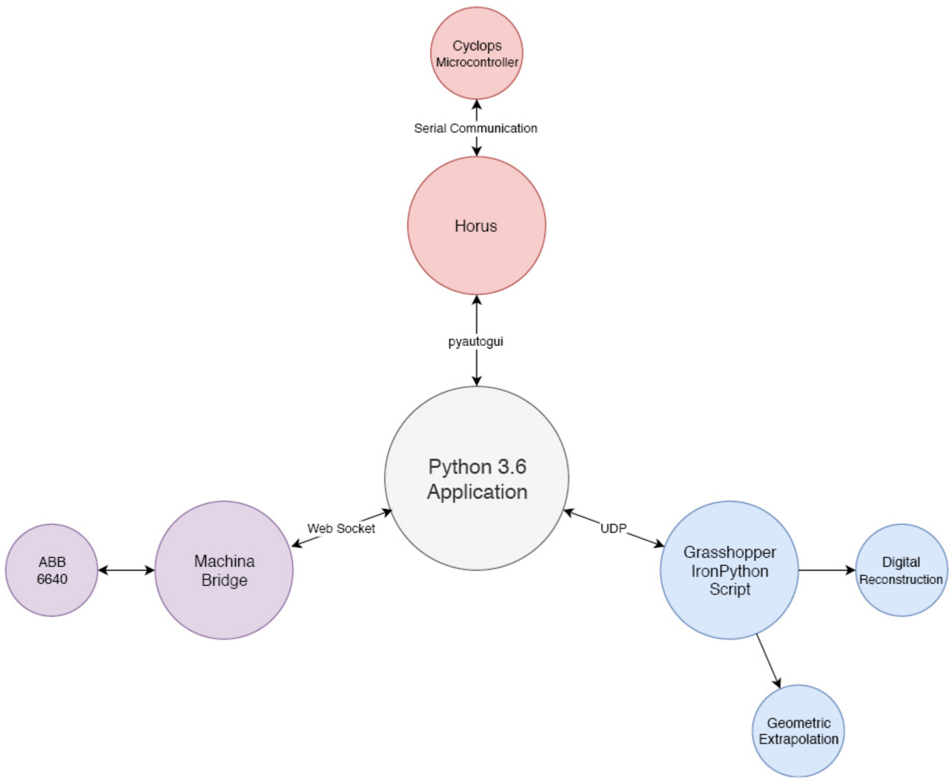

Figure 27. Communication between different software implementations.

Communication over the UDP connection between the application and Grasshopper requires specific encoding of the messages. A typical message convention implemented for this setup would consist of an indicator that specifies the recipient of the message and which specific task is requested to be performed by the geometric reconstruction algorithm along with necessary parameters required for this operation. In the example of handshaking between the application and the geometric reconstruction algorithm, an encoded message similar to *gh_handshake_20190423_100_2.5* is composed and sent over UDP. When split at the '_' character, the message can be decoded into an array of [*'gh', 'handshake', '20190423', '100', '2.5'*]. Each element in this array can be read by the reconstruction algorithm to modify subsequent values. In this particular case, the first element in the array, *'gh'*, signifies the recipient of the message. The second element, *'handshake'* informs the reconstruction algorithm that a handshake is requested. Following two elements, *'20190423', '100'* and *'2.5',* inform the function of the session tag, desired curve division count for each layer and layer height respectively. Unlike Transmission Control Protocol (TCP), UDP inherently does not wait until all message packages to be confirmed by the other end. In order to circumvent this problem, another UDP connection is established to return a message of *py_success* to signify that the requested task is executed by the algorithm to ensure the progression of the workflow without necessary information obtained from any side of the connection.

3.7 Workflow Walkthrough

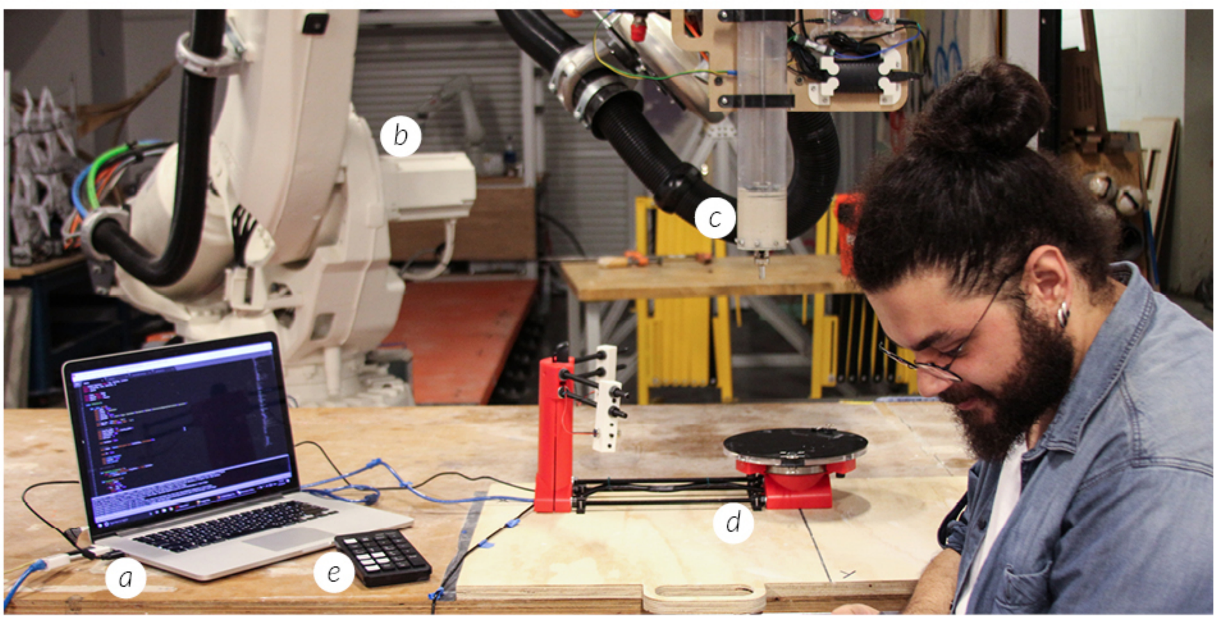

Figure 28. Proposed experimental setup. (a) computer, (b) industrial robotic arm, (c) Mechanical Paste Extruder, (d) Laser-Stripe Triangulation, (e) keypad.

As previously delineated, the proposed experimental setup consists of a (a) computer which, (b) an industrial robotic arm, (c) a Mechanical Paste Extruder, (d) a Laser-Stripe Triangulation setup and (e) a keypad as shown in Figure 28. These elements constitute the set of hardware users engage throughout the proposed workflow. This section delineates the user's interaction with these hardware and documents an exemplary interactive fabrication scenario throughout two complete cycles of fabrication with the experimental setup.

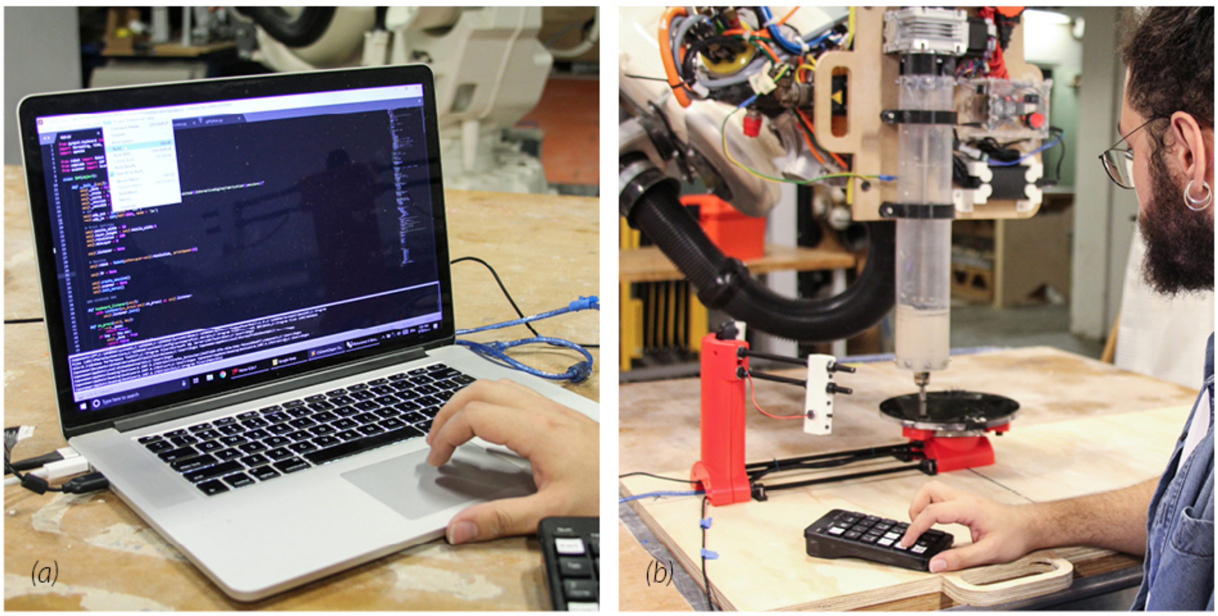

Figure 29. (a) Initiating Python 3.6 application, (b) initiating the fabrication of the initial geometry.

