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Adaptive Frameworks for Robotic Non-Planar Additive Manufacturing

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by

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Abstract

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Recent advances in additive manufacturing and robotic fabrication have had a profound influence on the architectural design field, giving rise to novel design opportunities and viable construction applications. The integration of these technologies is transforming the construction industry, reducing costs, improving construction efficiency, and addressing important limitations of traditional manufacturing methods.

Despite the substantial potential of additive manufacturing as a groundbreaking tool in architecture and construction, it remains underutilized. Most importantly, when applied on a large scale, additive manufacturing encounters significant geometric constraints inherent in the nature of the viscous and cementitious materials being employed. Extruded materials cannot sustain high tensile forces in their wet state and are susceptible to deformation.

To address these design limitations and fabrication challenges, this thesis focuses on broadening the capabilities of additive manufacturing in the architectural design field through novel experimental developments at the hardware, software, material, and process levels. Situated at the nexus of architectural design, engineering, computation, and robotic fabrication, the thesis investigates, formulates, and evaluates innovative models and processes that utilize non-planar 3D printing and innovative formwork integration solutions to expand current technological capabilities. The research examines a variety of inventive support solutions, highlighting three key strategies: formwork reduction, alternative formwork approaches, and formwork elimination.

To evaluate the effectiveness of the proposed approaches, the research initially focuses on developing task-specific processes and tools. This focus includes the introduction of an innovative additive manufacturing technique that aims to utilize bending-active structures as formwork for conformal 3D printing. This new approach significantly mitigates material waste without compromising structural integrity.

The research then investigates alternative approaches to free-form 3D printing using granular materials as both a temporary formwork and an efficient alternative to conventional 3D printing materials. The research led to the development of a novel technique that utilizes recycled granular materials to rapidly construct unsupported 3D printed forms, capitalizing on abundant waste resources. Additionally, drawing inspiration from historic precedents, the research proposes a method that entirely eliminates the need for formwork, referencing ancient construction techniques and adapting time-tested principles to modern additive manufacturing contexts.

The newly developed tools and processes undergo testing throughout the research and are then subjected to benchmarking against conventional methods as well as against each other. The thesis concludes with a reflection on its contributions and the future outlook of the presented work. It also encourages the next generation of researchers and designers to expand upon the presented work.

To Rabab Al Mutawa and Abdulaziz Darweesh,
my first educators

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Chapter 1

Introduction

1.1 Overview

In a world where the humming of machines and the ubiquity of assembly lines dominate, we find ourselves surrounded by a reality that is molded by mass manufacturing. Since the inception of the Industrial Revolution around 1760, mass manufacturing has led us away from producing items that are individual and distinct toward those that are efficient and functional but often monotonously similar. This trend has also affected architecture. A once diverse architectural landscape, rich with craftsmanship, has been eclipsed by another, characterized by readily available components and prefabricated assemblages.

In contrast to automotive and aviation sectors, which adhere to standardized production processes, architecture stands out by avoiding design uniformity. Every building is a new challenge that presents a distinct set of considerations, encompassing site characteristics, program requirements, and integrated design solutions. Consequently, automating architectural processes has proven challenging, leading to a deficiency in innovation. Nevertheless, architectural design and construction have been characterized by technological experimentation that has led to the emergence of creative approaches to design conception and fabrication. Driven by cross-disciplinary research within the arts, sciences, and engineering, architecture's pedagogical orientation has focused on embedding the logic of material systems and digital fabrication methods into form and structure [218].

The use of digital tools in particular, such as Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) software, has definitively redefined the relationship between design and construction, opening up new ways for architects and designers to think about their design approaches. This integration requires that architects reconsider their comprehension of buildings from the design to the construction phases. This entails shifting away from standardized component assemblies towards adopting mass customization. Moreover, Large-scale additive manufacturing technologies and robotic construction platforms are some of the most recent transformative innovations in architectural design that have led to innovative construction applications. The convergence of these technologies represents a pivotal shift in the construction landscape that not only focuses on reducing costs and enhancing construction efficiency, but also aim to overcome some the current limitations of conventional manufacturing operations.

Robotic Fabrication

An industrial robot is defined as an automatically controlled, reprogrammable, multipurpose manipulator that can move in three or more axes and may either be fixed in place or used in industrial applications [281]. In the scope of this study, the term *industrial robot* pertains to six-axis robotic arms commonly used in industrial factories for mass production. Since the 1960s, industrial robotic arms have emerged as a solution to tasks requiring high precision and repeatability, outperforming human operators, but they have also been able to provide skill versatility and adaptability to changing operations. The versatility of industrial robots enables the rapid production of standardized parts in high quantities and precision or customized parts with high complexity and unique features. Thus covering the full range from mass-production to mass-customization. While the assembly lines in the aerospace and automotive industries value robots for the first role, industrial robots are increasingly being used in design and architecture for the second role, offering creatives new ways to approach architectural design and create uniquely tailed solutions.

More precisely, in the aerospace and automotive industry, robots are typically valued for their precision, task repeatability, and rapid operational capacities. Within the domain of architectural design, however, industrial robots have become adaptable platforms for creative fabrication and construction tasks, able to handle complex assemblies and applications that require high skills and intense labor [46]. These processes include additive and subtractive manufacturing [277], fiber winding [248], pick-and-place applications, and formative fabrication techniques. These different manufacturing techniques are often carried out by the same robotic platform, with only the accessories and end-effectors being exchanged.

Additive Manufacturing

In recent years, additive manufacturing (3D printing) has demonstrated significant promise in architectural design and construction. Large-scale 3D printing is emerging as a key advancement in automated construction, enhancing material utilization and mitigating construction waste through intricate layer deposition. The technology also aims to incorporate benefits observed in smaller-scale 3D printing applications, such as speed, geometric complexity, and material versatility. At smaller scales, 3D printing has displayed significant promise in enabling mass customization, optimizing material usage, and rapidly producing components [169] [137].

Moreover, large-scale construction 3D printing now includes conventional construction materials such as concrete [140] , adobe [201] [55], composites [154], and other viscous materials [191] which are deposited as structured fluids before they are fully cured. Some of these materials are more sustainable than others, especially in terms of the embodied carbon. Many efforts are currently being made to improve their carbon footprint, e.g. by using less energy-intensive production processes, replacing certain ingredients with recycled materials or generally promoting biomaterials as an alternative. Independent of this discussion, however, the fabrication method of additive manufacturing with viscous materials is very effective and holds great potential. Wet deposition allows for more efficient material transmission, referring to its pumpability and extrudability during the printing process, while also enabling ease of object dimensional scalability. However, viscous materials are sensitive to unsupported structural conditions and depend on the structural support of the preceding layers for stability. This drawback makes it difficult, if not impossible, to print steep overhangs or wide-spanning horizontal surfaces without additional support. Most approaches use 3-axis gantry-style printing platforms which, although highly scalable in terms of size, allow materials to be deposited in horizontal layers only. Architectural-scale 3D printing of buildings and building components has, therefore, been utilized in layer-based manufacturing, where objects are printed in planar layers, tremendously limiting design possibilities to the production of vertical wall extrusions.

Auxiliary Structures

Formwork typically consists of temporary structures in the form of molds, which are used to contain wet concrete or other viscous materials until they harden. Formworks are usually supported by an underlying structure which acts as temporary support, particularly in new buildings, commonly referred to as *falsework*. Leveraging viscous and cementitious materials in construction is a longstanding practice. These materials have long been employed in casting methods that require temporary formwork or the integration of auxiliary supports to construct free-standing structures or larger spans such as columns, walls, slabs, roofs, and bridges. For generations, architects have risen to the challenge of developing formwork and scaffolding solutions that have made it possible to build breathtaking domes, vaults, and other wide-spanning structures.

In the world of small-scale 3D printing using thermoplastics, objects with overhanging and horizontal, unsupported features are usually achievable by 3D printing infill patterns and temporary supporting structures that are removed upon the print's completion. Although this method is very efficient and suitable for the production of smaller parts, it cannot be applied directly to large-scale printing applications due to several constraints. Viscous materials used in large-scale applications involve slower drying rates and are deposited through larger nozzles while responding to environmental factors and gravity [5], all of which influence both, inter-layer and intra-layer failures [116]. Furthermore, the ratio of the 3D printed material mass to that of the printed support structures at large-scales is incomparable to small-scale 3D printing applications, wherein the supports exhibit greater stiffness compared to the 3D printed components.

3D printing support structures using viscous materials can significantly lengthen the printing duration and the amount of produced waste, rendering it a less efficient solution. Given the aforementioned challenges, prevailing construction 3D printing methods typically steer away from unsupported geometries and spans, aiming to prevent material instability and potential failures during printing.

Building upon the insights from traditional and conventional construction techniques might offer a valuable research avenue to address challenges related to process and material efficiency. While the general use of formwork in concrete construction has been thoroughly investigated, there has been little work combining formwork integration into large-scale 3D printing.

Problem Statement

The rise of large-scale 3D printing holds the promise of revolutionizing conventional construction approaches, advancing process efficiency, material conservation, and mitigating environmental impact. Research interest in adapting 3D printing technologies for buildings and construction has increased exponentially in the past years with high hopes of achieving efficiency in construction time, material usage, waste mitigation, and labor cost when compared to conventional construction. A study by Tay et al. (2017) has identified current research trends in 3D printing for architecture and construction, classifying areas of development where 3D printing techniques and material developments are key topics [290]. The study pays attention to the increasing number of publications relating to the topic of 3D printing for building and construction. It also keeps track of the frequent appearance of keywords such as “additive manufacturing,” “additive construction,” and “concrete printing.”, proving the great interest and the available room for development while the technology remains at its early stages.

However, the reality of the current state of the technology– often described as 2.5 D printing – is currently limited to printing vertical structures (e.g. walls or discreet components) by stacking planar layers of printed material. One limitation comes from the intrinsic properties of the 3D printed materials. Often viscous, these materials, are printed in a wet state that is subject to gravity and environmental variables that affect stability. The sensitivity of the printed materials compromises their ability to support forms with overhanging or unsupported geometric features, requiring auxiliary support before fully hardening. Without supports, 3D-printed structures with overhangs or larger spans would deform or even collapse under their own weight. What is needed are methods for support integration into large-scale 3D printing procedures which allow for the creation of overhangs and larger spans. These methods must enable overhanging and unsupported structures without compromising material and process efficiency, and the structural performance of the printed entities. The current stage of the technology also calls for advancements across tool, process, and material levels to effectively support and facilitate these methods.

Research Questions

In construction 3D printing, it remains difficult to create overhanging forms or unsupported, long-spanning structures. This research aims to develop additive manufacturing methods that are capable of minimizing, integrating or completely eliminating auxiliary supports to achieve complex but structurally advantageous geometric shapes that are currently unachievable to produce. To achieve these objectives, this thesis examines alternative formwork strategies that can be adapted to a range of materials, platforms, and processes.

This leads to the research question: What if we could combine multi-axis robotic 3D printing with formwork integration to redefine the limits of current printable geometric designs? Can we re-envision the traditional methods of formwork construction to significantly reduce waste without compromising structural integrity? Can formwork be completely eliminated? How might alternative 3D printing materials revolutionize the construction industry's approach to waste and efficiency? By addressing these questions, this thesis explores the current limitations of large-scale additive manufacturing and proposes novel techniques to push the technological boundaries of non-planar 3D printing.

Research Significance

This research transcends current process limitations and traditional industrial protocols in construction materials. It demonstrates a series of experiments showcasing the promising potential of viable design and fabrication workflows, that specifically emphasize non-planar 3D printing and formwork integration strategies. These innovative approaches play an essential role in improving the adaptability, scalability, versatility, and efficiency of construction 3D printing for wide-spanning, unsupported forms.

The literature review of this thesis identifies several gaps, notably in technological, and material constraints which restrict large-scale 3D printing applications to layer-based approaches. Current practices also lack efficient formwork integration solutions, mainly due to their wasteful nature. In response, the experimental fabrication approaches outlined in this thesis aim not only to expand current technological capabilities, but also to address the many challenges of additive manufacturing in terms of material diversification, waste mitigation, and process efficiency. Drawing insights from these experiments, this thesis outlines a systematic approach for knowledge transfer, including developments in hardware and software that can potentially be applied to various additive manufacturing workflows and have an impact on the way we build in architecture and reuse materials. **Chapter 3** of the thesis delves into these experimental approaches in further detail.

Motivation

The motivation behind this research is not confined within a single research discipline, but intertwines multiple domains. Navigating through the fields of design, architecture, science, engineering, and invention, this exploration embodies the spirit of cross-disciplinary inquiry. At the core of this research lies the aspiration to harness the collective wisdom from diverse disciplines, positioning this research at the forefront of technological innovation. Driven by curiosity, the investigation embarks on formulating questions that bridge various neighboring fields. This experimental approach, by its nature, brings forward unforeseen discoveries, while simultaneously unveiling emergent possibilities. This research is also motivated by historical perspectives and insights from adjacent fields of research. The synergy of historic principles and more recent technological advancements promises to redefine the dimensional boundaries.

Thesis Objectives

The primary aim of this thesis is to conceptualize, initiate, and craft novel workflows for non-planar 3D printing, challenging and expanding the current-state technology. This endeavor is realized in this research through prototypical developments and experimental case studies addressing various strategies for integrating formwork:

1) Formwork reduction: This involves exploring methods to minimize material consumption and utilize minimal amounts of formwork, facilitating the construction of lightweight, long-spanning 3D printed structures.

2) alternative formwork approaches: Investigating the use of abundant, reusable granular materials both as temporary support material and printing material.

3) Formwork elimination: This aspect examines the feasibility of 3D printing funicular structures, by strategically placing materials and executing fabrication sequences that could eliminate the need of formwork during construction.

Central to this research is the adoption of a project-centric process, in which the outcomes are not predefined, but emerge during the research process. Thus, each discovery dictates the subsequent experiment and research direction, establishing an innovative, cross-disciplinary procedure.

