Integrated Workflows:

Generating Feedback Between Digital and Physical Realms

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ABSTRACT

As design thinking shifted away from conventional methods with the rapid adoption of computer-aided design and fabrication technologies, architects have been seeking ways to initiate a comprehensive dialogue between the virtual and the material realms. Current methodologies do not offer embodied workflows that utilize the feedback obtained through a subsequent transition process between physical and digital design. Therefore, narrowing the separation between these two platforms remains as a research problem. This literature review elaborates the divide between physical and digital design, testing and manufacturing techniques in the morphological process of architectural form. We first review the digital transformation in the architectural design discourse. Then, we proceed by introducing a variety of methods that are integrating digital and physical workflows and suggesting an alternative approach. Our work unveils that there is a need for empirical research with a focus on integrated approaches to create intuitively embodied experiences for architectural designers.

CCS CONCEPTS

• **Human-centered computing~Interaction design theory, concepts and paradigms**

KEYWORDS

Creativity Support, Design Methods, Embodied Interaction, Fabrication

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1 INTRODUCTION

Following the recent advances in immersive technologies, such as mixed reality (MR) and virtual reality (VR) (e.g., [5,79,99]), human senses have been introduced to new forms of interactions with physical and digital realms. Consequently, understanding the relationship between materiality and digitalization became crucial for many design disciplines. For this literature review, we focus on architectural design to explore this continual paradigm shift in the context of transitional workflows between virtual and physical platforms. Starting from the development of three-dimensional computer graphics in 1960s up until today, computer-aided design (CAD) and digital fabrication technologies have been allowing architectural designers to communicate their ideas through virtual visualizations alongside physical prototypes. While gaining creative, manual and technical knowledge, today architects are also acquiring computational skills to use a range of computational design methods as supplementary tools for their creations. Computer-based processes are gaining dominance over conventional design methods and physical properties (e.g., gravity, tactility, materiality) are being emulated by digital tools [37]. With the growing number of emerging technologies, integrating physical and digital mediums is becoming an important topic of research for both the HCI and architecture communities. Current research has been focusing on the areas of digital fabrication, robotic fabrication technologies, hybrid processes and tangible interfaces. However, there is considerably less research laying emphasis on the role of these approaches within the architectural discourse.

In this paper, we review various computational design and fabrication methods for bridging the gap between physical and digital manipulations by seeking answers to the following research questions*: Can we utilize the feedback obtained through a subsequent transition between physical and digital design, testing and fabrication techniques in the morphological process of architectural* *form? How can we create manipulable 3D environments for more intuitively embodied experiences for architectural designers?* By including literature from HCI and architectural design domains we answer our research questions with the information extracted from both fields of research.

This paper is structured as follows. We begin with an introduction of our review methodology and a clarification of the scope of our research. The following two core sections present the main topics of this paper: an overview of digital transformation in architectural design, plus approaches and techniques that integrate digital and physical workflows. Next, we briefly summarize the core sections and discuss some of the relevant sources. Finally, we present the starting point of this research, an alternative transitional workflow by introducing an earlier project, which manifested as an architectural scale structure. In the conclusion, we discuss the findings of our review and illustrate the potential future investigations we will undertake to expand our research.

2 METHODOLOGY

Our aim is to investigate an under-explored area in human-computer interaction and architectural design with a specific focus on the divide between digital and physical manipulations through the architectural design process. Both in the HCI and architectural design domains there are works studying the integration of physical and digital design techniques (e.g., [28,60,84,106]). Our contribution is to form a link between HCI and architectural design by suggesting an alternative integrated approach based on the literature from both fields. First, to review the relevant books and papers we have searched the keywords "computational design" and "digital fabrication" (478,996 returns) or "physical modelling" and "tangible interactions" (289,071 returns). Selected keywords returned thousands of papers which we did not have the resources to go through systematically. Thus, we primarily relied on existing reviews and books [22,25,29,30,32,41,56,78,100,106] augmented by going through abstracts of the first 50 results listed. We also checked the related work cited by the found sources. Next, more specific searches (e.g., "algorithmic design" and "digital fabrication", or "tangible interactions" and "haptic feedback") provided a manageable number of sources. Finally, we categorized the returns (518 returns) under three categories: 1) architecture (249 returns-41 included), 2) human-computer interaction (203 returns-50 included), and 3) haptic principles (66 returns-13 included) and included the most relevant ones in relation to our research questions. Our search was conducted through the ACM Digital Library (our primary search engine), ProQuest E-book Central, Google Scholar, and our institution's library database which allowed us to access literature from different publishers (e.g., Wiley, Springer, etc.)

3 SCOPE OF THE RESEARCH

Before continuing with our core sections, we would like to explain the scope of our literature review. Since our aim is to focus on the specific research problem, which is the utilization of the feedback extracted from digital and physical processes of architectural design, we prioritized to include the works that implement digital fabrication techniques along with analogue design methods. We did not include literature with a broad contextualization of computational design, digital fabrication, and tangible interfaces that are not relevant to our research questions.

This paper reviews and discusses related literature from the fields of HCI and architectural design. For this reason, included works have a common ground in terms of relevance to our research questions. Our specific focus is on the iterative feedback received from an integrated process of digital and physical methods and manipulable 3D environments to support the creation of seamless transitional workflows.

4 DIGITAL TRANSFORMATION IN ARCHITECTURE

This section reviews the digital transformation in architecture from 1960s to the modern-day.