The proposed design-fabrication workflow starts with the initiation of the Python application and the IronPython script (Figure 29.a). This initial step is crucial for establishing a robust communication between two software instances, and it is enforced by the Python application since during this stage, a virtual handshake is performed between different subsystems. This virtual handshake ensures that all subsystems connected to the Python application are ready to carry out any task execution requests. Furthermore, users can alter initial geometry within Rhinoceros environment. Within the scope of this example, a basic cylindrical geometry is set as the initial geometry. Following the software initialization, the user initiates the fabrication of the user-defined geometry (Figure 29.b).

This fabrication process is carried out until the system runs out of layers to fabricate or the user stops the fabrication.

Figure 30. (a) Physical deformation of the fabricated artifact, (b) 3D capturing of the modified artifact using Laser-Stripe Triangulation Setup

Once the fabrication stage terminates either due to lack of layers to fabricate or by user input, the proposed experimental setup transitions to the subsequent stage. In this stage, the industrial robotic arm moves out of the fabrication build volume and allows the user to engage with the material. As previously mentioned, the proposed workflow does not restrict the material deformation imposed by the user on the fabricated artifact. Although deformations that follow certain types of constraints yield better results, it is left open-ended on purpose to preserve the rich design space. Figure 30.a depicts the user manipulating the artifact using his hands. Once the user is satisfied with the geometry of the artifact, the user can request 3D capturing of the geometry through the keypad. The Python application processes the request and initiates the Laser-Stripe Triangulation setup through automated GUI and handles data transfer between different subsystems to reconstruct the geometry digitally.

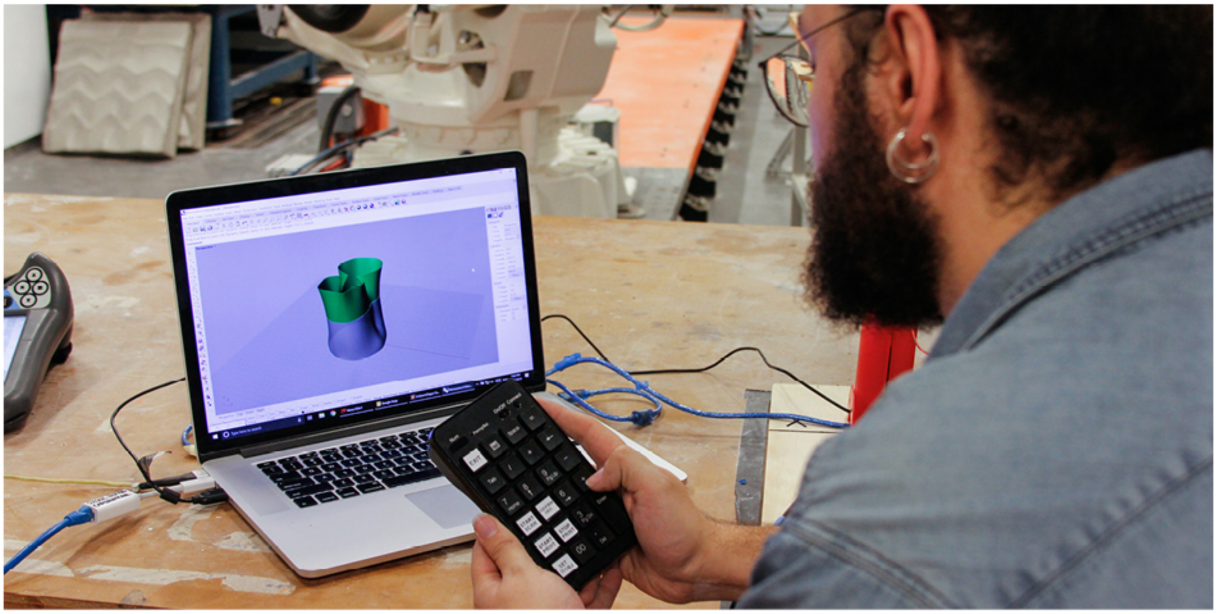

Figure 31. User cycling through design hypotheses generated by the extrapolation algorithm.

Following the digital reconstruction of the fabricated artifact using the 3D scan data, the geometric extrapolation algorithm proposes a design hypothesis generated using the captured surface tangency at the top edge of the artifact. As shown in Figure 31, the user can cycle through different hypotheses generated by the algorithm using '+' and '-' keys on the keypad. These keys increase and decrease compliance with the captured surface tangency, which enables the user to have greater control over the extrapolated geometry. Figure 32 shows the range of extrapolated geometries that the user can choose from, *vecMul* parameter signifying the deviation from geometric extrapolation generated using only the surface tangency data. In the case in which the user is not satisfied by any of the design hypotheses generated, the user can further deform the artifact, and request re-capturing of the new geometry and repeat this hypothesis generation multiple times.

Figure 32. Generated design hypotheses for the physical artifact.

After the user confirms the geometric extrapolation and target points for each layer are generated by the geometric processing algorithm, the fabrication of the extrapolated geometry begins. Throughout the fabrication of the extrapolated layers, the user can intervene with the process, end the fabrication if needed and transition back to physical deformation stage. The experimental setup allows for multiple iterations of user intervention to the physical artifact and generates different hypotheses depending on the state of the artifact. When the desired geometry is achieved, the workflow can be terminated through keypad input.

Figure 33. (a) User controlling the extrusion rate to ensure better adhesion between fabricated artifact and extrapolated layers, (b) finished fabrication of the extrapolated geometry.

4 Results and Discussion

4.1 Early Results

While developing the hardware and software, I have tested the validity of different variables in the proposed workflow. The variables tested in the early phases of the development range from the performance of the material used in the fabrication process to how compatible implemented subsystems are in executing tasks requested by other subsystems in terms of error tolerance. Although these variables are closely interlinked in determining the performance of the proposed experimental setup, I have conducted preliminary tests using readily available tools such as offline toolpath programming for the industrial robotic arm, and graphic user interface for the Laser-Stripe Triangulation setup. These tests were crucial in delineating limitations and potentials in the early phases and informed the development process greatly.

4.1.1 Material Affordance

Figure 34. Cross-section of an artifact fabricated using the implemented Mechanical Paste Extruder.

As an essential factor in determining the validity of the proposed workflow, I tested material affordances in detail, primarily focusing on how suitable the material of choice is to requirements of different subsystems. By using offline programming for testing purposes, I mounted the extruder on the industrial robotic arm end and tested both material properties, and the performance of the mechanical paste extruder through the fabrication of cylindrical samples. During these experiments, I tested the performance of the clay with two different layer height parameters and two different end-of-arm-tool speeds. Following the common additive manufacturing conventions, the tested layer heights were quarter and half the dimension of the 10mm nozzle used in fabrication, 2.5mm, and 5mm respectively. Additionally, I have set the end-of-arm-tool speeds at 25mm/s and 50mm/s. As per the initial tests, the porcelain clay offered high plasticity and a large window for physical manipulation after being extruded. Depending on the humidity conditions of the environment, the fabricated artifact allowed for deformation for two to three-hour time period, with no visible damage to the artifact due to deformation within that time frame. However, when tested for layer adhesion, 2.5mm layer height in combination with 25mm/s end-of-arm-tool speed proved to perform better.