Limitations and Expectations

The studies presented in this thesis mainly focus on materials and experimental scales that are feasible within an academic and lab-scale environment. The selection of tools and materials enable rigorous validation and evaluation of the research findings. However, to broaden the applicability of the presented research, certain experiments are extended through industry partnerships, utilizing industrial materials and robotic platforms. Therefore, the dissertation should be seen as a pioneering effort and groundwork that paves the way for subsequent research, and illuminating potential research avenues deserving of deeper exploration.

The strategies and methodologies developed and discussed in this thesis address multifaceted challenges from various directions. However, each of these approaches, while promising, remains ripe with room for expansion. The summaries concluding every chapter and research experiment serve not only as recaps, but as pivotal launching points for future research. By establishing the groundwork for several new approaches, these summaries are intended to facilitate further academic debate so that others can build on the findings presented in this dissertation.

1.2 Organization of the Dissertation

The organization of this thesis encompasses a cross-disciplinary approach and touches on a wide range of topics, which are illustrated in **Fig. 1**. This graphic presents a clear overview of the diverse aspects of this work.

Following this introduction, **Chapter 2** serves as the foundation section of this thesis and provides an overview of four main areas of research: additive manufacturing, robotic fabrication, material extrusion and deposition, and auxiliary Structures, particularly in the context of architectural design. The first part of this chapter traces the development of additive manufacturing in architecture from its infancy to its current state. This section discusses key breakthroughs in additive manufacturing that led to its adoption in the construction industry. The narrative of the chapter subsequently shifts in its second part, towards a related key theme, which is robotic fabrication in the context of architectural design. This part of the chapter differentiates between the use of industrial robotic arms for mass production in the context of industrial automation, and its integration into architectural design which takes the advantage of robotic versatility and its use for mass customization and creative fabrication. The chapter also provides an overview of the use of viscous materials in construction throughout history, with a particular focus on concrete. The construction industry's familiarity with concrete, along with its advantageous qualities such as ease of handling, strength, and tunability—the ability to adjust material properties to adapt to different applications—, make it an ideal material to adopt into the construction 3D printing domain. However, concrete and other viscous materials being utilized in construction 3D printing are challenged by their temporary instability in their wet state. This instability requires the use of an underlying auxiliary structure to enable unrestricted 3D printing. Furthermore, this chapter discusses the topic of formwork in construction, providing insights into historical precedents as well as current strategies for integrating formwork into construction and digital fabrication in particular.

As a whole, **Chapter 2** introduces the overarching background themes of the thesis, setting the stage for the subsequent chapters. The core content of the thesis is presented in **Chapters 4** to **7**. These chapters explain the primary focus of the thesis, which is based on iterative testing, manufacturing, and prototyping.

Chapter 3, (Titled: Methodology), delves into the limitations and challenges that currently limit the use of large-scale additive manufacturing in architecture. It not only outlines the objectives of the study, but also highlights recurring themes and pivotal questions the thesis aims to address. The main themes discussed in the subsequent chapters revolve around the question of toolpath design and formwork integration into the 3D printing process. These themes are dissected in depth in **Chapters 4** through **7**, reflecting on the experiments, challenges, and findings encountered along the thesis journey. The main objective of the thesis is to develop alternative workflows that enable non-planar 3D printing of viscous materials at various scales. This is achieved through novel support integration solutions that can reduce costs and mitigate waste. While each of the following chapters is unique in its approach and content, it collectively contributes to the overarching narrative of this thesis.

Figure 1.1: Diagram to illustrate the content organization of the thesis.

Chapter 4 discusses the development of software tools that provide enhanced levels of control over 3D printers. It forms the core basis for the central theme of the research: Non-planar 3D printing. This approach maximizes the potential for multi-axis robotic extrusion, offering innovative avenues in robotic 3D printing. The approach to toolpath design explained in this chapter is reflected in the projects discussed in the following chapters.

Chapters 5, **6** and **7** are the focus of the discourse in this thesis and deal with different approaches to the role of auxiliary structures and the integration of formwork for non-planar 3D printing. **Chapter 5** discusses strategies aimed at formwork reduction in the context of non-planar 3D printing using viscous materials. The chapter demonstrates case studies and experiments utilizing bending-active formwork, as a strategy for mitigating material waste without compromising structural integrity.

Chapter 6 shifts the focus towards alternative approaches to free-form 3D printing using granular materials as both a temporary formwork and an efficient 3D printing material alternative to conventional cementitious materials. This chapter introduces a novel technique that utilizes recycled granular materials to rapidly 3D print unsupported forms. The chapter delves into some of the advantages and challenges affiliated with the proposed approach. The chapter explores the myriad possibilities it introduces to the additive manufacturing landscape, including functional gradients and multi-material printing capabilities. Through multi-scale experimentation, the chapter dissects the components of the technology and demonstrates its capabilities.

Chapter 7 takes a progressive approach, suggesting a method that enables the complete elimination of formwork in the 3D printing process by constructing vaulted structures, in which the overhanging print layers support each other. The chapter draws parallels with historic precedents, referencing ancient construction techniques and the applicability of historic principles to modern additive manufacturing techniques to address current-state challenges.

Concluding the thesis narrative, **Chapter 8** functions as a reflective culmination of the thesis. It combines the theoretical, methodological, and technological insights presented throughout the earlier chapters. This chapter discusses the core contributions of the research and underscores the significance of the findings in the broader context of architectural design.

1.3 Chapter Summary

The following sections outline the structure of this thesis. Each includes the chapter title and summary. Certain content is adapted from self-authored papers and includes relevant citations.

Chapter 2: Background

This chapter deals with three domains: construction additive manufacturing, robotic fabrication, and the use of viscous materials in additive construction. The chapter discusses historic precedents and present-day technological advancements, laying the groundwork for the research carried out in the thesis. Brief summaries of each main subtopic of **Chapter 2** are provided below.

Additive Manufacturing in Architectural Design

Since the 1980s, additive manufacturing (3D printing) made possible the creation of complex objects that were traditionally constructed from multiple components. Because of its economic feasibility and the manufacturing workflow simplicity, 3D printing was utilized at its early stage in rapid prototyping and the development of test models. In contrast to conventional manufacturing, which requires intricate process planning, additive manufacturing relies on the digital design of 3-dimensional objects using computer-aided design. Typically, after the digital 3D model is designed, it is then segmented into two-dimensional cross-sections that are sequentially printed, constructing the designed object through layer-by-layer material deposition.

While layer-based manufacturing remains dominant, recent advances have been made towards non-planar 3D printing. This process employs synchronized multi-axis platform movements, enabling material deposition beyond the confines of 2-dimensional layers. *Conformal 3D printing*, for example, refers to material deposition onto an undulating surface or substrate, allowing the printing platform to follow the surface or base geometry. *Free-form 3D printing* is another method that deposits materials freely in 3-dimensional space, often extruding materials with a fast curing time so that they can quickly become load-bearing structures.

There has been a growing interest in harnessing 3D printing in architecture and construction applications for the production of entire houses or building components to enhance efficiency, material economy, and safety. In large-scale applications, viscous materials are 3D printed using a large-scale robotic platform or gantry system. The process takes place either in factory settings, where components are prefabricated in controlled environments, or on the construction site.

Robotic Fabrication

This section of **Chapter 2** examines the transformative role of industrial robotics in the realm of architectural design. In the past, industrial robot arms have helped to enable production processes with high labor input and high repeatability, especially in mass production. In industrial settings, the true potential of industrial robotic arms lies in their ability to outperform humans in tasks that require high productivity and precision, especially in environments where noise and potential hazards may exist. In the architectural field, on the other hand, industrial robots are being used to transcend existing limitations of traditional manufacturing and construction and to offer customized components in small quantities or even as one-offs. Treating robots as instruments of creativity has ushered in a new era of design-driven research and spawned a range of new innovative manufacturing methods. In this context, robots are admired not only for their mechanical endurance and strength, but also for their versatility and adaptability as they complement human operators in crafting intricate designs.

Material Extrusion and Deposition

Historically, granular materials like clay, sand, lime and other cementitious materials have been activated using water, serving to enhance hydration and workability. Since the discovery of hydraulic lime in the 1700s and Portland cement in the 1800s, the malleability of viscous composites has enabled the construction of varying forms and structures. Concrete, a composite material composed of various components, one of which is cement, ranks among the most used materials globally. One of concrete's main attributes, is its ability to transition from a fluid state, easily filling formwork molds, to a robust, durable material that is capable of bearing structural loads. This, among other attributes, makes concrete ideal for construction 3D printing applications. The extrudability and pumpability of the material allows for easy handling and precise material deposition by the 3D printing platform. However, viscous materials including concrete encounter several challenges when 3D printed. First, the instability of viscous materials in a wet state limit the geometric possibilities they are able to achieve without using auxiliary structures or formwork during the printing process. Secondly, cement-based materials contribute negatively to the environmental footprint. The widespread use of concrete highlights the need for strategies that mitigate its carbon footprint. These strategies include reducing cement usage, or exploring environmentally-cautious alternatives.

Auxiliary Structures

The concluding section of the chapter delves into the use of auxiliary structures, discussing their critical role in shaping concrete and other viscous materials. This section provides an overview of different types of formwork, detailing their advantages, areas of classification, and applications. The chapter also discusses the role of auxiliary structures as temporary supports in the additive manufacturing domain, drawing comparison between support integration in small-scale 3D printing applications, and in large-scale construction 3D printing.

On the desktop scale, 3D printers often print temporary, removable support structures that aid in producing complex geometries that include overhangs, voids, or other unsupported geometric features. This technique, however, does not work in large-scale construction 3D printing applications. Translating the technique of 3D printable supports from a desktop scale to the large-scale may seem as a viable solution, but is marred by drastic waste production and increased printing durations. This challenge demands further investigation, and alternative approaches to auxiliary support integration which can potentially unlock geometric possibilities in large-scale construction 3D printing.

Chapter 3: Methodology

This chapter begins by identifying overarching topics and research challenges in connection with 3D printing of viscous materials. In particular, the problem that viscous materials cannot withstand large forces in their wet state. These limitations affect the potential design possibilities and geometric freedom of the structures being 3D printed. Temporary support structures are required when dealing with designs with overhanging parts and unsupported forms. Despite the advances in construction 3D printing, there remains a significant gap in the availability of tools for support integration and custom toolpath control.

This research addresses core questions related to formwork integration using non-planar 3D printing on the hardware, software, material, and process levels. An important aspect of the proposed research methodology is the development of multi-scale prototypes designed to answer these research questions. Large-scale prototypes provide insight without the legal and economic barriers that often hinder architectural innovation. These prototypes essentially serve as a test medium with which the proposed manufacturing process is demonstrated, evaluated, and further developed.

In response to the identified challenges and methodological framework, this research introduces three categories of experiments that focus on formwork integration and non-planar 3D printing. The experiments cover three primary areas of support classification: support reduction, alternative support integration, and support elimination.

Chapter 4: Beyond Planarity: Designing with G-CODE

Conventionally, 3D printed objects are digitally modeled, then processed through slicing software to generate planar contours, which are next converted into machine-readable G-CODE. This workflow offers only restricted control over the 3D printing process. **Chapter 4** introduces a framework that maximizes the potential of CNC machines and 3D printing platforms, eliminating the need for slicing software in the toolpath generation process. The framework offers high levels of customizability, enabling users with enhanced control over 3D printers and opening up a spectrum of possibilities for unconventional 3D printing applications.

A primary motivation behind this approach is to enable the design of non-planar toolpaths, a concept further explored in subsequent chapters. The chapter demonstrates the practical utility of the software tools by presenting a variety of printing processes spanning different materials and scales. Ultimately, this chapter establishes the groundwork for the overarching theme of non-planar toolpath generation that takes advantage of the full capabilities of 3D printers and multi-axis robotic extrusion.

Chapter 5: Conformal 3D Printing Using Bending-Active Formwork

Chapter 5 investigates the potential of conformal 3D printing that deposits materials directly onto a base formwork or substrate, enhancing printing speeds, reducing material waste, and unlocking new 3D printable geometric possibilities. The chapter begins by outlining some of the key advantages, limitations and challenges associated with existing approaches to conformal 3D printing, including the use of mesh formwork, mechanically shaped granular substrates, and the use of high-strength textiles as auxiliary structures.

Building on this research, the chapter introduces a novel approach for conformal 3D printing that utilizes bending-active formwork. This technique not only significantly limits material waste, but also capitalizes on the bending-active formwork as an intrinsic stay-in-place reinforcement layer in the printed structure, resulting in even lighter prints and material savings.

To test the viability of this approach, a series of design experiments was conducted utilizing a 6-axis robotic platform. Initially, experiments involved printing using single bent strips as formwork. The knowledge gained from this preliminary experiment then informed the construction of a full-scale prototype: a bending-active roof structure in form of a gridshell. Throughout these experiments, multiple formwork registration techniques were explored, including 3D scanning and vision-based position estimation.

The chapter then discusses developments of computational tools tailored to address geometric toolpath planning challenges associated with the complexity of the gridshell formwork. The chapter concludes by contemplating the potential applications of the proposed methodology in crafting gridshell structures and roofs, using direct printing onto bending-active formwork.

Chapter 6: Non-Planar Granular 3D Printing

The first part of **Chapter 6** provides an overview of notable technologies that utilize granular materials in 3D printing, both as a 3D printing material and as a temporary support medium that enables complex, unsupported shapes. While there have been several approaches to free-form 3D printing with granular substrates, this chapter presents a newly developed method called non-planar granular 3D printing. The benefits of this approach include scalability, platform versatility, and the capacity to incorporate a broad spectrum of recycled materials.

Chapter 6 then provides a comprehensive technical background to the proposed method and points out its particular advantages and potential limitations. It then continues by describing a series of experiments that demonstrate how the technology works in detail. The experiments cover a range of materials and printing parameters and open up new perspectives in the field of granular 3D printing.