4.1 The Digital Geometry and Fabrication

After the advent of personal computers in the 1970s, computer-aided design (CAD) technologies have been providing a wide range of digital tools for creating and manipulating geometric representations of the built environment. One of the first versions of the CAD software was Sutherland's *Sketchpad* [91] in 1963. Sketchpad introduced a new Graphical User-Interface (GUI) that allowed direct manipulation of the geometric representations on the screen with an interactive pen. Sutherland's new interface had a substantial impact on the relationship between the designer and the machine. Vogel explains: "*When drawing in Sketchpad, the designer could make use of constraints in order to form new relationships between elements and to force them to behave in specific ways.*" [91] With its technical features, Sketchpad allowed designers to interact directly with the represented geometries without involving any coding or a numerical procedure.

Over the years, computer graphics evolved and became more sophisticated in parallel with technical improvements in computer technology. Two-dimensional (2D) geometric representations were replaced by three-dimensional (3D) graphics. Virtualization prompted researchers to seek for the characteristics of the physical world within digitized realms. Along with complex 3D models and photo-realistic renderings, the potential of 3D graphics has been explored further to generate deformable digital models that emulate the behavior of physical objects [87]. Deformable digital models facilitated the creation and representation of non-Euclidian, complex geometries. Thereafter, with the rapid development of graphical user interfaces in 1990s, free-form design tools emerged. A notable example is *Teddy* [33], a sketching interface that produces hand-drawn expressive digital models. Differently from creating geometrical representations with mouse and keyboard, free-form interaction allowed an enhanced physical engagement with represented geometries on a display.

According to Menges [60] the role of geometry has been increasing within the field of architecture. *"Geometry has always played a central role in architectural discourse. In recent years, the importance of geometry has been reemphasized by significant advances in CAD and the advent of digital fabrication and performance analysis methods."* With the evolving comprehension of geometry through digitalization, architectural designers began to implement complex computing software for creating calculus-based geometrical formations for their designs [8,51,76]. The evolved digital geometry established a ground for current digital fabrication techniques.

'*Digital fabrication*' is a broad term that refers to "a host of technologies that are capable of producing physical objects out of digital representations." [91] Digital fabrication technologies enable users to quickly create physical models from digital files [93]. Most of the current digital fabrication machines are tied to computer displays and require a two-dimensional (2D) vector drawing or a three-dimensional (3D) model to translate as a physical data [91]. A 2D vector drawing can provide precise details for subtracting, cutting or engraving procedures, while a 3D model contains the geometric features of an object for additive procedures. Along with precise vector drawings produced by CAD software, objects translated to splines (vectors defined with direction) [51], NURBS (Non-Uniform Rational B-Splines), meshes or subdivision surfaces can become the primary sources of data for fabrication technologies, (e.g., computer numerical controlled (CNC) milling [55], laser cutting, 3D printing, etc.)

According to Willis [96], computer output is moving beyond 2D representation into the world of 3D physical objects: "*It is clear that most current interfaces catering to digital fabrication remains focused within the GUI paradigm. A design is created using a GUI interface, saved to file, fed to an output device, and finally manifested in physical form."* The recent digital fabrication methods proceed similar to the desktop publishing logic and depend heavily on GUIs without generating a flow of information between the visual representation and the physical outcome.

4.2 Morphology and Algorithmic Logic

In recent years, parameterized modelling tools are gaining dominance over widely-used CAD software, due to their capability to generate and rationalize complex geometric compositions [76]. Oxman [65] opposes the exploitation of digital media as tools and claims that there's a linkage between "*digital design*" and "*digital design models*" as a form of architectural knowledge and it is a profound ideational resource for design. However, there is a point of view among architects that evaluates 2D architectural plan as the key of the evolution of a design [45]. Kolarevic [41,43] believes that the plan no longer generates the design: *"The digital generative processes are opening up new territories for conceptual, formal and tectonic exploration, articulating an architectural morphology focused on the emergent and adaptive properties of form."* With the continual advancements in the current digital design tools, the focus has been shifting from making the of form to the derivation of form and its *morphology*.

The term morphology was first described by Thompson as a way to study the deformation of form in living creatures through mathematical formulas [51,91]. In architecture and design contexts, morphology refers to the topological continuity and diversity of form and its continuous transformation [19,65]. For instance, to study the formal transformation of structures, Reichert et al. [73] developed an architectural scale fiber-reinforced polymer pavilion based on architectural morphology and *biomimetic* design principles. By abstracting and translating biological role models into design strategies, they have created generative algorithms for optimizing and exploring novel design solutions. Knippers and Speck [40] believe that today's aesthetics are focusing towards nature-inspired movements through free-form geometries and this linkage between biological and architectural evolution processes can provide opportunities for architectural design.

4.3 Critical Voices

Within the domain of digital design there are increasing concerns over the influences of digital tools on the creative thinking [25,41,86,91]. Poulsgaard [71] asks: *"If this is so, how can we begin to understand this new digital terrain, and what might its impact be on creativity and cognition?"*

Several researchers argue that if the generative algorithmic language and computer-controlled fabrication techniques preclude the design intent and merely depend on an automated numeric process, they can misguide the visual, tactile and iterative thinking processes of designers and distort their focus to the end-product rather than an examination of the entire design process [25,41,86,81]. Kolarevic remarks, it is worth considering what we are intending to achieve *"before immersing ourselves in these technologies* [41,42]*."*

As highlighted by some researchers [29,81,91] computer-controlled design and fabrication methods are decreasing the time consumption of design and manufacturing processes, but also missing out the manual dexterity and material knowledge of the designer. Vogel [91] and Carpo [16] acknowledge that computation helps designers to produce drawings that would have taken days with conventional methods. However, Vogel [91] also notes that even with their formidable capacity, drawings produced by computers were considered a *"poor substitute"* for hand drawing. Bryden [14] affirms that design processes involve an iterative process of research, analysis, thinking, conceptualizing, visualizing, model making, prototyping, testing and refining. Therefore, designers have tactile contributions to the design and fabrication processes alongside their cognitive and creative abilities [48,57]. According to Gramazio and Kohler [29], *"a scaled physical model can only embody a limited amount of information, however, despite this intrinsic limitation, physical models retain distinct advantages over the digital ones."* Physical models provide a direct tactile and sensual information to architects for comprehending the three-dimensionality of their designs which is difficult to obtain through graphical representations.