During these tests, another critical advantage of using paste material I have observed

Figure 35. Clay deposition recovering from fabrication errors: (a) layer-layer adhesion, (b) layer-build plate adhesion.

was the material plasticity. As with all the additive manufacturing processes, the flow of material can sometimes be disturbed. In the scope of this setup, some of the main reasons for such fabrication problems were due to air pockets present in the chamber or partial blockage of the nozzle due to material losing water content over time. Throughout long testing cycles, the nozzle that was exposed to the air dried up much quicker than the rest of the clay stored in the chamber. In some cases, this resulted in a delay between the moment the stepper motor started running and the moment the clay started extruding out of the nozzle. This problem was due to higher forces needed to displace the dried clay out of the nozzle, and the Mechanical Paste Extruder would need to build up pressure over a short period to displace the blockage. The partially blocked nozzle posed some problems especially during the fabrication of the initial geometry. Air pockets trapped in the chamber, however, caused problems during the ongoing fabrication of layers, disturbing the steady flow of material. Even though the flow of material was disturbed during some of the initial tests, the clay was able to quickly compensate for such imperfections within three layers of deposition by filling the gap with the help of clays inherent plastic nature.

4.1.2 Subsystem Compatibility

Before the Python application for coordinating the data flow is implemented, I have manually tested fabrication, scanning, and digital reconstruction processes to observe the working tolerances of each subsystem. As it can be seen in Figure 36, these tests were carried out at both 0.25 and 0.5mm layer heights. Throughout these tests, each subsystem yielded low tolerance outputs for the subsequent task. From digital toolpath to the physical artifact, the difference in dimensions averaged to ~0.5mm and ~1.25mm respectively for artifacts fabricated using 0.25 and 0.5mm layer height values. The deviation from physical artifact to unprocessed scan data were observed at ~0.75mm for both layer height parameters. Lastly, from unprocessed scan data to rebuilt digital representation the deviation averaged to ~1mm and ~2mm for 0.25 and 0.5mm layer heights. In comparison to the dimensions of the artifact used in these tests, the cumulative errors were less than 2% and 4% respectively for 0.25mm and 0.5mm layer heights. As initial tests, these experiments yielded promising results and relatively low tolerances that can be compensated with other implementation factors such as usage of large nozzle diameter and material plasticity.

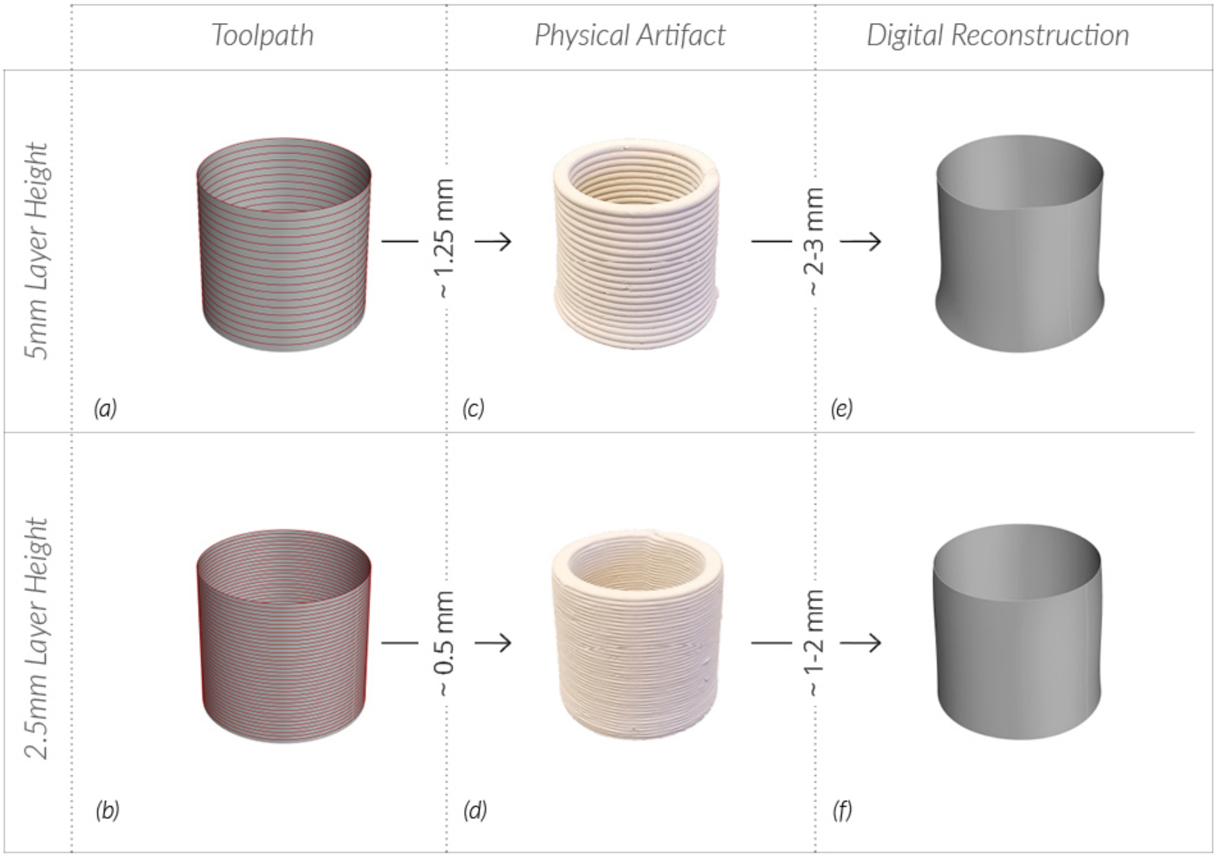

Figure 36. Laser-Stripe Scanning using porcelain clay: (a) fabricated artifact, (b) laser shining on the artifact, (c) Laser light extracted from red channel, (d) weighted average.

In addition to a small window of tolerance that the clay offers in the process of digital 3D reconstruction of the fabricated artifact. As briefly mentioned above, Laser-Stripe triangulation scanning yields better results with matte surfaces. Furthermore, since the material finish is white and matte, the laser stripe can be extracted with high precision as it can be seen in Figure 37. In combination with controlled external light settings, adequate calibration of the subsystem and desirable material finish of the porcelain clay, Laser-Stripe Triangulation system yielded accurate results with minimal noise.

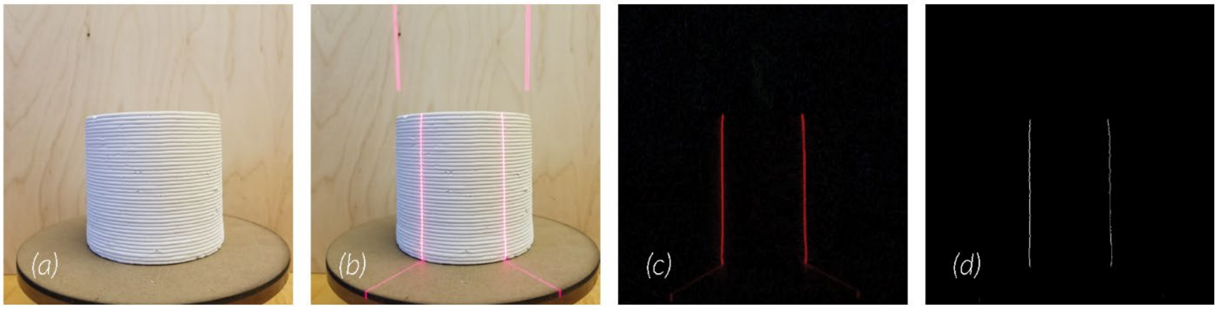

Figure 37. Dimension deviation from (a,b) 3D toolpath, to (c,d) fabricated artifact, to (e,f) digital reconstruction.

4.2 Experiment Results

4.2.1 Design Space

Following the initial tests with separate subsystems, I carried out additional tests using the fully developed experimental setup. Throughout the experimentation phase of this research, no specific design goals were set. Instead, these tests mostly focused on developing a keen understanding of the system's capabilities, pinpointing the limitations and testing the proposed workflow for validity. Many of the early tests with the implemented system were failures in terms of computational workings of the system. As I addressed these problems, I observed promising results, hinting at successful capturing of design intent through geometrical decomposition.