The chapter ends with reflections on practical applications of the non-planar granular 3D printing method in the field of 3D printing and suggests future avenues for refining and advancing this technology.

Chapter 7: Support-Free 3D Printing

Chapter 7 begins with the important topic of material scarcity and waste in the construction industry. It presents an approach that combines computer-aided design strategies with multi-axis robotic fabrication to arrive at a method of free-form 3D printing that allows for the complete elimination of formwork and auxiliary structures in the construction of vaulted roofs and dome structures.

To do this, this chapter explains the challenges associated with 3D printing roofs and presents some recent 3D printing projects in which vertical walls were printed. It then draws parallels between current 3D printing technologies and historical masonry techniques and highlights similarities between the two processes.

The chapter focuses on an experimental research approach using adobe - chosen for its similarity to a viscous material - to 3D print a series of small roof structures, including primary compressive load-bearing structures such as domes, vaults and apses. The experiments will use geometries that leverage non-planar 3D printing in combination with computational methods to optimize compression during the printing process.

The chapter then covers a final large-scale experiment in which a Nubian vault is 3D printed from adobe printed directly on site. The experiment uses a six-axis industrial robotic arm and locally sourced materials collected directly from the construction site. The intricacies of the computational and material aspects as well as the complete system setup are described in this part of the chapter.

The chapter concludes with a plea for a new approach to 3D printing in construction, emphasizing the wisdom anchored in historical precedent. The studies presented in this chapter point to an ecologically responsible and sustainable approach that leaves a minimal environmental footprint.

Chapter 8: Contributions and Future Outlook

The thesis concludes with **Chapter 8**, which contains an evaluation of the theoretical, methodological and technological findings of this work. The chapter addresses the key areas and findings of the research and points to unresolved issues and potential avenues for future investigation. The chapter should be seen as a starting point and an invitation to researchers to complement and extend the work presented here.

Chapter 2

Background

2.1 Additive Manufacturing in Architectural Design

Overview

Traditional construction methods are often characterized by their labor-intensiveness, long duration, and waste production [173]. Research indicates that the construction industry is one of the major contributors to the consumption of global resources, accounting for approximately a sixth of the world's fresh water usage, a quarter of the wood, and two fifths of the materials in use worldwide [262] [263] [80]. Additionally, construction processes, along with manufacturing, transporting, and installation activities demand substantial amounts of energy, significantly contributing to greenhouse gas emissions [318]. Due to factors such as resource depletion, global warming, and rapid population growth are driving the industry towards adopting responsible construction practices [292].

Moreover, the housing sector is also challenged by issues such as cost, construction inefficiency, and time overruns, contributed greatly to a rise in housing costs. In 2021, for example, the average increase in housing values surpassed the median annual earnings of a full-time worker [103]. This escalation in home prices is further reinforced by the high costs associated with building materials, construction methods, and labor cost.

Given these challenges, the adoption of innovative construction techniques is a vital step towards addressing environmental challenges and minimizing the construction industry's ecological footprint [303]. To address some of these problems, automated construction has produced significant research within the architectural design community. While past endeavors focused on standardizing buildings and building components, and on addressing concerns like production time and waste-management, designing architecture requires novel approaches that take into account factors such as site conditions and occupant requirements, necessitating higher degrees of design customization.

Over the years, research interest in adapting 3D printing technologies to architecture and construction has increased exponentially. 3D printing in construction holds the potential to amplify production rates and economize on material usage by depositing materials only where they are required, irrespective of the complexity of the design [286]. Given its success on smaller scales, the construction sector is well suited to take advantage of the design flexibility and complexity of forms that 3D printing offers. When juxtaposed with traditional construction techniques, 3D printing also promises to improve safety, labor, and production timelines [256].

Rapid Prototyping

The term *Rapid Prototyping*, widespread across various sectors, refers to the preliminary fabrication of products prior to their final manufacturing phase. A common characteristic of rapid prototypes is their production using additive manufacturing, more often recognized as 3D printing. Originating in the 1980s, the initial understanding of the term Rapid Prototyping has become obsolete, as it no longer describes the more recent applications of manufacturing finished and ready-to-use products additively [110]. As outlined in Wohler's Report (2014) and the ASTM International Committee F42, 3D printing is defined as the "fabrication of objects through the deposition of a material using a print head, nozzle, or other printer technology" [316]. The adaptability of this technology, coupled with the surge in global knowledge-sharing and dissemination of design data, celebrates 3D printing as a groundbreaking shift in manufacturing [108].

Additive manufacturing technologies offer unique, creative avenues for designers and creators [108]. The technology has enabled the fabrication of intricate objects that were traditionally conceptualized as assemblies, composed of multiple components held together with fasteners and assorted hardware. Owing to its cost-effectiveness, 3D printing has been primarily employed to produce prototypical models during developmental phases. While conventional manufacturing approaches require thorough process planning and geometric considerations to determine the order of fabrication and assembly, additive manufacturing relies on design features that are derived from 3D, Computer-Aided Design (CAD) tools, thereby simplifying the creation of complex, intricate objects [110].

3D printing encompasses techniques including Fused-Deposition Modeling (FDM), which utilizes thermally fused plastic extrusions; Stereolithography (SLA), which uses ultraviolet light to cure polymer resin; Binder-Jet Printing, which focuses on powder binding; Selective Laser Sintering (SLS), which sinters particles using a laser beam; and Liquid Deposition Modeling (LDM) [108][110]. These techniques have applications in the medical field [272][24], automotive, mechanical [198], the food industry [178], and fashion[52]. More recently, 3D printing has moved into architecture and construction. This study emphasizes large-scale 3D printing methods that utilize material extrusion and deposition, particularly using viscous and cementitious materials. The study is carried through various extrusion-based, machine platforms, and the diverse materials, employed to construct objects across varying scales.

Layered Manufacturing

Additive manufacturing systems rely on a process that begins by designing a solid 3D digital model. This model is subsequently segmented into a series of two-dimensional, planar slices using free or commercial slicing software that prepares models for 3D printing. Within the software, these sliced profiles are converted into machine commands that guide the 3D printer's extrusion of material, ultimately crafting the physical component [110]. This process is often referred to as *layered manufacturing* (LM), where an object is produced using layer-by-layer deposition of materials [51]. In the FDM process, heated thermoplastic filaments are extruded via a nozzle, tracing the initial cross-sectional path of the designed artifact. This results a single layer of the thermoplastic being deposited on the flat printer build-plate. In this method, material deposition occurs in a single plane, creating a single layer of the 3D model. Upon completion of the initial layer, the nozzle ascends vertically to a distance equivalent to a layer's thickness, and the procedure is repeated. Notably, the Z-axis movement is activated only when the X and Y motions are stationary. Owing to its reliance on two-dimensional planar printing, this method is often referred to as *2.5-D printing* [202] [307] [186]. A limitation of the LM process is its potential to yield poor surface and mechanical attributes, especially in high-curvature designs and increased layer thicknesses, leading to a stair-stepping appearance. This defect is a result of converting solid geometry into planar layers as shown in **Fig. 2.1 (a)**. .

Non-Planar Additive Manufacturing

Contrary to the principles of layered manufacturing, non-planar 3D printing is a technique, illustrated in **Fig. 2.1 (b)** that instructs the 3D printer to operate concurrently across the X,Y, and Z axes. This grants the printing platform the capability to navigate within true 3D space, unbounded by planar constraints or sequential material deposition. The terms *non-planar*, *conformal*, and *freeform* are often confused. To better identify the differences and overlaps between the terms, it is worth looking at their origins and most frequent uses.

In 1999, Klosterman et al. developed a process utilizing curved layers, coined *curved-layer laminated object manufacturing* (CLLOM). The process was used for the production of curved layered parts such as thin shelled objects that maintain continuous fiber orientation in alignment with the direction of the shell's curvature [145]. The process was then extended to FDM by Chakraborty et al (2008). and was coined *curved-layer fused deposition modeling* (CLFDM) [51]. The technique has been theoretically tested on parametric surfaces but was never implemented. Advantages of CLFDM include the elimination of the stair-stepping effect and improvement in the object surface quality by printing curved surface layers, achieved by slicing the input digital model using curved, non-planar layers. In 2018, Ahlers et al. (2018) at the University of Hamburg formulated a slicing algorithm that identifies regions of the printable object that would benefit from non-planar layers [10]. This innovative approach integrates both, planar and non-planar layers, producing surfaces that not only are smoother, but also possess enhanced mechanical properties.

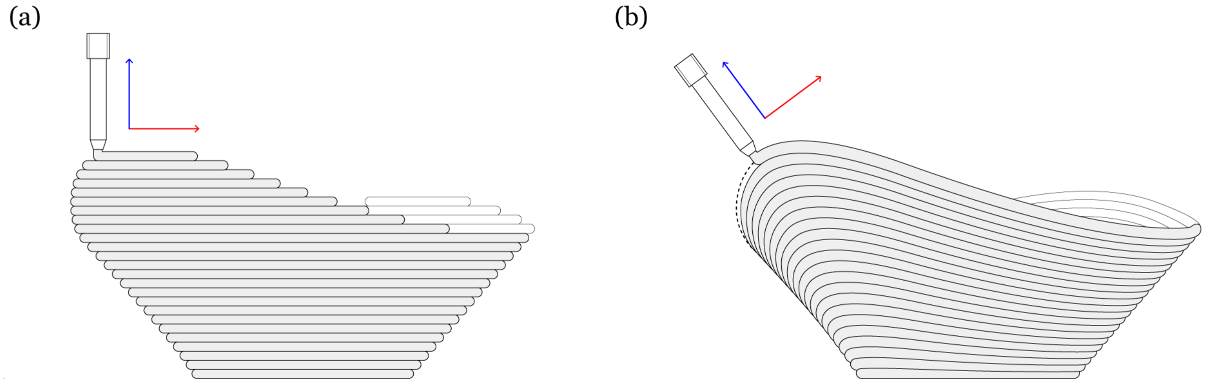

Figure 2.1: Comparison of planar and non-planar 3D printing processes. (a) In planar 3D printing, the extrusion nozzle maintains a vertical orientation, with layers deposited as horizontal slices. (b) In non-planar 3D printing, the nozzle can be aligned with the printed geometry, conforming to its curvature, which reduces the stair-stepping effect produced by planar slicing.

Demonstration of a 3D printed object created using Branch Technology's freeform 3D printing method known as Cellular Fabrication (CFAB).

Conformal 3D Printing - In the realm of additive manufacturing, refers to a technique where materials are deposited onto a surface or substrate [16]. While a three-axis Computer Numerical Control (CNC) machine can execute this method, platforms with extended degrees of freedom would ensure the extrusion nozzle aligns with the base-surface normals.

In this conformal 3D printing approach, materials may also be deposited in sequential layers. However, the Z-axis coordinates are constantly changing during the deposition of each layer [16]. This shift is inherently linked to the topology and complexity of the underlying surface, as shown in **Fig. 2.3**. Unlike traditional LM methods, where layer height is usually kept constant and predetermined by vertical travel after each printed layer, conformal 3D printing relies on an offset, usually normal to the base-surface, maintaining a fixed distance between the base-surface and the nozzle tip at any given location on the surface [51]. This maintained distance, coupled with nozzle alignment to the base-surface normals, fundamentally governs the shape and quality of the extrusion [16].

Freeform 3D Printing - While conformal 3D printing is contingent on the presence of a base-surface or substrate, there have been developments in multi-axis 3D printing methods that allow printing directly in 3D space, bypassing the need for supports. *Freeform* 3D printing refers to an approach where the platform moves synchronously in the X,Y, and Z axes, extruding materials directly in 3D space, usually taking advantage of fast glass

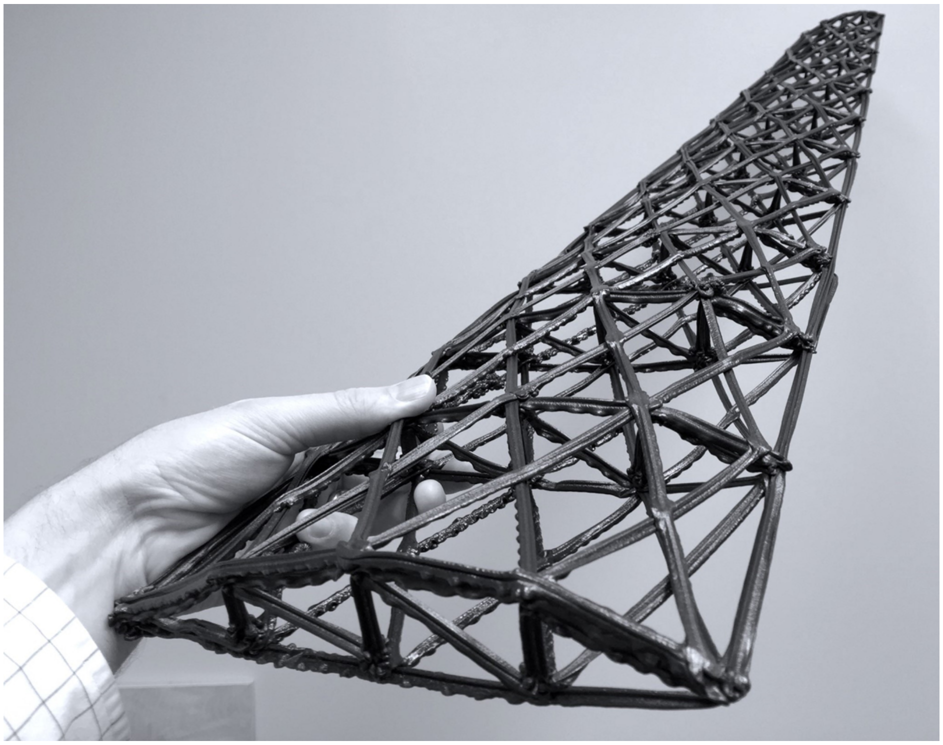

Figure 2.2: Demonstration of a 3D printed object created using Branch Technology's freeform 3D printing method known as Cellular Fabrication (CFAB) [277].

transition points, where the extruded material hardens quickly and becomes load-bearing [156] [217]. By eliminating support structures, this approach has the potential to increase printing speed and reduce material consumption.