4.4 Physical Model-Making in Architecture

Beginning from the conceptual phase of an idea to the construction phase, physical models play an important role in architectural design for apprehending the relationships between "*material and structure, space and proportions* [29]*."* Poulsgaard [71] explains the substantial contribution of physical making in architectural design with the *material engagement* framework. Material engagement acts as a fundamental cognitive resource on its own and by interacting with physical tools and materials we alter: *"the projective flexibility and material make-up of our minds* [71]*."* Materials and physical tools can provide stability to a complex design process while removing excessive cognitive load. Iwamoto [35] observed that material constraints encountered while physical modelling requires designer to take the physical world into account from the beginning of an architectural project. Thus, a tactile feedback can enrich and inform the design process and at the same time reduce the possibility of structural issues in the later stages of the design.

For many design disciplines, building physical models can bring distinct advantages over digitally created 3D models. McCullough [56] explains: *"The fact that traditional craft endures at all is because it satisfies some deep need for direct experience-and most computers are not yet providing that experience."* In widely-used CAD/CAM software, direct experience is provided through mouse and keyboard tools and their technical constraints generate digital 3D models that "*lack depth, texture and sense of materiality, despite the most advanced digital modelling and rendering software* [32]." At this point, physical models act as a strong backbone in terms of materiality, geometric exploration and alteration. Due to interaction limitations within graphical user interfaces of the recent CAD and parametric modelling software, formal explorations and alterations may also be limited in comparison to physical models. CAD technologies reduce the possibility of human error, but also eliminate *"moves that have unintended effects, with unexpected problems and potentials* [100]*."*

Pallasmaa [66] claims that our senses, including vision, are extensions of the sense of touch. Before visualizing a physical entity, we receive tactile feedback and the sense of vision supports the physical feedback. With the advent of digital fabrication technologies and endeavors in the HCI field to augment this tactile experience via tangible computing, there's a growing interest towards touch-based design knowledge (e.g., [17,70,102]) and physical model making (e.g., [37,54,64]).

In the architectural discourse, physical models are exploratory design tools which allow architects to create rough abstract concepts, as well as to extract more detailed information for the later stages of their designs. By providing abstract or detailed information, physical models establish a communication between the *"mind and materials* [30]*."* For students and practitioners, testing digital findings with physical prototypes can be supportive for assessing if a complex solution is really offering *"spatial, aesthetic and programmatic"* solutions to a project [1]. Therefore, each physical and digital phase of the project can inform each other subsequently and iteratively.

5 COMBINING DIGITAL AND PHYSICAL

This section reviews various works that implemented digital fabrication techniques along with analogue design methods discussed above and the generative influences of these integrated workflows on architectural design process.

5.1 Digital Fabrication

"The idea of integrating computational worlds and physical objects is a broad one; and there are many ways to pursue it [98]." For achieving an integration between physical and digital realms, digital fabrication is becoming an increasingly significant topic of research within the HCI community. On the other hand, there is less research addressing the impact of digital fabrication techniques in the architectural discourse. As mentioned previously, current studies on digital fabrication are proceeding with GUI paradigms without offering an iterative creative

process. Therefore, most of the studies are object and end-product oriented, while some of them are also focusing on creative processes of the design.

To illustrate, *Activity Sculptures* [82] investigates the influence of physical representations on a running activity. The digital data gathered through a mobile step tracking application is being translated into 3D digital sculptures. Visual 3D representations of sculptures are physicalized by a 3D printer to generate physical artefacts for the participants. *Rotatack* [98] is a computational craft item built with a similar point of view that introduces a computational hardware to be used in a variety of educational and home crafting projects. Mitani and Suzuki [61] propose a method for producing unfolded paper craft models by increasing the approximation accuracy of triangulated meshes. Digital deformation of unfolded geometries manifests as physical components ready for assembly. *MetaMorphe* [89] is a digital fabrication framework that allows designers to manipulate static 3D models with a scripting language and fabricate created digital models with a 3D printer.

Current digital fabrication machines require a sufficient knowledge of software and computation which can consume considerable time and energy during the learning process [5]. *Codeable Objects* [36] investigates how to make computational design more accessible for people who do not have proficiency using computational design tools. The aim of this study is to produce personal and functional objects by utilizing programming and digital fabrication technologies. After testing the object-oriented programming interface with two different workshops (consisting of specific product design and fashion design tasks), the study uncovered that a generative code-based procedure lacked the designer's progressive intuition, which is fundamental for creative practices. Based on participant interviews conducted at the end of the workshops, a series of digital transition processes leading to a physical object brought concerns about the role of the designer and computational design practice itself. *Printy* [6] is an augmented fabrication system developed by Ashbrook et al. specifically for novices to design and fabricate personalized objects. *NatCut* [77] is a tangible editor to create enclosures and covers for electronic devices by extracting their physical properties through an interactive surface. *NatCut* accurately rebuilds a previously created object and creates enclosures. With the digital data traced from the physical object, a physical enclosure can be fabricated quickly. Laser Origami, a rapid prototyping approach, produces physical 3D forms by employing bending as a prototyping method. This method eliminates the need for additional physical assembly processes [62].