As a tool for creative exploration, the proposed workflow enables a vast design space. Although this design space is subject to some significant limitations, further explained in the next chapter, the proposed design-fabrication workflow provides an open-ended method for creative inquirers. As a system that draws its input from the physical artifact and the user, the majority of the process is not defined by discrete representation methods. Instead, users are encouraged to define geometry through material interaction with the fabricated artifact. The definition of the designed artifact is embedded in the material form, rather than optimized computational representation methods. These experimentations proved that the proposed experimental setup could successfully capture different topologies such as flat, positive and negative curvature surfaces and perform geometrical computation over the data extracted from the physical artifact.

The proposed workflow not only helps users build a better understanding of the material and the technique employed in the process but also presents an opportunity to refine the design iteratively. Within the large window of interaction that the clay offers, the user can iterate multiple cycles of scanning, extrapolation, and fabrication. The initial design can change significantly during the design-fabrication process, allowing the user to develop design ideas as the workflow progresses. Furthermore, the proposed workflow embraces material and computational failures. Contrary to contemporary Computer-Aided tools where errors and failures are a substantial barrier to the user, the proposed workflow situates these as learning opportunities. Since the material used in the system offers material plasticity, the proposed setup can overcome minor failures through different iteration cycles, positively impacting the users understanding of the system.

Figure 38. Experiment outcomes.

Figure 38 above, illustrates the consecutive stages of experimentation with the system. Initial tests primarily focused on testing proper fabrication of the artifact for the user to manipulate and build upon. The subsequent stage shows clear progress in geometrically extrapolating the physical artifact. Even though experiments conducted in this stage failed due to implementation inherent problems, extrapolated layers followed the geometric contours of the fabricated artifact and the surface tangency, hinting that design intention was captured on an elementary level by the machine agent.

Additionally, the machine agent is enabled to contribute to the design space actively. Through geometric decomposition of the fabricated artifact, the machine agent can offer design hypotheses to widen possible directions the human agent can potentially take. Although the implemented digital reconstruction and hypothesis generation algorithms are very basic in computational complexity, it enables the machine agent to converse with the human agent over form. This behavior of the proposed system encourages the user to explore the design space through different approaches to physical manipulation or tuning the parameters for the design hypothesis. Throughout the testing of the proposed workflow, the experimental setup was successful at capturing geometrical data and use this information to generate design hypotheses. Figure 39 exemplifies three different geometries that are fabricated using the proposed design-fabrication workflow. Although both geometric reconstruction and extrapolation algorithms result in low fidelity digital reconstruction and minor errors in the fabrication of the extrapolated layers, these implementations successfully capture the state of the artifact and adapt fabrication tool paths accordingly.

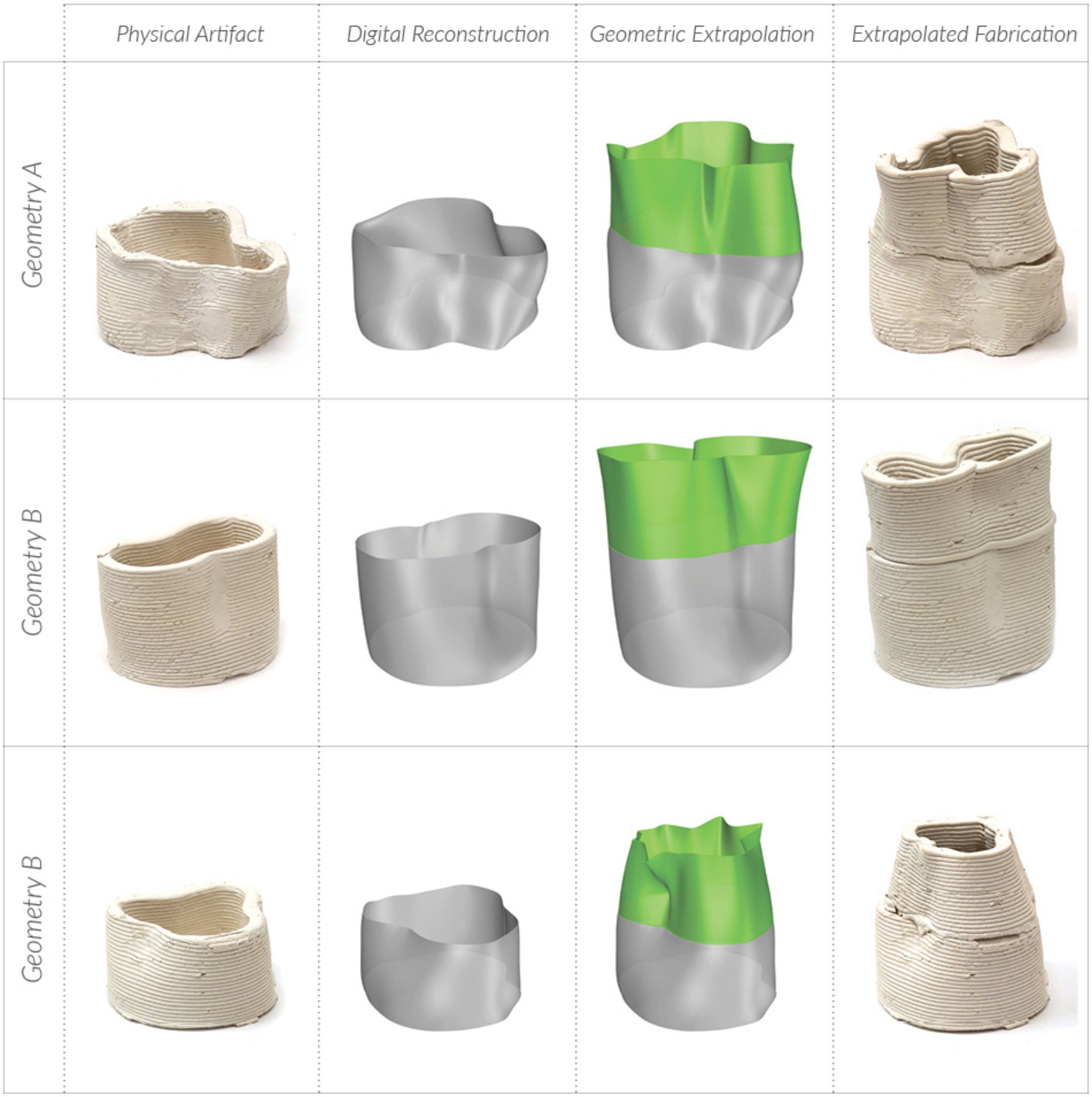

Figure 39. Processing of design hypotheses for three different geometries.

4.2.2 Facilitating Human-Machine Dialogue

As one of the main objectives of this thesis, the majority of the experiments conducted with the fully functional system focused on exploring the extent of human-machine dialogue facilitated by the proposed workflow. Since the proposed system primarily relies on user inputs throughout the workflow, moments of human-machine dialogue emerged frequently. Some of the most exciting interactions with the system occurred during the fabrication stage executed by the machine agent and deformation of the artifact executed by the human agent.

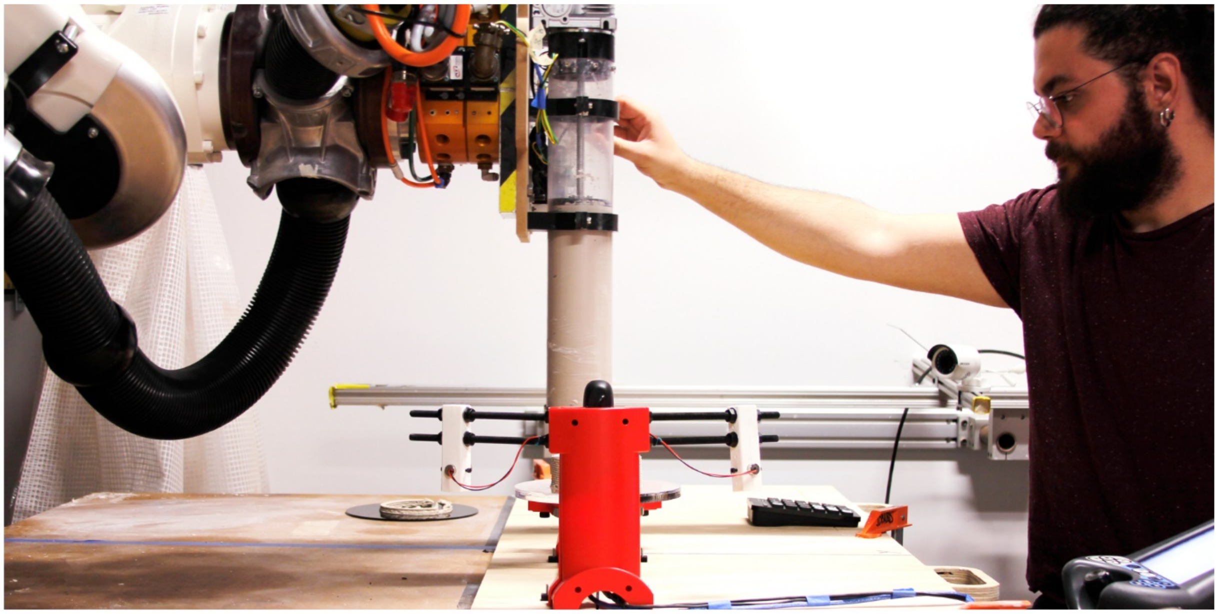

Figure 40. User controlling extrusion rate during the fabrication process.