Several demonstrations of freeform 3D printing have utilized proprietary extrusion tips and robotic end-effectors with varying designs and capabilities. For instance, Oxman et al. (2013) showcased a design of an extruder that is capable of printing self-supporting, fluid plastic strands [217]. The extruder is based on an auger screw design that deposits molten high-density polyethylene (HDPE) pellets in 3D space. In contrast, Laarman et al. (2014) developed an end-effector that extrudes a rapidly hardening, two-component thermosetting polymer [156]. The end-effector is equipped with a static mixer that instantly mixes the two components together, and air heaters that expedite the material's curing process.

Building on this concept, a full-scale demonstration of freeform 3D printing has been executed by Gramazio Kohler research at ETH, Zurich. An architectural installation named "Iridescence Print" was displayed at the Palais de Tokyo in Paris featuring a continuous, free-standing mesh structure [125]. The mesh structure measured over 8 cubic meters in volume and was printed in 12 segments that were assembled at the venue. The freeform 3D printing process used in fabricating Iridescent Print is a continuation of the ongoing

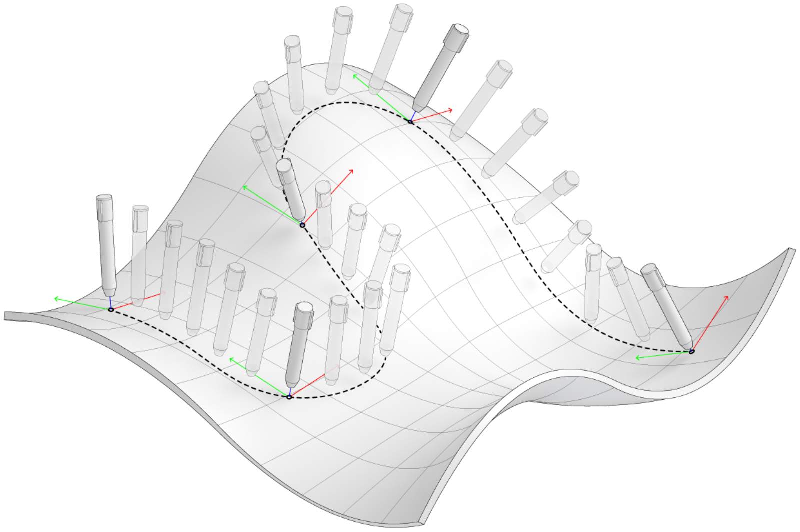

Figure 2.3: In a conformal 3D printing process, the orientation of the extrusion nozzle is determined by the local coordinate system at each point of a base surface and can, for example, be aligned according to the changing surface normals.

research project termed *Mesh Mould* that was initiated at the SEC Future Cities Lab and was continued at ETH, Zurich [118]. Mesh Mould investigates a freeform 3D mesh structure that is used as formwork and reinforcement for concrete elements. Mesh Mould has been made possible through the design of a custom extrusion end effector capable of 3D printing complex mesh structures using Acrylonitrile Butadiene Styrene (ABS) in free space.

Freeform 3D printing solutions have transitioned beyond research-based design to practical applications in commercial contexts. For instance, The U.S-based company Branch Technology has embraced freeform 3D printing through their proprietary method known as *Cellular Fabrication* (CFAB). The patented CFAB technique uses a 6-axis robotic arm to extrude thermoplastic filaments that solidify in open space to create skeletal mesh structures. The elongated extrusions are fused together at corner nodes to form 3-dimensional lattice structures, producing large-scale components, as shown in **Fig. 2.2** [277]. Among Branch Technology's innovative applications of CFAB is the extrusion of carbon-fiber reinforced freeform girds. The 3D printed grids are subsequently filled with spray-foam insulation, and coated with a concrete cladding layer to produce wall panels, now referred to by the company as BranchClad [40].

A parallel approach was explored by Nagami Design in collaboration with the UCL Bartlett School of Architecture-Design Computation Lab in fabricating Voxel Chair V1.0. The chair is designed by a proprietary software that is intended for robotic 3D printing applications which generate a mesh structure made of discrete voxels. The chair is 3D printed using an industrial robotic arm and a continuous line of plastic measuring 2.4 kilometers [133].

The aforementioned projects and technological developments in the domain of non-planar 3D printing demonstrate the nuanced distinctions between *conformal* and *freeform* as terminologies that are used to describe specific processes within this domain. While both terms refer to the deviation from conventional planar methods, each highlights unique attributes of non-planar 3D printing. In light of these developments, and to ensure consistent terminology throughout this thesis, the term *non-planar 3D printing* is used to encompass all additive manufacturing methods that involve simultaneous multi-axis material extrusion beyond 2-dimensional layers.

Construction 3D Printing

3D printing applications have evolved from their initial use in various sectors, to a significant role in the construction domain. Considering the global demand in reducing CO2 emissions, particularly in the construction industry, makes 3D Construction Printing (3DCP) an appealing area of research and potential development in both, academic and construction practices. The technology promises to open up novel opportunities and address some of the current challenges of traditional construction workflows. This section discusses key aspects of 3DCP, including an overview of the key players shaping the field of construction 3D printing, and highlights notable technology demonstrators that exemplifies recent advancements. To achieve this, a literature review was carried out, on the basis of which several main aspects of the C3DP field can be presented. The review process involves sourcing and evaluating relevant scientific articles in the field of 3D printing in construction, as well as research from various interdisciplinary experts, academic institutions and private companies.

Technological Origins

The concept of layered construction can be traced back to the 1930s with William Urschel's endeavor through the development of the "Machine for Building Walls" [79] [300]. Urschel's machine operates on a rotating boom arm with an adjustable height **(Fig. 2.4)**. At the end of the boom arm is a deposition head that is equipped with a hopper and a material feeder, which dispenses solidifiable materials such as adobe, cob, or rammed earth in radial strips. Similar to modern-day 3D printers, the machine deposits materials layer by layer, gradually constructing a radial wall.

The inception of true automated concrete construction, however, originated with Joseph Pegna at the Rensselaer Polytechnic Institute in New York [223]. His method entailed a repetitive, layer-based fabrication process derived from a CAD model. The model is segmented into planar layers and then converted into machine movements. In this process, powdered materials are deposited in a cross-sectional toolpath, then solidified using a reactant/catalyst. Although Pegna's experiments yielded a modest 3" x 3" x 6" layered-concrete sample, his studies demonstrated the viability and scalability of the proposed method for on-

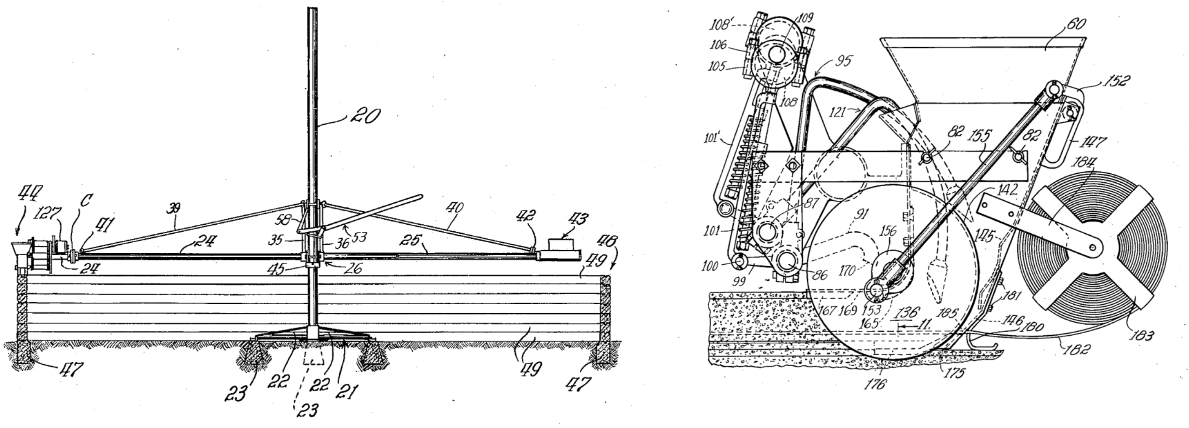

Figure 2.4: Patent illustration by William Urschel for a Machine for Building Walls [300].

site construction. Furthering this field of study, Khoshnevis et al. (2001) of the University of Southern California introduced Contour Crafting (CC) in 1998 [223] [142]. This innovative method integrated an extrusion nozzle for layer deposition with adjacent smoothing blades, facilitating both surface forming and finishing. Like many preceding additive manufacturing processes, CC constructs components in layers. The apparatus is composed of a flat rotary worktable and a vertical extrusion head capable of linear movements along 3 axes. Initial explorations used plaster and clay as extrusion materials because of their availability, low cost, and extrudability at ambient temperatures. The range of materials then expanded to cementitious materials, the aim being to expand the scale of the method to structural elements and even entire buildings. The method proposed by Khoshnevis et al. employs a gantry system installed on the construction site which moves the extrusion nozzle along two parallel lanes. Advantages illustrated by Khoshnevis et al. include design adaptability, potential for material diversification, reinforcement integration, and an enhanced surface finish achieved by the smoothing capability of the CC platform [139]. Khoshnevis et al. (2004) further explored the potential of exploiting the versatility and adaptability of the gantry setup for printing in remote locations such as the moon or Mars [140].

Advantages of Construction 3D Printing

There are many advantages to using 3D printing in construction. The first obvious one is process automation, which not only enhances construction efficiency, but also reduces the amount of required labor and equipment. Traditional construction methods often involve labor-intensive tasks, such as laying bricks, plastering, and building formwork molds. In contrast, C3DP allows digital designs to be materialized through automated machine operations that require minimal human intervention.

Secondly, when compared with traditional manufacturing methods, 3D printing can dramatically reduce construction time. A notable example is a building produced by Apis Cor that was constructed in only 24 hours [21]. The project demonstrates a considerable advantage in terms of construction time frame, particularly important in projects requiring fast production time, such as in areas where natural disasters may occur.

Compared to traditional construction, 3D printing also reduces the amount of material consumed and generates much less waste. Because 3D printers deposit materials along a programmed path, they are able to place materials only where they are required [226]. However, material reduction may not necessarily reflect a reduction in construction cost. One of the current limitations of the technology is that the materials commonly used in construction 3D printing feature significant amounts of cement. That is because the printed material must meet pumpability and extrudability requirements, while also retaining its shape post-extrusion [279] [158]. Due to its high cement content, the material cost is considerably higher than the cost of conventional concrete, while also raising concerns regarding embodied CO2 and the contribution to greenhouse gas emissions [318]. Nevertheless, the technology continues to exhibit lower environmental impact in comparison to conventional construction due to the reduced emissions associated with transportation, raw material extraction, and processing , irrespective of the amount of cement being utilized [14] [193]. Later in this chapter, viscous materials are discussed further, paying closer attention to their use in deposition and extrusion operations.

The integration of 3D printing into construction offers another compelling advantage, which is the ability to fabricate intricate geometric designs, normally difficult and costly to produce using traditional construction methods. Recent projects have showcased the capacity to 3D print walls with designated openings, which subsequently can be filled with insulating materials or even utilized for electrical conduits [112]. Other projects have demonstrated intricate wall textures, made possible by the incremental placement of materials [241] [236]. Nonetheless, current construction 3D printing technologies are challenged by geometric constraints, particularly when dealing with structures composed of significant overhangs or long spans. Such configurations often require auxiliary structures or formwork integration, posing challenges for seamless 3D printing. While this remains an active area of research, this challenge calls for further advancements in the field.

3D Printing Platforms

Within the C3DP domain, two common printing platforms are predominantly utilized: gantry-style platforms, and industrial robotic arms. Each of these platforms has its own set of advantages and disadvantages, with particular characteristics that make each platform most suitable for particular tasks and projects. Some of these important factors that differentiate the two platform types are the scale of construction they can achieve, the level of control over printed toolpaths, and the types of materials they commonly use **(Table 2.1)**.

Gantry 3D printers - Due to their simple programming and design, gantry 3D printers are the most widely used and most developed printers in the C3DP domain. This platform

	Year	**Platform**	**Scale**	**Material**	**Construction Approach**
Contour Crafting	1998	gantry	construction	clay, plaster, cement	prefab, in-situ
Spetsavia	2009	gantry	lab, construction	cement, sand, gypsum	prefab, in-situ
WASP	2012	gantry	lab, construction	Earth	pre-fab, in-situ
Cybe	2013	robotic arm	construction	concrete	pre-fab
Win Sun	2013	gantry	construction	concrete	pre-fab
University of Nantes	2015	robotic arm	lab	polyurethane foam	pre-fab
XtreeE	2015	robotic arm	lab	concrete	pre-fab
IAAC	2015	gantry	lab, construction	Earth	in-situ
COBOD	2016	gantry	construction	concrete	in-situ
Apis Cor	2016	robotic arm	construction	concrete	in-situ
ICON	2017	gantry, robotic arm	construction	concrete	in-situ
Incremental 3D GmbH	2017	robotic arm	lab	concrete	pre-fab
MIT Media Lab	2017	robotic arm	construction	polyurethane foam	in-situ
ETH Zurich	2017	robotic arm	lab	concrete	pre-fab
Baumit	2019	robotic arm	lab	concrete	pre-fab
PERI	2020	gantry	construction	concrete	in-situ
Twente AM	2020	robotic arm	construction	concrete, Earth	in-situ
UC Berkeley	2022	robotic arm	lab	concrete, Earth, Granular Materials	pre-fab, in-situ

Table 2.1: Table listing the key players in the construction 3D printing sector, with details of the type of construction process, the scope of their platforms, and the materials used.

system is characterized by simple linear-axis movements that navigate the extruder through Cartesian space. The relatively uncomplicated setup ensures easy access to the printed objects and offers high precision and printing accuracy due to the few moving parts. A notable advantage of gantry-style printers is their large build volume, which allows entire structures to be built on site. However, as the printed structures are produced within the dimensions of the individual linear axes, the printed objects are limited by the size of the gantry, meaning that a gantry-style printer must always be slightly larger than the produced print itself. Another benefit of gantry 3D printers is the increased load capacity which facilitates the use of large extrusion tips and high-volume material extrudability.