Besides fast production, digital fabrication machines can allow exploratory testing, iterating and manifesting complex structural systems [13]. For instance, Deuss et al. [20] suggest a method for fabricating complex self-supporting surfaces and test their structural performances through 3D printing and physical assembly of scaled models. With an algorithm developed through Rhino Vault software, they were able to simulate the physical performance of an architectural scale masonry structure. Hereby, digital fabrication technologies do not only produce models or components of a structure, they also provide information about material performance through physical testing.

Maher [52] argues that while developing new technologies for supporting creative tasks, we do not consider "*design principles for supporting creativity that are grounded in scientific studies of the use of these new technologies.*" Although computational design and digital fabrication offer efficiency for architectural designers, it is important to comprehend to what extent and how machines can facilitate the origination of novel design 'intentions' and 'planning', rather than merely representing architectural geometries to select and manipulate.

5.2 Automated Processes and Robotic Fabrication

As an extension of digital fabrication technologies, automated manufacturing techniques are being adopted to create physical prototypes in various scales [15]. Robotic fabrication can be evaluated as an emergent method to integrate digital and physical phases of design. Gramazio and Kohler [29] reutilize the physical model as a critical explorative tool in addition to computational design by developing and testing assembly procedures of complex structures with robotic arms. By implementing the robotic fabrication technology, they intend to form a "direct and rigorous" link between the physical model and its digital origins. Robotic fabrication acts as a method to translate the cumulative design process into physical materials and construction processes in the later stages of the design. As a result, robotic fabrication technology augments the computational process and generates tangible models. Although this method shifts the focus from an isolated architectural form into a broader conceptual development, it follows a linear process in terms of fabrication. Following the morphological evolution of a design idea, the digital data is being transferred to the robotic arm system for the production and assembly of a physical structure. In other words, designers cannot interact and manipulate materials directly, and the separation between digital and physical processes remains.

Artificial Ontogenies [74] is an autonomous assembly system that does not require any human involvement. The aim is to create *buildable objects* through visual representations which consider the basic rules of physics over the course of the entire assembly process and reduce the need for an additional physical assembly process. Although, the aim of *Artificial Ontogenies* was to eliminate the human involvement through the assembly process, Reiffel and Pollack [74] acknowledge the fact that while translating a visual representation "*human involvement is required in figuring out how to assemble an object matching the evolved description.*"

Willis et al. [96] introduce an interactive fabrication technique that converts the digital input to the physical output in real-time with *Shaper,* a prototype device using expanding polyurethane foam. *Shaper* reduces the complexity of the digital transitional process for fabrication by obtaining real-time visual feedback and designers' tactile input. Nevertheless, their automated approach of real-time physicalization of digital data does not go beyond a linear digital to physical design process.

Robotic technologies can offer an efficient assembly and physicalizing process without the tactile contribution of the architectural designer. Automated robotic arms produce models faster with more precision and less human error. The immediate transition from digital to physical is especially feasible for economic reasons, however, detaching digital design and assembly procedures from designers' cognitive and physical involvement may result in a design process that lacks the progressive intuition of the designer [36]. Reduction of human error might be significant especially in a final assembly process, while on the other hand human error can bring valuable feedback and inform the final process in the earlier stages of the design. Therefore, a balanced integration of robotic technologies and tactile human interaction can create more intuitively embodied design processes.

5.3 Hybrid Approaches

Within the architectural discourse, there have been works that aimed to move beyond the restrictions of the GUI paradigm by fusing physical and digital modes of design. Digital translation techniques (e.g., 3D and laser scanning, algorithmic translation) have been utilized to generate fluid design, testing and prototyping processes which sequentially inform each stage of the creative process. Therefore, to generate an "*interactive connection*" by integrating human and machine ability [97]. Between 1989-2003, a similar approach was implemented by Gehry & Associates for the well-known Disney Concert Hall building. Oxman [65] elaborates: "*Disney Concert Hall and other projects by Gehry introduced new geometric approaches freed from a priori formalism, such as linguistic formalism. The Gehry office was deeply committed to researching the potential role of digital technologies.*" The design team employed computational design software and computer-aided manufacturing (CAM) technologies for the entire design process. CAD/CAM technologies have been used by the aviation, automotive and shipbuilding industries for many years and Disney Concert Hall was one of the first projects that has implemented a fluid workflow between physical and digital processes into the architecture practice. Dunn [22] describes the project: "*Already heavily reliant on physical model making techniques to develop their intricate designs, the practice initially used such models in conjunction with a 3D digitizer to feed data into the computer.*" Employing a digital translation phase (3D scanning), initiated a dialogue between the digital and physical phases of the project.

As discussed previously, there are two distinct views on computer-controlled fabrication techniques. Alongside considering machines as "*cold*" and overly complex substitute to conventional methods [56,91] for some designers, machines unlock a great creative potential to generate bespoke design ideas [13,16]. At this point, '*hybrid*' approaches aim to maintain a balance between these two counter views. The term *hybrid* is defined by Davendorf and Rosner [21] as the unification of "*distinct and often contradictory entities, whether it refers to the offspring of different species or a mixture of heterogeneous entities.*" Although the term itself has biological roots, in HCI and architectural contexts *hybrid* can be addressed as a combination of analog and digital design, testing and fabrication processes. Several researchers have used the term to refer to a cumulative and iterative design process that evolves through a flow of data between physical and digital modes of design (e.g., [28,60]).