The implemented microcontroller circuitry enables an interesting dialogue during the fabrication process. One of the original intentions for not fully automating the mechanical paste extruder was to allow users to intervene with the fabrication of the artifact. As tests were being carried out to test the system, small imperfections explained in the previous section due to lack of adhesion between the build plate and the clay or partial nozzle blocks due to drying material over time were observed. Even though the system recovered from these problems, real-time control of the extrusion rate proved to be very valuable during the recovery of the fabricated artifact. The user was able to manipulate the extrusion rate accordingly to help the system overcome the problem faster. For example, in order to ensure proper adhesion to the build plate, the user can slightly increase the extrusion rate during the fabrication of the first layer or slightly decrease it to apply more torque on the extruder plunger to prevent the stepper motor from jamming which would result in extrusion to stop. Moreover, any significant gaps within the layers due to small air pockets trapped during the loading of the clay chamber can be circumvented by tuning the extrusion rate accordingly on subsequent layers.

In addition to the real-time tuning of the fabrication system, another instance of the human-machine dialogue was observed over the design hypothesis proposed by the machine agent. In this intended instance of creative dialogue, both parties engaged in a conversation where the human agent altered the parameters and the machine agent proposed a geometrical extrapolation in return. Although the implemented geometric extrapolation algorithm is very basic in complexity, using only surface tangency to generate the extrapolation, a range of hypotheses was observed. In response to the generated hypothesis, the user was given the flexibility to tune the parameters or re-deform the physical artifact and initiate reconstruction of the new geometry.

Furthermore, the proposed experimental setup was successful at introducing deliberate seams to the workflow. Since the human agent is given more control over the geometry and fabrication parameters, moments of learning-in-action occurred throughout the process. Similar to the case of real-time control of the extrusion rate, these moments allowed users to have a better understanding of the tool and the material overall. Moreover, users can iterate on their newly gained knowledge of the tool or the material, to engage a more fruitful conversation with the system. These insights range from learning how to help the system to have better adhesion to discovering the extents of possible geometric manipulations. These reflections would help the user to take informed actions during the design-fabrication process.

Overall, the proposed design-fabrication workflow was successful in facilitating a creative conversation that contributed to the design and fabrication of the artifact. Even though this conversation facilitated by the implemented experimental setup is a low fidelity one due to system limitations, the computational systems was capable of supporting the creative exploration first by capturing the fabricated artifact through computer-vision based feedback and updating the digital representation, and by presenting design hypotheses generated by the data obtained through digital reconstruction of the artifact.

4.2.3 Affordances of the Proposed Workflow

Figure 41. Alternative initiation of the proposed workflow: (a) Hand sculpting the clay artifact, (b) extrapolated layers from digital reconstruction of the artifact.

Within the scope of this thesis, the implemented design-fabrication workflow is initiated by the fabrication of user-defined geometry, further detailed earlier in this chapter. This workflow facilitates the envisioned interaction by providing an adequately sized physical artifact, which the user can manipulate in later stages. However, the proposed system does not necessarily enforce this initial stage. With the help of flexible implementation of subsystems detailed above, the workflow can afford different interactions to enrich the potentials of the workflow. In an alternative configuration, the user can initiate the proposed workflow with the scanning stage. This flexibility in how the workflow can be initiated enables the machine agent to develop a hypothesis over hand-shaped clay artifacts and prefabricated artifacts that made out of suitable materials for the implemented system. For the purpose of testing this potential, I have initiated the workflow with the 3D capturing of a hand-sculpted clay object shown in Figure 41.a. The 3D scan data was accurate and captured a considerable amount of detail from the hand sculpted artifact. Using the implemented extrapolation algorithm, I have later extrapolated the hand sculpted geometry. The extrapolated layers were promising, successfully tracing the outer edges of the artifact and incorporating tangency data from the reconstructed artifact (Figure 41.b).

Figure 42. Incorporation of sculpting tools into the proposed workflow: (a) subtracting material from the artifact, (b) applying surface finish on the fabricated artifact.

In addition to how the workflow can be initiated, the proposed system does not predefine the method of geometrical deformation. The proposed workflow envisions the deformation of the fabricated artifact through hand manipulations, which implicitly ensures that the geometrical deformations effect a large volume of the geometry and change in surface curvature is gradual. This inherent limitation works in favor of the scanning setup implemented in the system which uses much fewer numbers of sampling. However, the incorporation of tools is possible to a certain extent. Using traditional clay sculpting tools, such as ribbon tools, potter's ribs, and sponges can be used throughout the process to shape the artifact, subtract material and finish the surface. In order to test the potentials of incorporating sculpting tools into the proposed workflow, I have tested the fabricated artifacts for (a) subtracting material from the top rim of the geometry and (b) applying a smooth surface finish, depicted in Figure 42. These tests yielded promising results as the sculpting tools provided better control over the geometric deformation process.

Even though these alternative workflows and incorporation of sculpting tools are not tested extensively, the proposed system is inherently capable of affording these potentials without any additional implementation on the software or hardware level. These kinds of open-ended potentials can play a crucial role in widening the design space presented by the proposed workflow.

4.3 Discussion

Throughout the development of the proposed design-fabrication workflow, this thesis aims to address the shortcomings of computer-aided systems described in the first chapter. As tools mainly concerned with representation, providing high accuracy and consistently replicable results, contemporary computer-aided systems still stand as valuable tools to designers in various fields. Rather than completely negating the advantages proposed by these systems, the proposed workflow offers an alternative approach to how these systems can facilitate creative exploration through physical mediums and assist human-machine dialogue. As an experimental setup, the proposed workflow probes computer-aided systems beyond representation-heavy role in contemporary design practice.

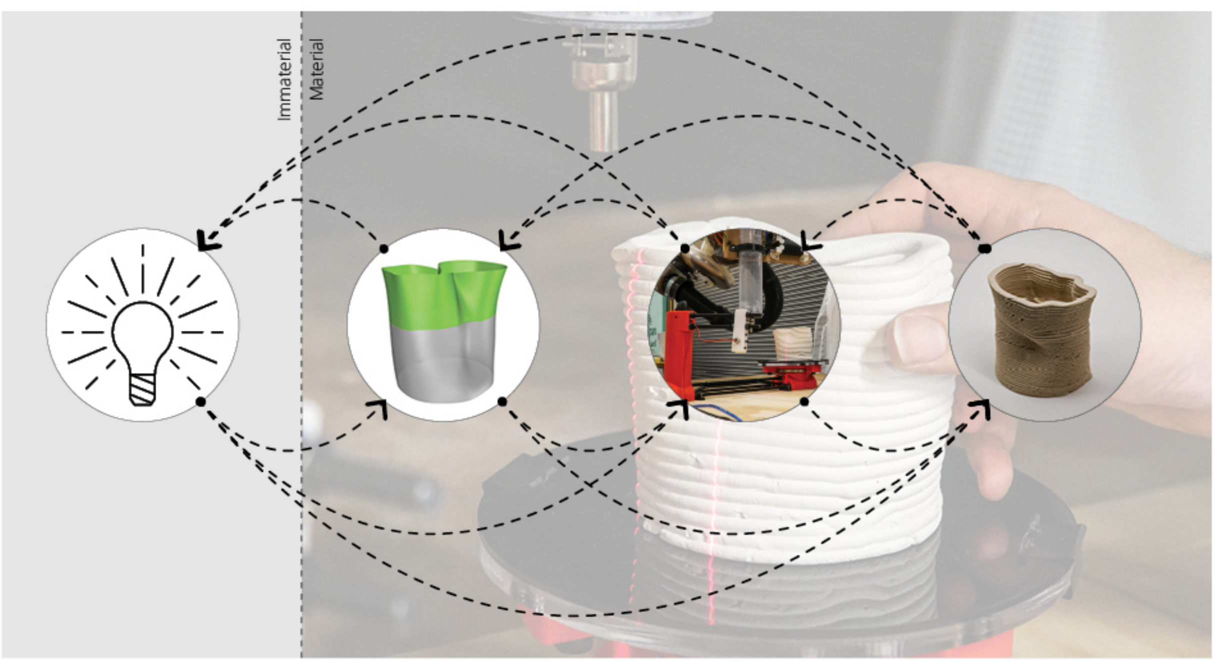

Figure 43. The evaluation of the proposed workflow over immaterial and material stages.