3D printers with a gantry design do have some disadvantages, however. Their size limits mobility, as they need to be assembled and disassembled at each construction site. When you consider the costs associated with transporting and assembling the gantry components, this disadvantage can have a negative impact on logistics and overall project costs[185]. Another main limitation of gantry systems though is the limited degrees of freedom that restrict gantries to vertical material extrusions.

Arguably, one of the earliest prominent illustrations of gantry construction 3D printers is Contour Crafting, which has been discussed in the earlier sections of this chapter [323] [158]. Demonstrations of the Contour Crafting technology, presented by Khoshnevis et al. (1998), exhibited superior surface quality, owing to the integration of a trowel into the extruder, which effectively smooths out the printed layers [141].

Since the development of Contour Crafting, the use of gantry-style 3D printers has become widespread across the C3DP industry. A pioneer at the forefront of large-scale on-site 3D printing is the Texas-based company ICON, which develops 3DCP projects across various scales. ICON's Vulcan is a gantry-style 3D printer that is capable of 3D printing single-story homes and structures up to 3,000 square feet [129]. The Vulcan's design allows the print head to travel along a metal rail in three axes, while also being equipped with wheels, providing unrestricted travel along the longitudinal axis [301]. This feature allows ICON to 3D print long walls, offering a significant advantage over more common gantry-style platforms that are restricted by a fixed printing volume.

ICON's projects include low-cost 3D printed housing communities, energy-efficient training military barracks, a Martian habitat, and the first permitted 3D-printed home in the United States [29] [128][291]. In collaboration with one of the nation's leading home builders, Lennar, ICON is also developing the largest community of 3D printed homes in the world. The community features 100 3D printed concrete homes that are co-designed by Bjarke Ingles Architects, and developed by Hillwood Communities.

Another notable example of a company that currently utilizes gantry-style 3D printers is the Danish company, COBOD. The company uses the BOD 2: a gantry-style 3D printing platform that is modular, and expandable [57]. By attaching additional steel framing to the gantry system, the scalability and modularity of the BOD 2 enables it to cater to client-specific requirements, adapting to any specified size and configuration, regardless of the 3D printed design [56]. The company claims that the BOD 2 is capable of 3D printing multi-story structures with areas up to 1000 square meters. Unlike ICON, COBOD manufactures and distributes their 3D printing platforms to be used by construction companies, such as the PERI Group. The practice of technology developers leasing their tools and platforms to construction companies plays a significant role in democratizing the 3DCP technology, and making it accessible to a wider spectrum of users. This approach also allows this relatively new construction process to expand in both, the commercial and academic research domains.

A different type of gantry platform is developed by the World Advanced Savings Project (WASP), which is designed in a delta configuration [1]. In contrast to the above-mentioned gantries, the Crane WASP platform consists of three legs, and a central column carrying the print head. The Crane WASP is also designed to allow for various assembly configurations that can adapt to the dimensions of the printed structure. Perhaps, one of the most distinctive features of WASP is their use of natural materials in C3DP in contrast to most companies who utilize mortars and cement-based materials. Their eco-habitat project named TECLA, for example, consists of a double earthen dome structure that is constructed using multiple Crane WASP platforms that operate simultaneously [2]. TECLA was printed over the course of 200 hours, using 150 km of extruded material [2].

The common use of gantry systems within the C3DP domain attests to the reliability of this platform type. However, gantries remain challenged by their substantial size and restricted degrees of freedom. The aforementioned projects and printing platforms mainly operate in 3-axes using a layer-based approach. While effective, there has been a shift from construction companies and research entities towards the use of industrial robotic arms in C3DP. This alternative approach offers enhanced flexibility and a more compact design that can open up new possibilities within the C3DP domain.

Robotic Arm 3D Printers - The integration of industrial robotic arms into 3D printing in the construction industry is a recent development. Such systems enable the production of highly precise and intricate objects thanks to their high accuracy and compatibility with a wide range of end-effectors, tools, and advanced controllers. While some robotic arms, like gantries, are limited to three or four degrees of freedom, commonly used industrial robotic arms surpass these limitations by offering six degrees of freedom[235]. In the construction industry, the mobility of robotic arms that allow for free alignment of tools and end effectors is a major advantage.

The Russian company, APIS COR, for example utilizes a radial industrial robotic arm named Frank, capable of printing cylindrical structures around itself [258] [61]. The robotic arm is capable of reaching up to 8.5 meters, enabling the construction of radial objects with an area up to 130 meters cubed. Frank is a mobile platform that can easily be transported without the need for cranes or heavy machinery. Because of its ability to print in a radial toolpath, and the possibility of being deploying to the next floor, the circular printer can 3D print curved structures up to 3 stories high. In 2019, the company demonstrated a two-story 3D printed office building in Dubai measuring 9.5 meters high and 640 square meters [**sakin**]

While this platform type falls under the robotic arm category, it only offers 3 degrees of freedom, restricting the printing process to vertical extrusions. As mentioned earlier, one of the core advantages of using industrial robotic arms is their enhanced level of flexibility, and the ability to tilt the angle of extrusion.

Cybe is another key player in the C3DP field, also utilizing an industrial robotic arm platform[64]. In contrast to Apis COR, Cybe's platform is equipped with a the Cybe Crawler System: a mobile, tracked platform base. The Design of the Cybe platform not only offers the mobility advantage over the Apis COR platform, but also surpasses operational flexibility by using a 6-axis ABB industrial robotic arm. Although limited by the reach of the robotic arm, calculated movements of the robot's base allow for flexibility in transportation and the possibility of printing large-scale structures that exceed the robot's reachability. This advantage allows for the production of components at different locations of the construction site, and reduces logistic costs by bringing the robot to the construction site. Cybe Construction has demonstrated a range of projects in large-scale 3D printing, including a Robotics and Drone Laboratory at the Dubai Electricity and Water Authority[64]. The structure measures 168 square meters, printed over the course of three weeks. Although the platform is deployable onto construction sites, the size of the platform limits prefabrication to individual components. This limitation also negatively affects 3D printing quality of the projects, as small-scale sections show clear seam lines.

On a similar note, an interesting platform setup is presented by Keating et al. (2017), which is referred to as the Digital Construction Platform (DCP). The DCP is an industrial robotic arm on a mobile base which allows for easy transportation before, after and even during the printing process[136] [15][69]. Keating et al. described the design of the DCP as a mobile industrial robotic arm composed of a robotic arm on a digitally controlled tracked base [136]. The platform is based upon a macro-micro manipulator, in which a high precision, electric, six-axis robotic arm is mounted as the end-effector of a large hydraulic boom arm. Coupled together, the system is able to reach extremely long distances while maintaining high precision. The project demonstrated various fabrication methods including a 3D printed dome that was constructed on-site using expanding spray-foam.

Following a similar approach, ICON has recently announced their latest construction 3D printing platform, Phoenix[3]. Departing from the traditional gantry-style 3D printing platform which ICON has predominantly used, Phoenix features a robotic boom arm, mounted onto a rotating base. enhancing the platform's mobility, and liberating it from the design limitations imposed by gantry systems. Similar to the DCP, Phoenix features a dynamic stabilizer on it's end-effector, ensuring precise motion control and toolpath correction[291].

In another recent endeavor, Darweesh et al. showcased the utilization of an industrial robotic arm that is mounted on a transportable trailer [69]. The configuration was employed to 3D print a Nubian vault using locally sourced adobe. The project is discussed in detail in **Chapter 7.** The above-mentioned projects underscore the versatility of robotic arm platforms, potentially allowing for 3D printed structures that are larger than the platform's footprint. However, it is important to note that industrial robotic arms are classified based on payload and reachability. Although robotic arms are manufactured in different scales, the weight of the end-effector, and the size requirements for construction 3D printing makes this type of platform more common in the construction of individually prefabricated components.

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Approaches to Construction 3D Printing

Two primary approaches are predominantly being utilized in the C3DP field: *Prefabrication* and *In-Situ* 3D printing **(Fig. 2.5)**. It is important to note that these two approaches are not tied to the type of 3D printing platform in use. Both, gantries and robotic arms, as

Figure 2.5: Comparing additive construction processes. (a) 3D printing prefabricated concrete components using an industrial robotic arm [115]. (b) In-situ construction 3D printing, featuring the BOD2 gantry-style 3D printer [120].

discussed in the previous section are currently being utilized in both approaches. While prefabrication involves 3D printing components off the construction site, which are later transported and assembled, In-Situ construction refers to the process where structures are 3D printed directly on the construction site. This section aims to outline both approaches by highlighting a selection of notable companies and projects. By doing so, a contextual overview is provided, offering insight into the unique characteristics of each approach, and their application within the C3DP field.

Prefabrication - A widespread and increasingly adopted approach in construction 3D printing is to 3D print building components off-site, in a controlled factory setting. Prefabrication offers a number of advantages, one of which is the significant reduction in product scale. Controlled, modular, factory-based production of building elements can significantly reduce costs and mitigate the risks associated with on-site construction conditions. Moreover, prefabrication not only simplifies automation but also enhances printing quality, as each component is produced in a consistent manner that minimizes the variations associated with external factors such as weather conditions and other site-specific challenges. Below are examples of key players who take advantage of prefabrication as a construction method. This section examines their 3D printing platform configurations and highlights several noteworthy projects.

The Chinese-based company WinSun, for example, is a major player that has been involved in a number of prefabricated 3D printed concrete buildings, including an office building in Dubai [93]. The project used a gantry concrete 3D printer measuring (6m high x 36m long x 12m wide). The printing process took place over 17 days at the Yingchuang Suzhou factory. The components were then transported by sea to be assembled in Dubai over the course of 2 days. The building consists of 17 modules with a width of 3 meters and a height of 3 meters. Due to this workflow, the company claims the ability to 3D print an entire house in less than 24 hours for a relatively low cost. Nevertheless, claims regarding short printing durations or the completion of projects over short periods of time should be approached with caution. These assertions typically pertain to the production of the main components of the building, such as walls, in this instance. These statements often overlook the time required for completing other crucial components of the building, such as foundations, roofs, and the addition of facade elements.

Another notable key player is Incremental 3D GmbH, based at the University of Innsbruck. Their team is composed of multi-disciplinary designers, architects and engineers. The company focuses on 3D printing intricate concrete components using an industrial robotic arm, coupled with a concrete end-effector, developed by the Austrian company Baumit. A recent project showcased by Incremental 3D is the Striatus bridge, designed in collaboration with the Block research Group at ETH, Zurich, and the Zaha Hadid Architects-Computation and Design Group (ZHACODE). The project featured a 3D printed arched footbridge in Venice, Italy, measuring 12 meters by 16 meters. The 3D printed components are composed of layers that are not printed horizontally, but instead follow the compressive forces of the design, thus eliminating the need for reinforcement or post-tensioning. The design uses compression-only components, combining principles of traditional vaulted construction with robotic concrete 3D printing [33].

Within the prefabrication domain in C3DP, a few companies extend their focus beyond 3D printing and production services. As mentioned earlier, Baumit provides innovative solutions tailored for concrete 3D printing applications. Their printing system, known as the *BauMinator*, stands out as a lightweight extrusion system in comparison to many other concrete printing platforms. When coupled with a 6-axis industrial robotic arm, the system is capable of achieving high printing resolutions and intricate designs [18]. In addition to Baumit, The French company XtreeE, for example, is a developer of 3D printing solutions to produce large-scale 3D printed components made of concrete [4]. The company offers rentals and sales of its proprietary robotic concrete printing end-effector capable of printing ultra-high-performance (UHPC) concrete. According to the Portland Cement Association, UHPC is characterized as a cementitious concrete material with a minimum compressive strength of 17,000psi, meeting specific requirements for durability, tensile ductility and toughness [22]. The XtreeE system uses a six-axis ABB industrial robotic arm, coupled with a concrete pump that delivers the concrete to the robotic end-effector. At the end-effector, concrete is mixed with a catalyst in the final stages of the material extrusion process. XtreeE has demonstrated several medium to large-scale, complex 3D printed components, including a truss-shaped column. The column is built by 3D printing a lost formwork, that is subsequently filled with UHPC, and coated [**107**]. The printed column measured 4 meters in height, and was printed in four parts, over a period of fifteen hours [107]. Once all parts were printed, they were assembled and concrete was poured into the component cavities. The 3D printed structure was then broken apart to expose the column. Thanks to the fast curing of the 3D printed material and the mechanical capabilities of XtreeE's end-effector, the printed designs can include openings, which would be challenging to achieve otherwise due to the requirement of stopping and retracting the concrete flow. In-Situ Fabrication - In-Situ fabrication now dominates 3D printing, especially for large-scale demonstrations. This technique is facilitated by the modularity and the resulting adaptability of gantries, which can be deployed to various construction sites for the construction of homes or other monolithic structures. Other approaches to In-Situ 3D printing investigate ways to mitigate the environmental footprint associated with transportation by utilizing locally sourced materials and adapting to site-specific parameters. This section focuses on key players who are at the forefront of In-situ construction 3D printing, highlighting project demonstrations and examining their distinct approaches on the process and platform levels.

In 1969, Artur Schwörer and his wife founded PERI, a company that aimed to find safer, faster, and easier solutions for concrete construction [224]. Over the years, PERI has successfully developed an array of product and process solutions that have served new market demands and enabled safe and efficient construction practices. These contributions range from advancements in formwork systems to facade scaffolding products and other material solutions. In 2020, PERI entered the construction 3D printing domain, creating the first 3D printed multi-story residential structure in Germany, which at the time was Europe's largest 3D printed apartment building [224]. Since that time, PERI has earned a prominent reputation. The company's development and interest in additive manufacturing highlights the immense potential of the technology, motivating significant investment from construction pioneers and proving that architectural-scale 3D printing has the transformative ability to redefine conventional construction.