Menges [60] predicts that a potential fusion of computational and physical processes will have profound effects within the domain of architectural design. Correlatively, Symeonidou [84] introduced a hybrid design method that employs physical modelling and digital algorithmic modelling for creating bending rod structures. Computation was utilized to enrich the design research, instead of replacing physical form-exploration methods with the digital ones. Besides physical prototypes, the parametric model developed through the process provided a real-time feedback for shape exploration.

Zoran introduced 15 hybrid projects as part of the *Hybrid Craft* [106] exhibition *Hybrid Craft* to study the influences of conventional crafting practices on contemporary digital design processes. The exhibition included alternative implications of a hybridized process that combines physical and digital workflows of design. For instance, digitally fabricated acoustic guitars, jewelry, decoration elements, sculptures were some of the exhibited creations. Zheng et al. [103] aimed to combine crafting and interaction design practices through a co-design driven collaborative task. A *"task-driven and object-focused"* study has been conducted with the participation of an interaction designer and a ceramics crafter. However, their work evaluates design and craft practices as two separate domains, while hybrid practices aim to merge and establish an iterative communication between each practice through the design process. Tseng and Tsai

[90] introduced three methods to document the iteration process of a design through digital fabrication: *process heat maps, process stacks, and process textures.* Each method physically manifests how a single objects' physical properties are evolving throughout the design process. Final fabricated components are representations of each digital alteration phase of created geometric formations. The study presents an iterative and linear transition from physical to digital platform.

Several researchers suggest supplementary tools to integrate digital and physical workflows. For example, *Modelcraft* [80] is a system that translates the information obtained through a physical model into the digital world by tracing physical freehand annotations. *Modelcraft* uses a digital pen to capture real-world geometric information efficiently. The linear transition from the physical platform to the digital one does not support complex manipulations performed manually. This limits the designer with annotations and makes it more suitable for the massing (a brain storming phase done by iterating mock-up models), rather than the formal exploration process. *FreeD* [105] is a digital milling device which increases human control in the fabrication process. *FreeD* reduces designers' mere dependence on CAD models and provides a direct engagement with the physical materials. Tian et al. [88] built a personal CNC machine for supporting skilled wood crafters by enabling fast fabrication of stable joinery systems that do not require additional hardware to assemble. The aim of their hybrid workflow is to support users' manual dexterity and help them for transforming design intent to physical prototypes while maintaining their autonomy. Yoshida et al. [101] implemented the formative capability of the stick aggregation technique to build architectural-scale structures. With a custom designed stick dispenser which drops glued wood chopsticks, they have built aggregated organic structures.

There is also research with a focus on creating hybrid workflows through CAD software. *MakerVis* [83] is an alternative software that facilitates the creation of fast and efficient visual representations ready for subtractive and additive fabrication processes. Although the aim is to generate a hybrid workflow, *MakerVis* does not introduce an iterative fusion between physical and digital techniques. The design process begins with a digital data, which continues with digital iteration. With a generative algorithm, the system can fabricate components which are ready for assembly to build complex physical representations of digital data. The design workflow allows designers to physically engage with the fabricated materials during the assembly procedure.

To form a link between physical prototypes and their digital representations, several studies implemented laser scanners or camera-based scanners that can trace contours of 3D models and transfer this physical information to computer software [22]. Due to its malleable and solid nature, the most commonly used testing material with volumetric 3D scanners is clay [69]. As an example of this, *Illuminating Clay* [69] is a hybrid approach for altering landscape topographies through real-time capturing of physical manipulations via a ceiling mounted laser-scanner. The laser triangulation approach offers an accurate and a fast scanning performance for providing real-time visual feedback. "*The use of a laser scanner to input physical geometry in real-time offers an alternative vision for computer interaction where the user is free to use any object, material or form to interface with the computer* [69]." With its capability to translate real-time physical information, 3D scanning can offer more embodied translation processes in comparison to interpretations through CAD or algorithmic language. *ReForm* [93] integrates analog and digital design workflows through a bidirectional fabrication system developed by Weichel et al. A linear translation of the virtual information into fabrication machines creates a *"rigid separation between workspaces."* Therefore, *ReForm* employed a production process that allows designer to contribute physically to the design by manipulating the shape of a clay material. Then, a 3D scanning technology converts the physical manipulation data in real-time into a virtual model to be fabricated via a 3D printer. Such approach has similarities with the aforementioned Disney Concert Hall [22,65] project and *Illuminating Clay* [69]. Differently, *Reform* also aimed to reduce human mistakes by including an 'undo' option in the design process. In contrast, recoverable mistakes contributed to the development of the final outcome for Gehry's Disney Concert Hall. Due to the lack of human error and material limitations, current studies with 3D scanners [44,69,93] do not provide a constructive negative feedback to develop a tactual understanding of material properties and constraints.

The main reason that makes hybridization a necessity has been elaborated by Goldsteijn et al. [28] as follows: *"The digital phase happens entirely on the computer through the selection of media, experimenting with the composition and uploading media, while the physical creation happens entirely away from the computer."* Goldstjein et al. conducted a workshop to investigate a hybrid crafting procedure through a prebuilt prototype. The prototype consists of prefabricated block cubes with built-in displays, and Lego blocks. The aim of this study is to engage people in an integrated process of physical assembly and digital image browsing for producing personal, meaningful and dynamic objects. The study presents CAD and digital fabrication techniques as non-hybrid and non-interactive. However, despite the limitations among commonly used CAD and fabrication technologies, they will continue to profoundly influence contemporary design practices.