A straightforward goal achieved by the proposed design-fabrication workflow is that the experimental setup establishes a bi-directional workflow beyond point-click-type interactions. As discussed earlier, this workflow is composed of different stages and different subsystems that inform one another. These stages and the flow of information between those stages are carefully orchestrated at the implementation level. The proposed system is capable of facilitating more conversational workflow and introduces seams throughout to allow users to develop a better understanding of the tool and the technique deployed. Furthermore, users are given greater control over the transition between different stages which rarely results in the execution of these stages in the same order.

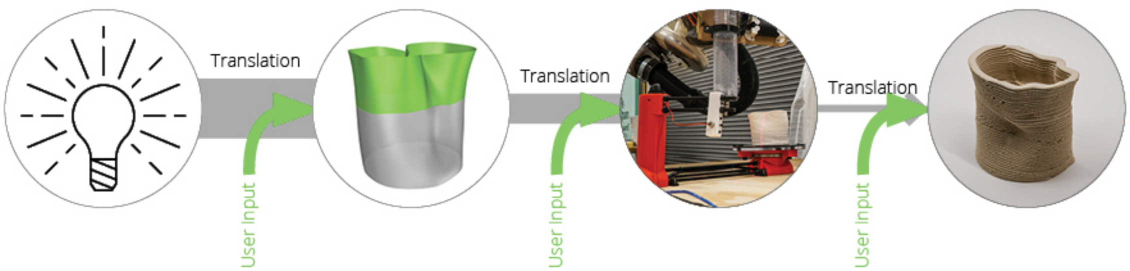

Figure 44. Incorporation of user input in the proposed workflow.

In addition to addressing linear implementations of contemporary systems, the proposed workflow also presents an alternative approach to how computation can be executed over physical mediums. As the medium for interaction with the fabricated artifact, this workflow places design-fabrication process away from well-established interfaces such as screens, pointing devices and keyboards. The flow of information within the proposed design-fabrication workflow executes design-fabrication process over bodily interaction with the matter itself. Although the reliability and the fidelity of the information obtained from the artifact remain questionable due to limitations detailed in the next chapter, it is evident that the systems can capture design intention on an elemental level through the geometrical decomposition of the physical artifact. This information can inform the digital representation of the artifact, synchronizing the physical and the digital.

As detailed in previous sections, the experimental setup proposed in the scope of this thesis still relies on discrete computation to process scan data, reconstruct the digital representation and provide a design hypothesis. Although the processing of information can be less accurate and more discrete at times due to system limitations on machine-driven tasks, higher control over the workflow given to the dexterous human agent can still introduce ambiguity to the proposed workflow. Since the fabricated artifact is the medium for introducing design intention to the computational algorithms, the inputs intrinsically are variable and can be iterated by the human agent to explore the capabilities of the systems. Moreover, by introducing parametric control of the hypothesis presented by the machine agent and enabling fabrication of non-uniform geometries with varying Z height, the proposed system can provide more adaptive workflow beyond discrete and generic processing of geometries.

Overall, the proposed design-fabrication workflow addresses the majority of the shortcomings detailed in previous chapters with varying degrees of success. The proposed experimental setup proved that once necessary calibrations for each subsystem is made and coordination in between these subsystems are established, the proposed workflow proved to provide much needed human-machine dialogue and facilitate creative exploration with the use of computational systems.

5 Conclusion

5.1 Conclusion

Through the development of this experimental setup, this thesis provides an alternative workflow for Computer-Aided Design and Manufacturing systems that facilitate human-machine dialogue. By enabling users to design through the fabricated object, the proposal shows that computation can be executed through physical mediums and embodied actions by incorporating a reciprocal flow of information to facilitate creative exploration.

The proposed workflow detailed in this thesis addresses the shortcomings of Computer-Aided design systems detailed in the first chapter. As the primary goal of this research, the experimental setup demonstrates the value of human-machine dialogue in contrast to imposing ideas and forms. Although the experimental setup detailed above relies on the carefully orchestrated flow of information and algorithms, the proposed design-fabrication workflow illustrates the power of conversational interaction with computer-aided systems in informing the designer throughout the workflow. It encourages users to learn in action with the materials and the tools available to them and iterate over the knowledge-in-action built over interacting with the system.

Furthermore, through the integration of already existing computational techniques, this thesis shows that discrete digital representations and physical artifacts do not necessarily have to be different entities. Instead, it exemplifies how digital representations can work hand in hand with physical artifacts to facilitate creative explorations in design. Lastly, the proposed experimental setup solves the problem of multiple layers of discretization by deliberately introducing user inputs within the workflow. By giving more extensive control over both the design and fabrication process, the proposed workflow positions the user as an active agent within the process. Active participation in design-fabrication workflow allows creative inquirers to directly impose design intention over the fabricated artifact and converse with the machine agent to discover different potentials.

Additionally, the proposed workflow addresses the generic implementation problem of contemporary computer-aided systems. The implemented setup demonstrates how adaptive design and fabrication tools that provide much-needed flexibility in creative exploration beyond highly structured representations and implementations. The flexibility offered by these tools is very critical in the design and fabrication process as adaptive systems have the capability to harvest the full potential of materials and forms alike.

Within the scope of historical and contemporary theoretical body of work detailed in the background chapter, this research delineates how the paradigm shift in the role of the designer within the practice limited designers to the immaterial realm, primarily concerned with the representation of the artifacts. Through these precedents in tandem with the proposed workflow, this thesis was able to exemplify how knowledge gained through deliberate seams within the workflow can play a crucial role in informing design decisions. Moreover, this thesis argues that computer-aided systems need to be explored beyond typical *hylomorphic* and unidirectional implementations in order to better reflect design potentials inherent in material nature. It exemplifies how arduous tasks of design, primarily fabrication is integral to the design process.

5.2 Contributions

This thesis proposes an alternative approach to appropriate Computer-Aided Design and Manufacturing tools for creative exploration by introducing real-time interaction elements to the widely popular additive manufacturing process. The proposed design-fabrication workflow explores the potentials of computer-aided systems in creative scenarios enriched by human-machine dialogue, expanding on the discourse surrounding interactive/adaptive digital fabrication area. Through the introduced interactivity, this thesis aims at embracing ambiguity and failures during the design-fabrication workflow and encouraging users to learn from these moments of learning-in-action.

Building upon the existing body of work investigating interactive and adaptive fabrication, the proposed experimental setup introduces computer-vision based 3D reconstruction algorithms to capture geometrical information obtained from the physical artifact in interactive and adaptive fabrication scenarios. As an immediate impact, the incorporation of computer-vision based algorithms allows the computational systems to capture geometry in three dimensions. Additionally, this thesis demonstrates how simple geometric processing of data obtained from 3D scanning setup can be used to generate design hypotheses that informs the user by illustrating a range of possibilities. Using this 3D data obtained from Laser-Stripe Triangulation and the geometric processing algorithms, the proposed workflow exemplifies how additive manufacturing can be appropriated to adaptive fabrication scenarios, facilitating three-dimensional extrapolation of the artifact.