A further illustration of using gantry 3D printers for on-site construction can be seen in the work of the Russian company Spetsavia [287]. The company has been developing a range of 3D printers that extend from smaller, lab-sized models to expansive platforms capable of 3D printing an entire building, on-site. One of their models, the AMT S-500 configuration printer, boasts the capacity to construct structures that are five stories tall, made possible by the platform's 15m base height.

Alternative In-Situ construction 3D printing methodologies have also been investigated, utilizing a palette of environmentally conscious materials. The Oakland-based firm Emerging Objects, led by UC Berkeley Professor Ronald Rael and Professor Virginia San Fratello, is known in the additive manufacturing field for exploring materials and techniques while keeping sustainability and material afterlife in mind. The projects presented by Emerging Objects generally explore novel granulated 3D printed materials such as clay, cement, sawdust, rubber, and grape skin and other powder-based materials. This range of materials has been demonstrated in making the interior and exterior tiles of the firm's Cabin of 3D printed Curiosities project [240]. Emerging Objects has long been conducting research in clay 3D printing technologies, with known developments in texturing techniques, and designing with G-CODE, through the development of a proprietary pottery design interface called "potterware" which is discussed further in **Chapter 4** [212] [260].

On a larger scale, however, Emerging Objects has worked on an array of 3D printed structures, including Mud Frontiers, and Casa Covida, which aims to promote sustainable construction using 3D printed adobe [236] [241]. Mud Frontiers features four circular structures that were constructed using a low-cost deployable SCARA robotic arm designed to be carried to the construction site, where local materials can be harvested and printed. Similarly printed with the same SCARA platform, Casa Covida is an experimental house for co-habitation that was constructed during the time of Covid. The house is composed of three cylindrical buildings, each for sleep, bathe, and gather.

Research in Construction 3D Printing

As a rapidly evolving field, C3DP has expanded beyond the domains of industry-driven initiatives, attracting immense scholarly attention, with academic institutions and research groups adopting distinct approaches. This expansion into the academic field highlights some of the challenges restricting current approaches, and emphasizes the growing importance of C3DP as a field of research.

For instance, the University of Nantes in France has employed a unique approach, concentrating a research project on the development of emergency shelters using their INNOprint 3D printer [220]. The INNOprint is capable depositing polyurethane foam, a material with high insulating properties, to construct a small, emergency shelter in under 30 minutes. The group has also demonstrated the use of the printed foam as formwork that is subsequently filled with concrete. While this method has the potential to substantially reduce the printing time, it demands greater post-production efforts in order to achieve adequate surface quality.

The Digital Building Technologies group (DBT) at ETH, Zurich also stands out as a significant contributor in the field of C3DP. DBT's projects showcase the use of various 3D printing approaches including Binder-Jetting and extrusion-based methods. The *Airlements* project, for example, explores a method of 3D printing lightweight, cement-free, insulated walls that are made of mineral foams [31]. The demonstrated method offers the dual benefits of structural strength, and insulation through the precise placement of porous materials in varying densities. On the other hand, DBT has also presented *Concrete Choreography*, a project that focuses less on structural performance, and more on formal expressions [19]. This initiative explores toolpath strategies in the creation of ornamental textured surfaces using 3D printed concrete. Both projects exemplify both, functional, and aesthetic versatility of large-scale 3D printing, highlighting the significant potential for implementation in the construction field.

Moreover, the University of California, Berkeley has recently ventured into the C3DP field, investigating the application of conformal 3D printing onto bending-active structures, a project that is further discussed in **Chapter 5**. The method involves coupling non-planar 3D printing strategies with formwork registration techniques, to create curved, long-spanning structures using minimal formwork. This approach marks a significant advancement in the C3DP field, showcasing the potential for material-efficient construction strategies.

A prominent research institution in the C3DP field is the Institute for Advanced Architecture of Catalonia (IAAC). In collaboration with WASP, IAAC has developed an impressive portfolio of projects primarily focused on 3D printed earthen architecture [8] [197]. Demonstrating their commitment to the C3DP field, the institution offers a specialized study program that is specifically focused on research within this domain [7]. A notable example of their cutting edge research is a project that features a timber staircase that is integrated into a 3D printed wall section [111] [280]. The printed wall is designed to support steps that can be anchored to the printed structure. This project demonstrates a significant step towards load-bearing, printed earthen structures, and point towards the potential and evolving nature of the C3DP technology in research institutions.

Summary Concepts

The emergence of 3D printing technologies within the design and manufacturing disciplines has revolutionized the way objects are manufactured. Procedures which used to go through rigorous stages of process planning and sequential assembly can now be 3D printed with ease. In contrast to conventional manufacturing methods, 3D printing predominantly hinges on designing digital models using CAD tools, significantly streamlining the production of complex, intricate components. These technological capabilities have been implemented across various industries, from pharmaceuticals to automotive, mechanical, aerospace, fashion, and notably, within the realm of architectural design and construction. 3D printing has presented itself in various forms, from the fusion of granular powders and the extrusion of thermoplastic filaments, to the precise sintering of powder and the extrusion of viscous composites.

In architecture, additive manufacturing mainly adopts an extrusion and deposition-based process, employing viscous, and cementitious materials. This adaptation takes advantage of the construction industry's extensive familiarity with concrete and other cementitious materials in the conventional construction of large-scale structures. However, using wet, viscous materials in large-scale construction additive manufacturing becomes problematic when structural components are printed in a layer-based approach. While reliable in constructing vertical walls and straight wall extrusions, this method often results in the loss of geometric detail when dealing with complex curved objects. This approach also results in a stair-stepping surface texture, a flaw that becomes more pronounced due to the increased layer height and the planar slicing of objects. Due to these restrictions, the technology is mainly limited to 3D printing vertically extruded shapes that lack overhangs or to structures without long spanning forms, designs which often require supporting formwork.

Other avenues within additive manufacturing have explored the possibility of 3D printing beyond planar extrusions. In the process of freeform 3D printing, for example, the 3D printing platform is instructed to operate along multiple axes simultaneously, enabling the creation of structures within true, 3D space. The process is, however, dependent on the material's curing duration and its ability to carry its own load without relying on previously printed layers. Concurrently, conformal 3D printing utilizes an auxiliary structure or formwork that serves as a base onto which the 3D printed materials can be deposited. While this method can dramatically reduce the amount of used material and mitigate waste generated by 3D printed supports, conformal 3D printing introduces complexities in ensuring the precise placement and localization of the printing platform in relation to the formwork. These advanced strategies have the potential to improve printing speeds and greatly reduce the amount of used material. Yet, these innovative techniques remain under-explored and demand further research and development.

Meanwhile, driven by the technology's proven success on smaller scales and its ability to craft highly complex geometries, the construction industry has lately become very interested in adapting additive manufacturing technology to construction. This growth promises to revolutionize construction through enhanced construction automation, while reducing construction time and improving worker safety. In recent years, construction 3D printing has exhibited a diverse portfolio of projects, illustrating a wide range of 3D printing platforms, robotic setups, and construction methodologies, from components that are fabricated off site to in-situ fabrication.

Gantry-based 3D printers capitalize on their scalability and ability to deposit significant volumes of materials directly onto the construction site, and have proven their ability to erect sizable multi-story buildings. Nevertheless, gantries are hampered by their limited range of motion, confining them to three-axis operations. Industrial robotic arms, on the other hand, offer a compelling alternative, providing precision, speed, flexibility, and above all, six degrees of motion. Despite their lower payloads and limited reach, industrial robotic arms have demonstrated consistent performance within the prefabrication domain, and have the potential to be adapted to multi-axis, 3D printing processes. That is made possible by the ability of the robot to rotate and reorient the extrusion tip, enabling conformal or freeform 3D printing. Moreover, projects have showcased the ability of industrial robotic arms to exceed their conventional reachable scale when combined with a mobile base or additional axes of motion, making them a viable alternative to gantries for large-scale construction.

Each approach to construction 3D printing, regardless of the platform size and printing process, exhibits distinctive advantages and challenges with respect to scalability, printing quality, operational flexibility, and material diversity. To maximize the potential of the construction 3D printing domain, a synthesis of these systems' most effective features may pave the way for further advancements to unlock new possibilities, propelling the construction 3D printing industry forward.

2.2 Robotic Fabrication in Architectural Design

Overview

Over the past 15 years, research in architecture and design has been renowned by cross-disciplinary collaboration. Faced with the growing complexity related to the built envi-

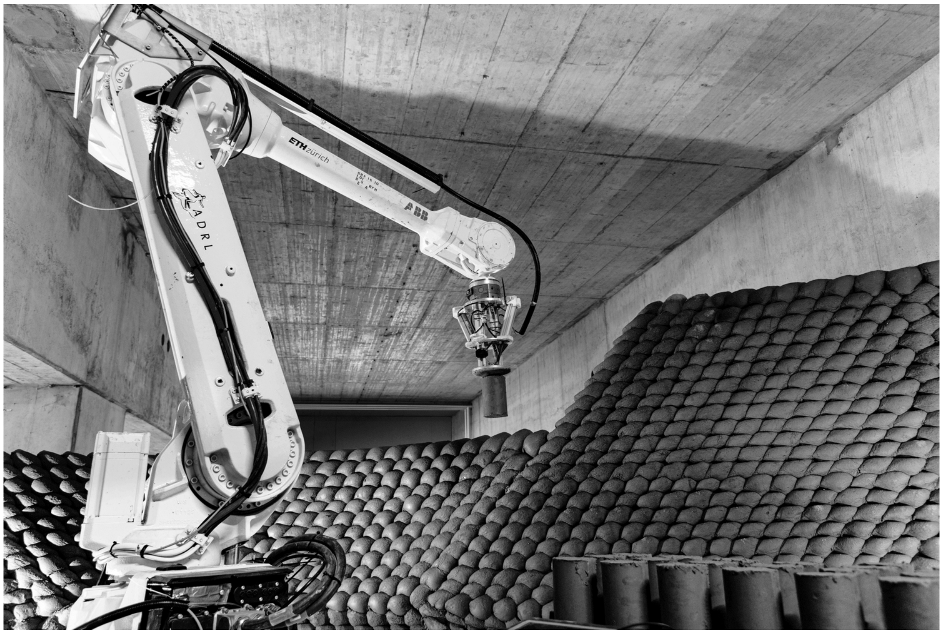

Figure 2.6: Example of a creative application of industrial robotic arms in architecture, demonstrated by Gramazio Kohler Research, ETH Zurich, in their Clay Rotunda project [250].

ronment, a diverse range of researchers and professionals — such as architects, designers, scientists, and engineers — are actively seeking novel methods that push the boundaries of their respective fields [315]. The integration of CAD and Computer-Aided Manufacturing (CAM) tools has transformed design methodologies, infusing material considerations and fabrication logic into the conception of architectural form and structure [278] [9].

In recent years, research in architecture has shifted towards the possibilities of employing industrial robotics into architectural design applications. This integration not only seeks to streamline production or cut costs, but rather to liberate designers from the constraints of traditional fabrication tools and manufacturing operations. Through the use of industrial robotic arms, designers have the ability to materialize their parametric models into tangible forms [43]. This research has most recently focused on fabrication techniques and the integration of material logic into design. The Gramazio Kohler Research Group at ETH, Zurich, has been at the forefront of this movement, introducing the notion of *Digital Materiality*. This term refers to processes rather than products, encapsulating a cycle where data is transformed into things, and things into data [114].

The reconceptualization of industrial robots as instruments for creativity has opened up new avenues in design research and inventive problem-solving. In recent years, we have witnessed creative robotic fabrication applications and innovative adaptation of robots into traditional construction techniques. The flexibility of industrial robots, coupled with their diverse capabilities made possible through the exchange of end-tools, makes them particularly appealing to creative applications. Like computers, the "generic" nature of industrial robots allows them to be used across a broad spectrum of tasks [113].

Prior to their integration into design and architecture, industrial robots were used primarily in factory settings, working on assembly lines where their high-speeds, precision, and task-repeatability are most valued. To better understand the emerging impact of industrial robotic arms in design and architecture, it is necessary to take a look at their conventional use and triumph in mass production.

Lights-Out Automation

Historically, the goal of manufacturing was to create factories that ran like machines. This pursuit aimed to reduce human intervention and minimize production downtime [311]. The Industrial Revolution played an essential role in the increasing demand for process automation. The term "Lights-out automation" refers to a manufacturing approach in which machines are left to operate unattended around the clock. Lights-out automation was approached as early as 1784 by Oliver Evans through the innovation of the first production line [97]. Since then, historical strides towards lights-out automation have been recurrent, with significant momentum gained with the birth of computers in the 1950s. This period also promoted the introduction of transformative technologies such as CNC machines and integrated circuits [253]. Some examples of Lights-out automation factories include component manufacturing by the Polaroid Corporation in the 1960s and processes of computer keyboard assemblies used by the IBM corporation in the 1980s [311]. While automation has long been a component of factory operations, it was not until the 1950s that industrial robotic arms emerged as a significant milestone.

According to the International Organization for Standardization, a "robot" is defined as a programmed, actuated mechanism with a degree of autonomy allowing it to perform locomotion, manipulation or positioning [131]. Within the context of this study, the term "robot" or "industrial robot" is specifically used to refer to a subset of robots, namely six-axis industrial robotic arms. These industrial robots are commonly used in factories for mass production. In contrast to common digital fabrication equipment like laser cutters, 3D printers, water jet cutters, and other CNC machines that are tailored for specific uses, industrial robotic arms offer a degree of adaptability to various tasks. This unique versatility is made possible by the ability of robotic arms to accommodate a variety of tool attachments at their *end-effectors*, enabling them to switch between different production processes.