Zoran [106] points out that advanced digital fabrication and computational design techniques are being considered as the third Industrial Revolution within some industrial and academic communities. On the other hand, Bergdoll and Christensen [7] argue: *"If the factory production has made such a revolution then why is the culture of building so resistant to the transformation?"* As Iwamoto [35] notes, current CAD and fabrication technologies are not yet fully developed and they still contain critical issues in terms of material fluctuations, fabrication limitations and physical constraints. In addition, current digital fabrication technologies are limited to smaller scale objects. Available materials for 3D printing are not suitable for architectural scale prototypes. Laser cutters CNC machines have a limited work space [101]. Also, most fabrication processes are strongly tied to CAD software which brings limitations with their GUIs. Although these technologies have certain constraints, hybrid approaches can support and enrich computer-controlled design processes with the complex creative flow and the manual dexterity of designers.

5.4 Tangible Approaches

Tactile manipulation and haptic feedback plays a fundamental role for the creative expression in architectural form-finding processes. As discussed previously, physical models are essential design tools for architects who take construction into account from the preliminary idea creation phase [80]. Throughout the entire design and fabrication cycle, both physical and digital manipulation techniques bring limitations and opportunities. For this reason, replacing physical models with digital ones, or the other way around, may result with a lack of the necessary information to iterate initial ideas further. To a certain extent, hybrid approaches can resolve the disconnectedness between these two seemingly contrary realms. As an extension of hybrid approaches, tangible user interfaces (TUIs) offer a wide range of interaction techniques with physical and digital models. Up to now, tangible interfaces have not been used prevalently among architectural design practices, due to their limited scope of application. Nevertheless, tangible interfaces can tackle the limitations of current CAD/CAM tools which are heavily reliant on their GUIs. According Ishii and Ullmer [78]:" *Interactions between people and cyberspace are now largely confined to traditional GUI-based boxes sitting on desktops and laptops."* Differently from GUIs, interacting with the digital creations by holding, grasping and relocating physical objects with hands is the essential advantage of TUIs. TUI obviates the separation between the mouse and the display while interacting with the digital information [53].

For creating embodied forms of interaction with the digital platform, HCI researchers have been enhancing, utilizing and testing recent technologies with integrated workflows. For example, Lucero [49,50] investigated the creative process of mood-boarding for designers and how augmented reality (AR) tools can support this collective activity. The *Funky Coffee Table* and the *Funky Wall* prototypes offer an interactive manipulation setting for creating mood boards by implementing proximity sensors, motion sensors and projection. The aim of this work was to support designers in communicating their design ideas, intentions and the narrative behind their creative processes. Terrenghi et al. [85] conducted workshops to study the interactive disconnection between digital and physical platforms through a tabletop puzzle and picture-sorting task. Physical cards and a touch screen display were tested in separate sessions with participants. By comparing physical and digital workflows, the workshops revealed that the digital platform restricted the direct and efficient manipulation of the objects in a digital 3D space. *Build-IT* [23] enables users to interact with a physical object to alter digital representations projected on a screen. Objects can be physically repositioned, rotated and fixed and the digital representation simultaneously changes. *Build-IT*, however, may not be able to handle complex 3D geometric manipulations which makes it difficult to be adopted by architectural designers.

There are works that utilize mobile device sensors (e.g., accelerometers, gyroscopes, electronic compasses, etc.) to interact with digital visual representations. Wiethoff and Gehring [95] and Boring et al. [12] have studied interactive media façades by integrating mobile devices. Findings of these studies revealed that built-in sensors of mobile devices can be implemented to manipulate a distant display.

By taking haptic principles into consideration, several previous HCI studies investigated virtual object manipulation methods with tangible tools (e.g., gaming devices, custom tools, etc.) [54,75]. *D-Coil* [68] is a 3D modelling approach implementing wax coiling as a method to interact with the digital models. *D-Coil* system allows designers to simultaneously design and construct. At the same time, the system restricts the creative engagement of the user with its 2D, planar user interface. Therefore, it may not be suitable for the creation of complex free-form geometries or 3D surfaces. *Active LENS* [34], is a tangible interaction system that forms a direct communication between the physical material and its digital representation on a display. Sheng et al. [78] introduced a real-time form manipulation technique by utilizing a physical proxy method to detect and emulate hand motions performed on sponge and clay materials. Although there are certain material restrictions for this method to be applied in architectural form-finding process, it is a significant leap for future interaction techniques with virtual 3D models.

Another area of research is tangible and interactive displays. There are various forms of interactions with tangible displays. One of the methods is the manipulation of actuated interactive displays or surfaces [38,72]. For instance, *Geomotion Screen* [64] suggests an actuated flexible planar screen that can be manipulated with certain hand gestures. With a fixated high-definition projector, that provides real-time visual feedback, and motion sensors, users can create non-linear surfaces. *Recompose* [9,47] and *Relief: 2.5D* [46] are later studies that extended touch interaction with actuated shape displays by implementing a set of free-hand gestures. *InForm* [24] is an actuated dynamic shape display that allows users to relocate and manipulate static objects by geometric restrictions created with cubic surface elements. *Materiable* [63] is a method to emulate physical material properties through actuated shape displays. *Materiable* creates '*an illusional haptic sensation*' supported with visual feedback that can be supportive for architects to explore and comprehend material properties, opportunities and limitations in the material selection process. On the other hand, due to large-sized and close-packed actuated elements of current shape displays, architectural applications of abovementioned methods can be limited in terms of creative exploration.