This thesis was constructed to probe the implementations of computer-aided systems beyond representation and automation oriented contemporary tools. It proposes a new model of design-fabrication workflow, by which this thesis aims to contribute to the field of computational design. The proposed setup exemplifies how computation can be executed over physical matter and how basic design intents can be captured through computational feedback systems to inform digital mediums. Both proposed workflow and interaction models presented in this thesis offer valuable insights into computational potentials offered by computer-aided systems that are yet to be discovered within the context of creative inquiry. As a larger potential, the proposed workflow demonstrates a framework for numerically controlled digital fabrication tools to be appropriated for active user engagement. This proposed workflow can be appropriated for different digital fabrication systems and fabrication techniques such as subtractive operations.

Finally, within the scope of the successful implementation of the proposed experimental setup, this thesis provides an example setup that can be elaborated by other inquirers. Careful documentation of the implementation process is published in the public domain to provide a well-founded starting point. Even though the current implementation is constrained to hardware limitations, the proposed experimental setup can be scaled and extrapolated to different fields such as Design Pedagogy, arts, and construction.

5.3 Limitations

Although different subsystems implemented as part of the thesis present promising result, their inherent biases pose some limitations to the proposed workflow. While some of these limitations help better define the design space and inform the envisioned workflow within the scope of this study, some of them are more restrictive, discouraging certain interactions altogether. Throughout the experimentation, some of these major limitations were observed in the Laser-Stripe Triangulation setup, the geometric reconstruction algorithm, and synchronization of multiple subsystems.

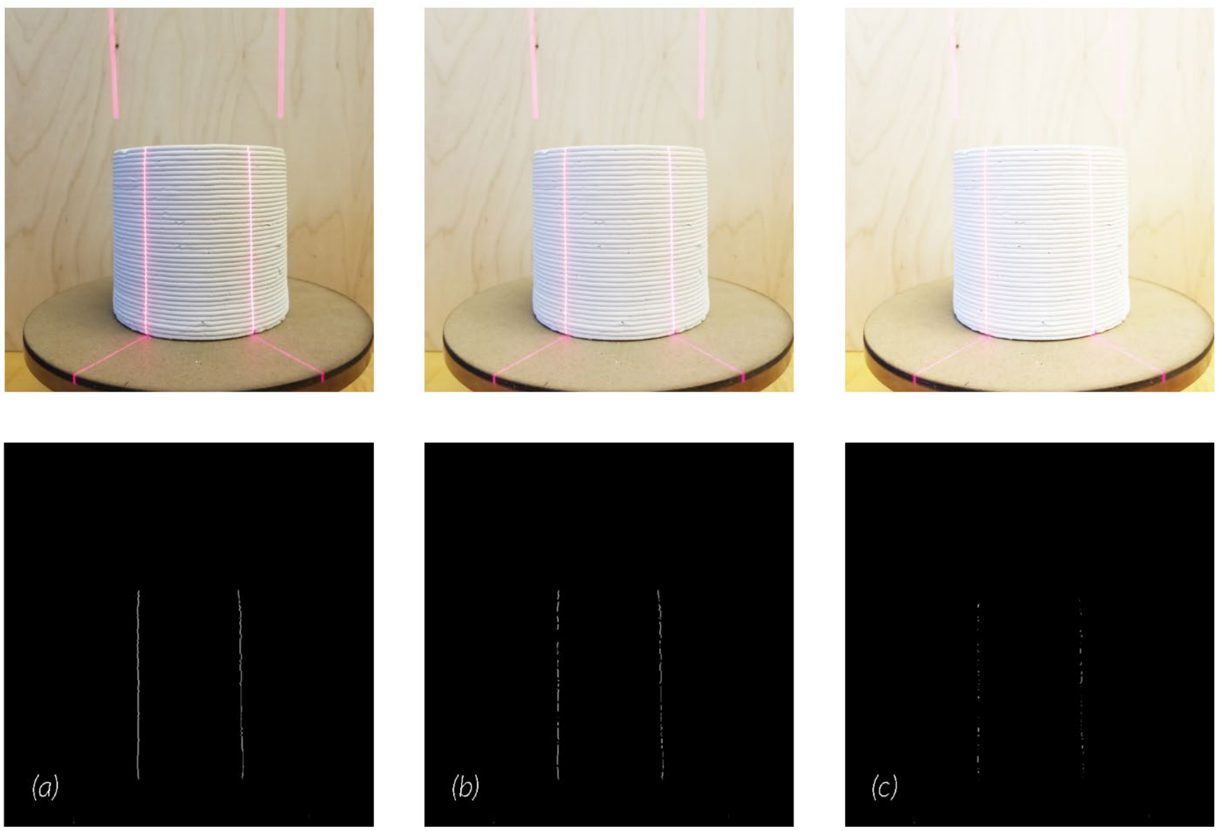

Figure 45. Effects of external light on Laser-Stripe Triangulation: (a) well calibrated setup, (b) slightly over exposed image, (c) over exposed image.

Among the implemented subsystems, the one with the most limitations was the Laser-Stripe Triangulation setup. Although these limitations can be resolved with the careful calibration of the system, the Laser-Stripe Triangulation heavily relies on previously executed calibration data throughout the workflow and cannot adapt to the changes in illumination on-the-fly. Even though the Laser-Stripe Triangulation setup was explained as an external light agnostic to a certain extent, this statement is true if the system is calibrated specifically for that lighting condition. In many occasions throughout the experimentation, light conditions drastically changed when for example additional lights were turned on in the environment during the execution of the proposed workflow. As can be seen in Figure 45, these changes in the external light conditions oversaturated the camera sensor that is calibrated to work with lower light conditions. This in return introduced considerable noise to the system drastically decreasing the number of points that can be sampled from the artifact. Since the clay used in the fabrication of the artifact is white, directional lights affected the overall scan quality considerably. Moreover, any directional light introduced would create a specular effect due to the high moisture content in the clay during the fabrication process, and this would result in failed capture of high curvature patches on the artifact.

In addition to the lack of adaptability to change in lighting conditions, the Laser-Stripe Scanner and the implemented geometric reconstruction algorithms work best with a certain type of geometry. These implementations rely on the fact that the Laser-Stripe Scanner Triangulation samples the artifact along its outer surface. Any extreme negative curvature that folds back on itself creates false-positive scanning data due to the artifact occluding the laser stripe. In such cases, the Laser-Stripe Triangulation Scanner samples the artifact partially on the outer surface and partially on the inner surface of the geometry. When processed by the geometric reconstruction algorithm, this extreme negative curvature could cause misaligned fabrication of the extrapolated curves. Moreover, as mentioned in the previous chapter, in order to ease the computation load during the reconstruction process, the Laser-Stripe Triangulation setup samples the artifact every 7.5-degree interval. Although this scanning frequency is adequate for detecting global geometry changes, any minute detail that lies in between two samples are approximated using surface tangency and often cannot be captured in detail.

Furthermore, the consistency of the material used in the fabrication process is critical to the performance of the system as a whole. Since the gear reduction rate is chosen to be lower than the reference setup, more viscous clay is needed in order to ensure a consistent flow of material. Many of the experiments conducted with this setup were successful at appropriating the clay mixture to facilitate malleability and deposition. However, in some cases where the moisture content is higher than the desired amount, highly viscous clay lacks proper adhesion and it is prone to collapse due to higher than the desired malleability of the material.