Automotive manufacturing facilities use industrial robots for various purposes, including welding, painting, assembly, and material handling [252]. The robots are strategically scattered across factories, executing tasks that vary according to their designated zone along the assembly line. Robots are valued for qualities such as reliability, productivity, speed, and precision. Advanced state-of-the-art robots are also equipped with sensing capabilities, enabling tasks requiring path planning and analysis [281]. In the aerospace industry, for example, known for its tight tolerances and strict manufacturing regulations, robots are

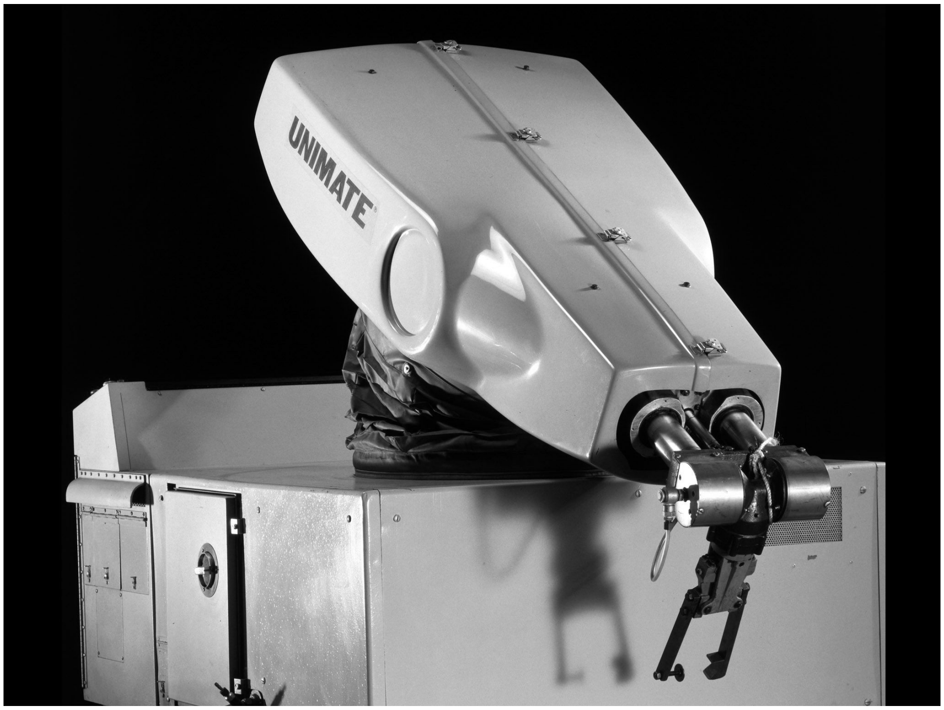

Figure 2.7: The first industrial robotic arm, called Unimate, was invented in 1954 [299][106].

used in non-destructive ultrasonic testing and inspection operations, as well as transportation and assembly tasks [294]. Today, the use of robots has expanded beyond their initial confinement to automotive manufacturing; robots are now being used in industries such as medicine, agriculture, and architecture [271] [72].

The first generation of robotic arms were defined as programmable machines that were not able to control modes of execution and could not communicate with the external environment [106]. Robots of the first generation were pneumatically actuated, producing loud noises when they collided with their mechanical stops [106]. These robots were used primarily in loading and material handling operations. In 1954, John Devol filed a patent for a "programmable article transfer, [78] leading to the development of the world's first industrial robotic arm, the *Unimate* **(Fig. 2.7)** [106]. The first Unimate was installed at the General Motors factory to perform die-casting operations and was later developed for more complex tasks such as spot welding. After the development of Unimate, industrial robotic arms became widely used, particularly in automotive factories such as General Motors and Ford. Other subsequent developments must be mentioned, including Marvin Minsky's *tentacle arm* (1967) [196], the *Stanford arm* [265] and *Vicarm* [105] developed by Victor Schienman (1969-1973), and KUKA's first electromechanically-driven six-axis robot, *Famulus* (1973) [17].

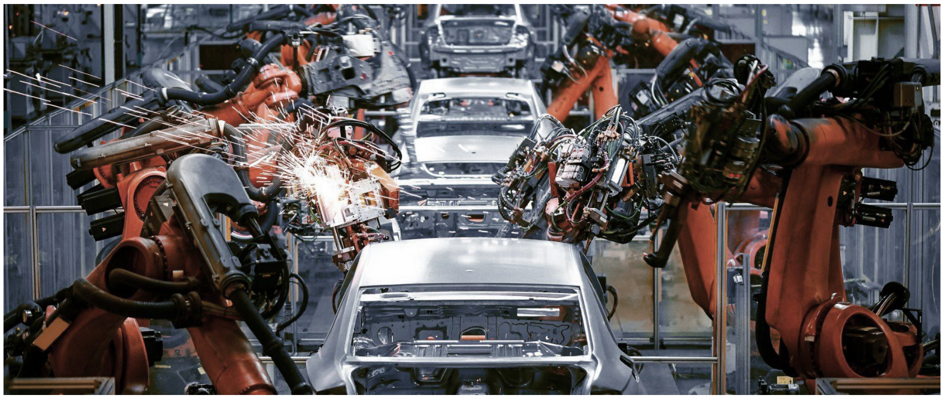

Figure 2.8: State-of-the-art automated robotic assembly line in an automotive factory [82].

Robotic Tasks in Mass Manufacturing

Automation has proven to be advantageous in tasks undertaken in harsh environments or requiring highly skilled labor **(Fig. 2.8)** [91]. In such environments, industrial robots offered speed and precision that can be difficult to achieve through human labor. Because of their high levels of productivity, industrial robots have become widely popular in factories, where they outperformed human labor by carrying heavier loads without tiring and being able to function in work environments where noise, vibration, odors, and danger can hinder humans physically and psychologically. Labor-intensive applications requiring high levels of craftsmanship moved to industrial robots early, exploiting their higher productivity rates at reduced operation costs.

Robots rarely make mistakes, working continuously at high speeds, taking no days off, and producing more work in shorter amounts of time [281]. One of the earliest adopters of industrial robotic arms is the automotive industry, contributing to its reputation of having the fastest automated supply chain in the world. The industrial robotic arm plays a critical role in the competitiveness of this industry. Some of the most common roboticized processes include material handling, assembling, paint spraying, welding, and visual inspection, while other applications are being explored with the recent development of robots with advanced sensing capabilities [27] [276].

Another industry employing heavy use of industrial robotic arms is aerospace. In contrast to automotive manufacturing, the aerospace industry demands lower production volumes and relatively more complex applications. Sectors include design, development, and deployment of military aircraft, space vehicles, rockets, and satellites [39]. Such sectors use state-of-the art technologies and manufacturing methods that include industrial robots that are capable of meeting tight tolerances and strict manufacturing regulations [39] [294]. While welding operations are the biggest employers of industrial robotic arms in automotive manufacturing, fastening tasks are predominant in aerospace. An aircraft such as the Boeing 777 has over a million fasteners, demanding the use of an automated drilling and fastening system; industrial robots are best suited for such tasks because of their speed and precision[294].

The use of industrial robots has expanded far beyond their initial confinement to automotive manufacturing. Today, robots in industries including agriculture, architecture, and medicine [271] [72]. More recent state-of-the-art industrial robots are equipped with sensing capabilities such as "touch" and "sight" [281]. The vision of Lights-out automation is no longer fiction. Developments in industrial robots, coupled with artificial intelligence (AI), predictive maintenance, sensing and vision systems, flexible feeders, and other technologies have allowed ultimate automation to become fact rather than fiction [311].

We are now on the brink of a period characterized by ubiquitous connectivity and advanced sensing capabilities, allowing factories to operate with higher levels of automation than ever before [271]. The term "Industry 4.0" was coined by Klaus Schwab, founder and executive chairman of the World Economic Forum during the 2011 Hannover Fair, to describe a fourth industrial revolution where "smart factories" are enabled by connecting physical and digital systems of manufacturing to create new operational methods [271]. The abundance of sensing capabilities alongside robots allow for real-time error detection and reduction while simultaneously improving productivity. One of the early applications of industry 4.0 robotics recently manifested itself in a Zero Down Time (ZDT) program developed by the collaborative effort of General Motors, Cisco and Fanuc [38]. ZDT is a predictive analytic tool, designed to foresee potential failures. The tool enables engineers and plant managers to schedule maintenance and repairs, thereby, mitigating the risk of breakdowns during production [312]. "The predictive analytics enable engineers to know when there's going to be a failure long before there is one so that the problem can be resolved without causing downtime," says Chris Blanchette, executive director for global accounts at FANUC America Corp [**312**]. Robots are now present in almost every part of a factory, each performing a specialized task and offering benefits such as high precision and quality standards, reduction of required manpower, time efficiency, and reduction in manufacturing costs – all contributing to the primary goal of industrial arm use, which is to maximize process efficiency and reduce downtime [**312**].

Automating Construction

The 20th century witnessed a number of attempts to industrialize building activity, reflecting an ambition to adapt architectural practice to the age of the machine [228]. Monsanto's "House of the Future," for example, exemplified a prefabricated, customizable modular housing unit that offered consumers options to personalize home features such as color and interior layouts [195]. Through the production of its houses, Monsanto used plastic as a material in the architecture and construction, highlighting the material's durability and customizability, along with its suitability for mass production on assembly lines. However, historic examples such as those of Gropius/Wachsmann, Frank Lloyd Wright, and Prouvé have proven that vision is not enough to realize the idea of automating construction [70]. Despite these setbacks, efforts to promote construction automation and prefabrication continued [109].

After the Second World War, Japan's industry adapted some of the Fordist techniques of automobile and aircraft mass production to produce customized solutions that were tailored to Japanese architectural culture. Taichii Ohno and Shigeo Shingo of Toyota developed the "Toyota Production System" focusing on mass customization and the utilization of economies of scope [285]. In 2004, the Japanese prefabrication housing market grew rapidly, producing around 159,224 prefabricated houses. This roughly translates to 1 in 7 houses built through factory manufacturing methods in Japan [285]. While the aesthetic appeal of the Toyota homes may not have been extraordinary, they illustrated a range of customizable home features made possible through an integrative approach to design and automation [285]. Questions of industrialization in the building sector arose later, influenced by the prevalent adoption of digital tools and the rapid increase of design as a form of research and experimentation in the CAM domain [229]. The contemporary perspective on building industrialization stems from the post-Fordist context of mass production, using industrialization to produce unique solutions and a belief in the endless possibilities for variability within design [**229**].

Despite the various attempts to automate architecture and construction, the level of automation remains low in comparison to that of the automotive industry [48] [26][104]. Construction automation remains challenged on many levels. Unlike standardized manufactured products, buildings are considered unique artifacts that are tailored for a specific context [83]. Different building features must be adapted to site conditions and user requirements. Moreover, automated construction is restricted by the scale of buildings: it is difficult to make and assemble sections in factories, then transport them to building sites. The integration of industrial robotic arms into construction also faces challenges on the software level such as collision avoidance, payload restrictions, and repeatability tolerances [30]. In the highly automated aerospace and automotive industries, the time spent programming robots is recovered by spreading the cost over high production volumes [30].Moreover, robots in construction are currently utilized at a reduced scale, demanding more efficient robotic integration workflows and newly efficient tool developments to maximize mass customization.

Mass Production To Mass Customization

The approach to customization today is different from that of the 1980s. Previously, construction automation generally referred to standardizing operations, adding little to architectural design. Recently, however, industrial robotic arms have been involved in performing highly customized tasks, unlocking possibilities that would have been difficult to realize otherwise. Industrial robotic arms are now more accessible and capable than ever, and cost relatively less than robots of the 1980s. Research institutions and construction companies use industrial robots not to exclude designers or conventional construction methods, but to work hand-in-hand towards an efficient and sustainable construction future. A demonstration of how industrial robotic arms have affected architectural design can be observed through various projects. Pike Loop, for example, was a robotically enabled brick structure constructed on Pike Street in Manhattan, developed by the Gramazio Kohler Research

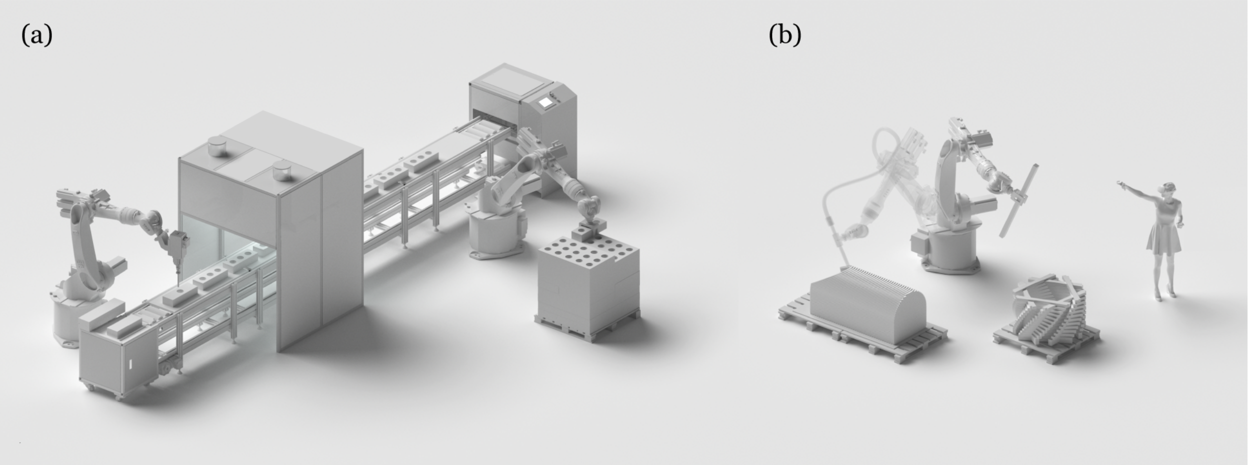

Figure 2.9: a) The role of industrial robotic arms in factories usually involves the repetition of tasks and standardization for the manufacturing of mass products in high volumes. b) The use of industrial robotic arms in creative sectors, on the other hand, involves task versatility, customization of components, and human-machine collaboration.