Several HCI researchers aimed to form a direct link between HCI and architecture domains through tangible interfaces [80]. For instance, Anderson et al. [4] developed physical building blocks that compute geometrical arrangements and interpret them into virtual architectural models. Although there are geometric constraints of the blocks, this method sets an example to the digital interpretation of tangibly manipulated physical forms. Äkesson and Mueller [2] studied real-time 3D direct manipulation for structural design exploration. The goal of their research was to enhance structural qualities of the built environment by improving the conceptual initial phase of architectural design with tangible manipulation techniques. Our bodies have an influential place in facilitating interactions with emergent technologies [48]. Therefore, to expand the range of structural solutions and possibilities throughout the architectural design process, physically engaging with materials or geometries can provide the necessary cognitive sources for solving design problems.

6 SUMMARY AND DISCUSSION

Some research evaluates emerging digital technologies as efficient tools without generative influence, while others frame them as a way of creating unimaginable complexities. A considerable number of research positions themselves in between by integrating physical and digital workflows with a wide-range of methods. Based on the reviewed sources, our literature review identified that merely depending on physical or digital approaches have deficiencies in terms of developing a deeper understanding of the digital realm with material knowledge and morphology [71]. Piper et al. [69] point out: "*Most three-dimensional renderings and simulations are still viewed on the computer screen, which as a two-dimensional and visual form of representation, does not support a more intuitive three-dimensional analysis that is afforded by physical models.*" Creation of a hybridized, feedback-based process of design, testing and fabrication through manipulable 3D interactions can communicate virtual and physical mediums with a comprehensive understanding of the digital design ecologies of the modern-day [91].

We reviewed papers and books related both to HCI and architecture domains. Some of the approaches are particularly relevant for achieving a feedback-based integrated process: bidirectional fabrication method of Weichel et al. [93], enhances the real-time 3D scanning technique of Anderson et al. [4] and implements a rotary table with a light LMI HDI120 3D scanner[1]. We have reviewed alternative methods to translate physical information to the digital model (e.g., [69,80,84]) and the enhanced real-time scanning method of Weichel et al. [93] differ from these methods in terms of applicability in the earlier stages of architectural design. Besides solid clay material, with the precision LMI HDI120 3D scanner provides, more complex scaled architectural models built with a variety of materials and manipulation techniques can be traced and transferred to the digital platform. Even though architectural design requires frequent modification of physical models, particularly in the idea creation phase, a similar rapid digital translation technique can provide an efficient process that physical feedback contributes to the subsequent digital phases. As a result, a transitional method can reduce the mere dependence on digital or physical manipulation and initiate a dialogue between these two realms [22].

The scanning setting of Weichel et al. provides a synchronized digital and physical manipulation. Therefore, digital manipulation is performed entirely in the physical realm. Current tactile manipulation methods introduce different approaches to interact with digital 3D models (e.g., [64,68,78]). Unfortunately, recent tangible interaction techniques bring geometric constraints and limits the applicability within the architectural design process. Due to the limitations of recent tangible approaches for performing free-form manipulations, 3D scanning can be more efficient to translate and reconstruct physical architectural models as digital 3D models.

By taking material engagement framework into consideration with previously elaborated research studying the role of physical model making (e.g.,

[1]https://www.aniwaa.com/product/3d-scanners/lmi-technologies-hdi-120/

[30,56,66,100]), a digitally emulated manipulation process may detach the designer from the physical materials which possesses morphogenetic properties of its own [19]. As Csikszentmihayli [18] highlights, a creative process is continuous and uncritical acceptance or complete dismissal of human contribution will not improve the process further. Due to this, implementing and testing the scanning technique used by Weichel et al. [93] in an architectural design process can provide a hybrid workflow that extracts digital and analogue feedback as a morphogenetic accelerator.

However, digital scanning of physical models may not provide sufficient data for the further stages of architectural design process. At this point, the material engagement framework can provide the fundamental cognitive resource to tackle the limitations of the digital workflows in the later phases of the design [71]. An iterative tactile feedback can be obtained through re-engaging with the physical materials.

Physical prototypes built for the conceptual development stages of the architectural design are inexpensive and rough models. As the scale increases further detailing and structural solutions are necessary. Therefore, an efficient translation process (e.g., [83]), can be implemented to produce accurate fabrication-ready 3D models from physical prototypes. By combining the Grasshopper plug-in for Rhino 3D with a hand-held milling device, Zoran and Paradiso [105] achieved an integration between the detailed algorithmic model and fabrication process. Differently from automated fabrication approaches (e.g., [29,74,96]), an integrated workflow can initiate an embodied fabrication process that reintegrates the intimate human control within the fabrication process.

7 THE TRANSITIONAL METHOD

Based on the introduced and discussed literature throughout the paper, in this section we propose an alternative transitional workflow. With the rapid adoption of digital design techniques in architectural design, "*machine intelligence had been overestimated and the complexities of the design process had been underestimated* [39]." The transitional method fuses machine potential with the creative input of the designer to inform each stage of the design with the feedback received from both platforms.

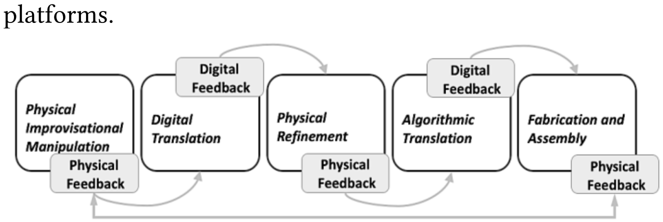

Figure 1: Transitional loop process.

The following study describes the transitional workflow through an example of our own work. This work is included as a concrete example of our findings from the literature review which could be utilized by other researchers and designers to implement the transitional workflow into their own work.