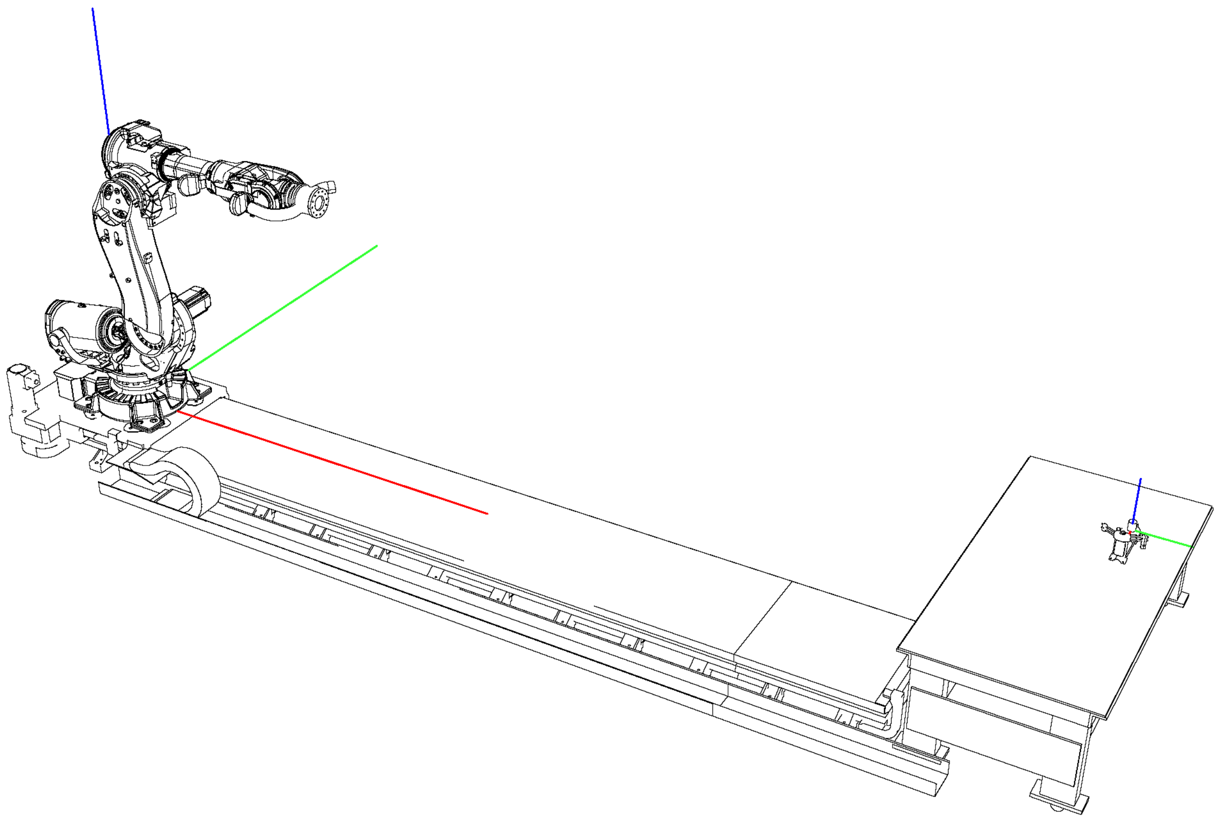

Figure 46. Illustration of different coordinate systems present in the proposed experimental setup.

Lastly, the proposed experimental setup heavily relies on the synchronous working of multiple subsystems. One of the problems that arise from this dependency is that different coordinate system of the Laser-Stripe Scanner setup and Industrial Robotic Arm can be misaligned during the setup process and this would result in the misaligned toolpath generation for the extrapolated geometry. As evident from artifacts presented in the previous chapter, this problem was very critical in determining the success of the proposed experimental setup and often these two coordinate systems were misaligned by 0.5mm to

3mm. This misalignment resulted in the partial failure of the fabrication system to continue fabrication on top of the previously scanned physical artifact. Such misalignment often resulted in a slight shift in the fabrication of the extrapolated geometry in X and Y axes, and in extreme cases, it resulted in irreversible damage to the already fabricated artifact especially when Z coordinates are misaligned.

5.4 Future Work

The proposed workflow is an example of how computational systems can be appropriated to facilitate creative exploration. In the scope of this thesis, the proposed setup utilizes an additive manufacturing technique due to the ease of access to open-source setups. As a broader concept, the reciprocal interaction proposed in this research can be applied in different numerically controlled fabrication tools and can be appropriated to subtractive manufacturing techniques as well. This flexibility in the proposed workflow provides exciting potentials to discover in different design-fabrication scenarios.

In its current stage of development, the proposed experimental setup is a prototype. More work is needed to obtain a more reliable result in geometric reconstruction and extrapolation of the geometry. This would potentially help with capturing design intent in higher fidelity. Considering the development cycles this thesis proposes, development of higher fidelity scanning setup and streamlining the reconstruction and extrapolation algorithms can significantly improve the proposed workflow. Development of higher fidelity scanning, for example, would help negate noise in scanning data better and can allow for real-time capturing of the geometric deformations. Moreover, improvements in geometric processing algorithms can enable the whole system to operate in higher precision. In the current implementation, the geometric processing algorithms are bounded by heavy computational loads which enforce the setup to sample at lower frequencies. This results in minute surface details to be neglected by the system which can inform the extrapolated geometry.

Lastly, the geometric processing algorithms utilize fundamental geometric decomposition and reconstruction methods to propose design hypotheses to the human agent. Although these algorithms were able to capture design intentions through geometric means, much more complex algorithms such as the incorporation of machine learning or genetic algorithms to extrapolate geometries can result in higher fidelity and a wider range of hypotheses.

6

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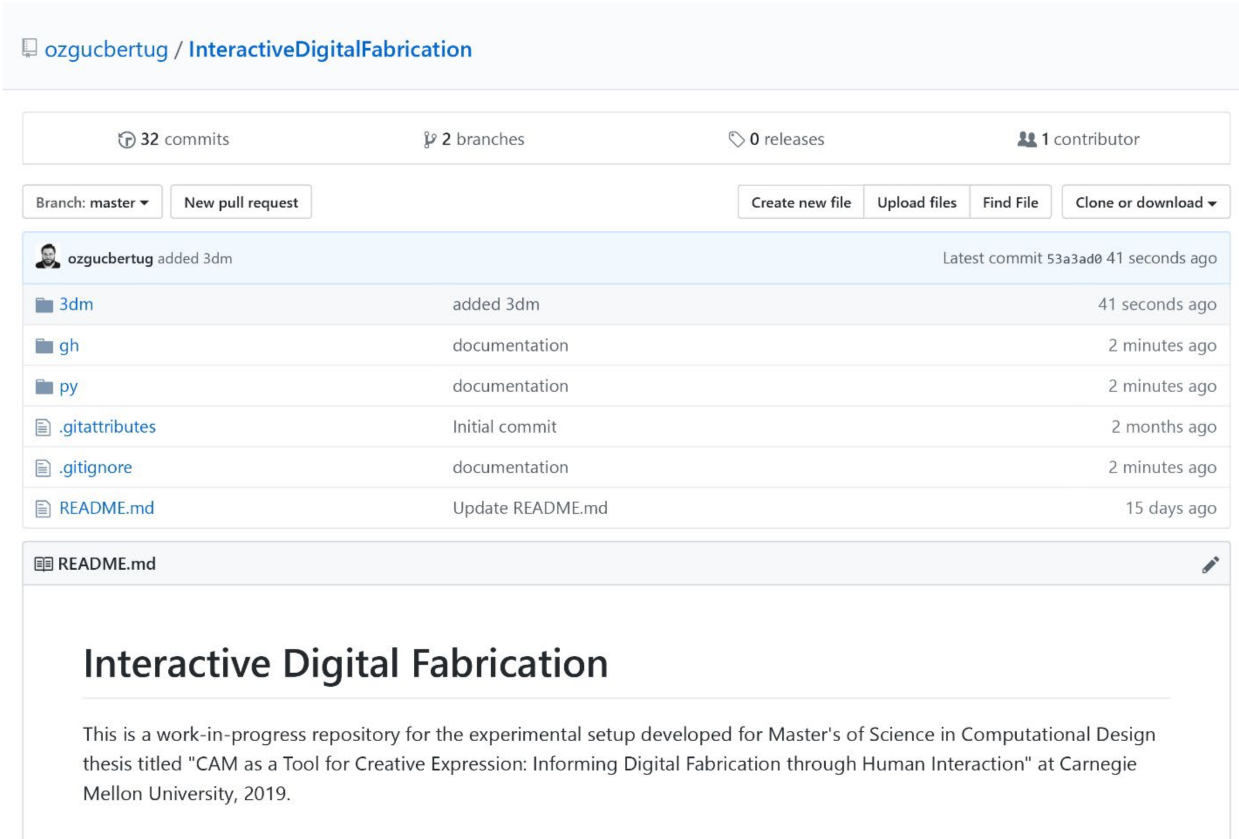
8 Appendix

Development Files and Codes



Large number of files were produced during the development of the experimental setup introduced in this thesis. These files including the Python 3.6 application, Grasshopper for Rhinoceros 6 application, IronPython script for Grasshopper, modified real-time communication library implementations and Rhinoceros 6 3D CAD models developed for the fabrication of the experimental setup are published on GitHub. The documentation can be accessed following the URL below.

github.com/ozgucbertug/InteractiveDigitalFabrication