As an initiative starting point, in our previous study A Mobius Process [31], we aimed to test an integrated process that extracts feedback from a sequential transition loop between physical and digital modes of design, testing and fabrication for creating linear displaced free-form structures made out of laminated plywood strips. The study was conducted at Canterbury School of Architecture (UK) between September 2015 and October 2016. The transitional process that led to a full-scale hanging structure consisted of a physical improvisational form exploration, digital translation of the physical model, physical refinement, algorithmic translation and final fabrication processes (Figure 1).

7.1 Physical Form-Finding

Experimenting with physical models creates a platform to extract tactile information about a material's characteristic, constraints and the amount of force needs to be applied for achieving desired geometries [84]. We employed an iterative physical folding process via sheet materials (paper, cardboard and plywood) for the preliminary stage of the design. Initialization is a challenging stage in computational rationalization [44]. Due to this reason, by starting with conventional model-making we aimed to consider structural and geometric rationalization from the beginning of the workflow. Following a series of physical manipulation, we have categorized the physical models based on their geometric properties and selected a linear-displaced continuously formed model for further investigation.

7.2 Digital Translation

After the selection, we tested a camera-based 3D scanner (Sense 3D[2]) to translate the physical model to a digital 3D model (OBJ. file format). The generated digital model was manipulated in the Unity Game Engine[3] by deforming its scale, width, height and orientation. We created a spatial walkthrough which can be experienced through Virtual Reality[4] and an Xbox[5] controller. We have selected five participants from various backgrounds to test our walkthrough simulation (Figure 2). With the experiential feedback received from participants we determined the full-scale dimensions for the final structure.

[2] https://www.3dsystems.com/shop/sense
[3] https://unity3d.com/
[4] https://www.oculus.com/rift/
[5] https://www.xbox.com/en-US/xbox-one/accessories/controllers

7.3 Physical Refinement

To test and detect the physical constraints of sheet plywood, we built a prototype twice the size of the conceptual model (Figure 3). The physical information obtained through 3D digital model transferred to the CAD platform for laser-cutting stripes. Due to the physical limitations of the laser cutting machine, we adopted a lamination technique. By engraving and gluing the joints (with a polyurethane binder) we designed a lamination detail that blends in with the overall design of the structures.

7.4 Algorithmic Translation

Thereafter, the built physical prototype was scanned by a laser scanner to create an accurate 3D model for structural simulation. The obtained point cloud data was converted and transferred into the Rhinoceros[6] software. Three loop structures were digitally manipulated and transformed into a hanging structural composition. To create a structural simulation of the full-scale installation, we employed the Grasshopper[7] and Kangaroo[8] plug-ins.

7.5 Fabrication and Assembly

With the digital feedback received from the previous process, we have created CAD files for the fabrication process. With the scale factor, there were new structural problems emerging. For instance, the number of laminated strips and size of the engraved joints have increased. A polyurethane binding technique could not be used in full-scale. Therefore, to join the edges a cross-stitching technique was adopted. Finally, an architectural scale installation was built and exhibited.

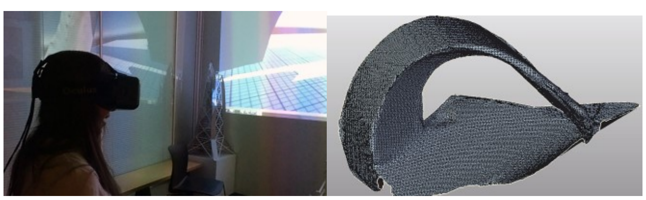

Figure 2: 3D scanning and VR tests.

Figure 3: Physical assembly of laser cut and engraved components.

[6] https://www.rhino3d.com/
[7] https://www.grasshopper3d.com/
[8] https://www.grasshopper3d.com/group/kangaroo

Figure 4: Full-scale loop structure installation.

As a result of this study, maintaining an equilibrium between physical and digital mediums manifested a cyclical feedback exchange throughout the design process. In an iterative design process, search for conceptual and structural design solutions will continuously redefine the problem [39]. Benefiting from creative skills of the designer and machine capability to the same degree originated quick and efficient solutions by linking design exploration to material realization (Figure 4) [44]. On the other hand, implementing an integrated method offered alternative design strategies for tackling the physical and digital limitations we have encountered during the process (e.g., undetected surfaces while 3D scanning, unstable laminated joints, etc.).

8 CONCLUSION AND FUTURE WORK

We have provided an overview of the widening divide between the digital and physical manipulations in the architectural design process, starting from the 2D drafting era to the modern digital design and fabrication techniques. We have introduced critical ideas towards the rapid digitalization and discussed the significance of physical model making for architectural designers. Our review unveils that, despite the growing number of computational methods, materialization and physical input of the designer remain as a fundamental accelerator for the evolutionary process of architectural form. The sources we have included predominantly follow a linear and non-iterative transition between physical and digital workflows. Thus, there is an open area that requires further experimentation and testing with fluid feedback-based integrated workflows.

As future work, we will be further exploring the physical interactions with scanned 3D models to create manipulable 3D settings for architectural designers based on the theoretical background presented in this paper and the transitional method we have suggested in the end. To strengthen the feasibility of our transitional method we will be implementing efficient scanning settings [93]. We also plan to enhance the algorithmic transition phase with accurate translation approaches [83,105]. Findings of these empirical studies can assist us for designing an iterative loop process between the physical and digital realities. Once we are able to reduce the contradiction between virtual and real-world interaction, we will test our integrated method with architectural designers to determine its impact starting from the early creative stages of the design and form-finding processes. By improving our transitional approach, we will be aiming to replace the distorted creative thinking with a multidimensional comprehension of digital design and fabrication tools.

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