Group [251]. A brick-laying robot on a trailer, called R-O-B, was deployed to fabricate the first on-site installation made by an industrial robotic arm in the United States . The installation featured over 7000 bricks aggregated to form an infinite loop weaving along a pedestrian island and lifted off the ground to intersect itself [**251**]. The installation took place in full view of the public over the course of four weeks. Pike Loop demonstrated that bricks – perhaps the most elementary of building materials – can be aggregated in changing geometric rhythms made possible only by robotic precision [42].

In design practice, multiple attempts have been made to integrate industrial robotics into production workflows. Many of these attempts have been realized through component prefabrication using a wide range of novel processes [147]. A notable project demonstrating the integration of robotics in prefabricated construction is the façade of the San Francisco Museum of Modern Art designed by Snøhetta, and fabricated by California-based fabrication company Kreysler & Associates. The project called for 700 unique individual panels that make up a textured surface, mimicking the rippling water of the San Francisco Bay [150]. The facade is made of glass fiber-reinforced polymers (GFRP) which are molded into robotically-milled, expanded polystyrene (EPS) blocks. While Kreysler & Associates has been primarily involved in mass customization operations, the company has recently expanded its tool set , integrating additional industrial robotic arms into their production workflows. Robotic tasks at Kreysler & Associates include prototyping, honing, washing, and milling for the production of GFRP components.

End-Effectors

To be suited for different functionalities and applications, an industrial robot's movements must be choreographed by programmed toolpaths. The program often defines parameters within Cartesian space such as the direction and orientation, as well as velocity and distance parameters. The parameters are then translated into corresponding robotic axis movements.

Key parts that make up an industrial robotic arm are the manipulator, controller, and end-effector [247]. The term "manipulator" describes the robotic arm's overall body, including the base and its power unit, which allows for multi-axis movements within Cartesian space. The controller's programming provides the robot with task versatility, defining trajectories through sensory units and command devices. An industrial robot's multi-functional capabilities reside in its hands, commonly referred to as "end-effectors." As the name implies, end-effectors are tools that attach to the ends of robots, allowing them to perform a variety of automated tasks. Through the interchangeability of end-effectors, an industrial robot can be transformed from a milling machine or a hot-wire cutter into a 3D printer or scanner **(Fig. 2.10)**.

Architecture and design practices have demonstrated creative applications for industrial robots through the development of custom-built end-effectors ranging from 3D printing extruders to brick-pressing and needle-felting applicators [183]. Additive processes of extrusion and dispensing using robotic arms have gained popularity, ranging in material palettes accuracy and scales. For example, The Ocean Pavilion by Mogas-Soldevila et al. (2014) is 3D printed using a pneumatic end-effector containing viscous biomaterials that are dispensed through a thin nozzle [192]. The end-effector allows for material tunability by varying air pressure amounts and nozzle sizes to accompany materials of variable viscosities. A different additive process is demonstrated in the Clay Rotunda project by the Gramazio Kohler Research Group [111], which uses soft clay extrusions in the form of bricks that are sequentially pressed into an interlocking aggregation. The fabrication process is dependent on a pressing end-effector that grabs the soft clay bricks from a picking station and presses them into their final location. Today, end-effector design and development play a major role in the robotic design process. These adaptations in manufacturing capabilities have led to robots no longer being viewed as mere mechanical production slaves, but as full-fledged collaborators and true master builders with human-like capabilities.

Control Software

A common challenge to operating industrial robotic arms in the context of architectural design is the efficient programming of robots to perform different tasks. In their typical setting – for instance at automotive factories – the main goal is to achieve maximum production rates and zero downtime [312]. Robots are thus programmed to perform a single repetitive task that may not require reconfiguration or alterations if the design changes.

Conventionally, industrial robotic arm manufacturers provide proprietary control software suites that are specific to their robots. ABB robots, for example, are controlled through

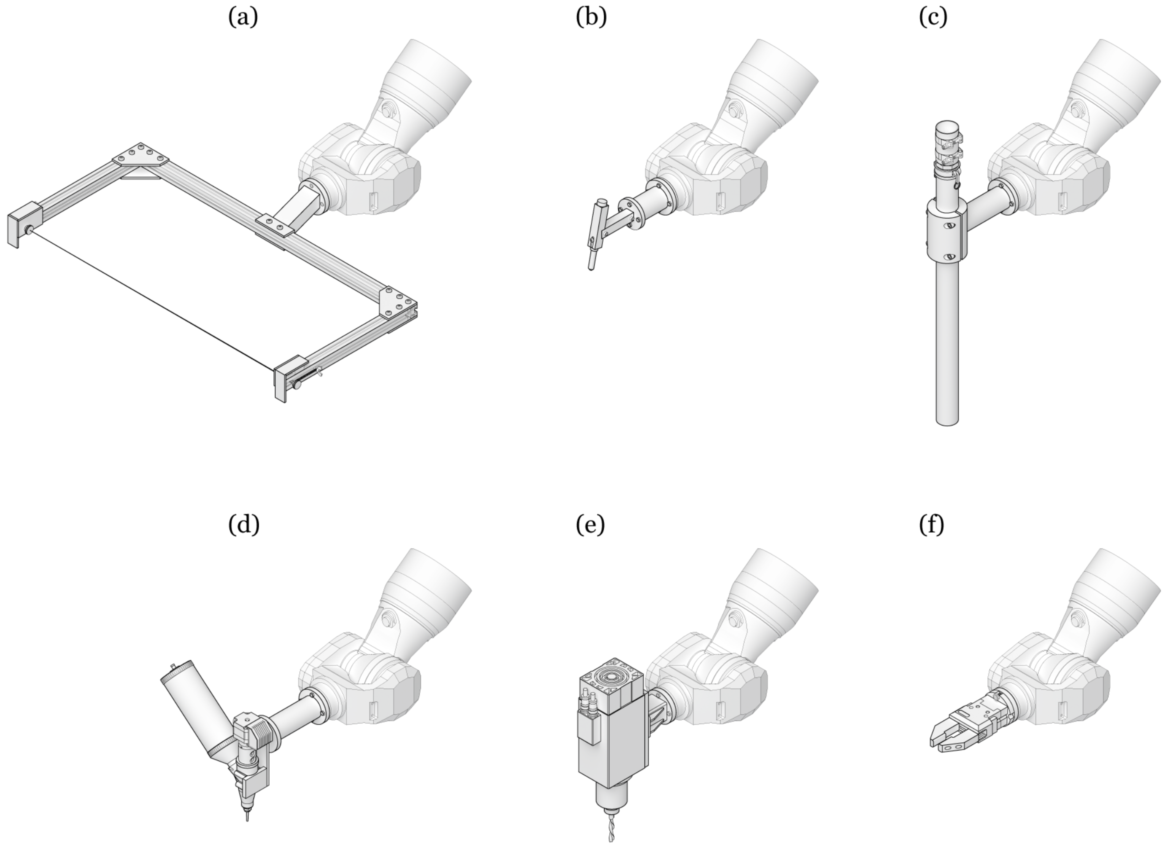

Figure 2.10: Thanks to the interchangeability of end-effectors, industrial robotic arms can achieve a degree of versatility like no other tool. his feature allows industrial robotic arms to seamlessly switch between different tools designed for different tasks, demonstrating their multi-functional capabilities.

a simulation and programming software called Robot Studio, while robotic arms manufactured by the German company, KUKA, use the proprietary KUKA System Software (KSS) [59] [153]. Other manufacturers provide software suites that are application specific, providing only the necessary tools for particular tasks. An example is Arc Tool, which is a proprietary Arc Welding applications software developed by the Japanese company FANUC that specializes in automation products and solutions [20]. While these tools may be fine-tuned to particular machines and applications, they are difficult to integrate into design workflows and add an additional level of complexity to the design and fabrication process. File exchange between design and control software, in addition to robotic real-time feedback loops between robotic interfaces, become challenging. Consequently, there is a need for new tools to facilitate seamless integration between CAD environments and robotic platforms.

The use of robotics in architectural design requires programming workflows that are adaptable to different applications and are capable of visualizing program simulations and outcomes with advanced forms of representation. Companies like Autodesk have developed tools such as Mimic, an open-source plug-in within their Maya 3D software, allowing creators without coding experience to design, animate, and program robots [23]. Other programming robotic control tools such as KUKA—prc, a plug-in developed by Braumann et al.(2015) to work in the Rhinoceros/Grasshopper CAD environment, have also enabled designers and non-programmers to generate robot control data locally using familiar architecture design software [41] [43]. Through KUKA—prc, users are able to think about and design robotic toolpath strategies and integrate the robotic fabrication workflow directly into their 3D digital design environment, generating robotic execution-ready data without the need to translate design data to alternative operational systems.

Such tools have allowed designers to create their own affordable software and hardware tools using architecture-centric CAD environments while not being constrained to existing fabrication strategies commonly used in CAM suites [43].

Summary Concepts

In recent years, there has been a paradigm shift towards the integration of industrial robotic arms into architectural design applications. This shift aims not to enhance efficiency of cut production costs, but rather to empower designers and architects, by surpassing the limitations imposed by conventional manufacturing techniques. Robotic integration grants designers the ability to transform their parametric models into physical entities.

For decades, the pursuit of lights-out automation and zero downtime production has been paramount. Industrial robotic arms have been utilized for mass production, often outpacing human labor in endurance and efficiency. Factories now feature robotic arms in every aspect, specializing in tasks that deliver time efficiency, reduced production costs, quality control, and incomparable precision.

While robots are found across various disciplines and practices, mass customization has attempted to industrialize building construction and automate the production of customizable, modular homes. However, unlike standardized products, buildings are unique entities that are designed for specific contexts and user requirements. This challenge requires the process to accommodate these variables, often complicating automation efforts.

The current approach to automation has evolved significantly since the 1980s. Industrial robotic arms are now engaged in highly specialized and adaptable tasks, opening up new possibilities in architectural design. Initial academic research in architecture and design has leaned towards producing non-standard assemblies using normative construction materials with the aid of industrial robotic arms [30]. The flexibility and adaptability of industrial robotic arms has made them particularly appealing to creative design. While industrial factory robotics are valued for qualities such as speed, reliability, precision, and repetition, robots in architecture are viewed as multi-functional creative tools, capable of performing highly crafted applications. An industrial robotic arm can change from a 3D scanner, to a milling machine, to a 3D printer, merely through the interchangeability of its end-effector, suiting it for ever-changing designs and methods of fabrication. This level of flexibility has led to emerging design opportunities, allowing users to approach architectural design through unconventional means.

Two critical components of an industrial robotic arm are its controller and end-effector. The controller is responsible for providing the robot with precise movement trajectories and sensing/actuating command versatility, enabling it to perform a range of tasks. On the other hand, the end-effector equips the industrial robotic arm with its multi-functional capabilities. Through the use of interchangeable or custom-developed end-effectors, industrial robotic arms can undertake creative, versatile tasks, functioning as both human-collaborators, and skillful builders. This adaptability makes them especially valuable in research-oriented design fields where creative ideas are materialized and tested.

Moreover, the control software by which the industrial robotic arm is programmed plays a pivotal role, as it allows designers to translate their digital models into executable robotic toolpaths and bring the robotic manufacturing logic directly into their CAD environments. Traditionally, robots have been operated by control software that are designed specifically for highly-repetitive tasks. However, more recent approaches to control software have specifically been tailored for designers, facilitating a seamless integration with CAD software. By developing both hardware on the end-effector level and software on the controls level, designers are able to forge custom, cost-effective robotic processes, liberating them from conventional fabrication methodologies and off-the-shelf software and hardware tools.

2.3 Material Extrusion and Deposition

Overview

The characteristics of 3D printed objects, such as their strength, durability, opacity, and elasticity, are significantly influenced by the types of materials used. The choice of materials, coupled with the printing technology employed, shapes the design possibilities. Fused Deposition Modeling (FDM), for example typically utilizes thermally extruded materials in the form of filament spools. This method is relatively forgiving, allowing for the creation of structures with slight overhangs when printing unsupported geometries. This possibility is mainly due to the thermal adherence properties of polymers.

Recent projects have highlighted the potential of 3D printing viscous materials, ranging from small to large scales. These materials offer advantages in property tunability and ease of handling during production. However, the slower setting or curing times of viscous materials, and instability in their initial wet state make them more challenging to work with, especially under unsupported conditions. Therefore, 3D printing workflows utilizing viscous materials typically involve extruding them in layers. This approach limits the geometric diversity and angular flexibility of the printed structures.

In large-scale 3D printing applications, concrete continues to be used as a dominant material in construction. The properties of concrete and other viscous materials allow them to circulate through the extrusion platform while being malleable in their wet state, allowing for easier material placement before materials set and take their final form. Recent projects have also demonstrated the ability to alter material mixtures to become more suitable for 3D printing workflows with higher levels of control regarding mixing and curing times [112].

Despite the significant potential of viscous materials in 3D printing applications, they remain challenged by their instability during the construction process making them difficult to handle for the production of support-free geometry that requires structural support. Due to the difficulty of integrating temporary support structures into large-scale 3D printing and varying material properties, there is considerable potential for improvement.

Viscous Materials

The American Concrete Institute defines an aggregate as a granular material like sand, gravel, crushed stone, crushed hydraulic cement concrete, or iron blast-furnace slag [58]. Aggregates are the building blocks of civilization. The use of sand, gravel, earth, and limestone as building materials or as a form of reinforcement for viscous compounds dates back thousands of years [180] [138]. Ancient Egyptians, for example, used cut and crushed sandstone and limestone in the construction of some of the most notable buildings in history, including the pyramids and the great sphinx of Giza [89] [284][86]. Granular materials are typically loose, requiring a binding agent. Historically, granular materials have been activated with water to form clay, bricks, and other hardening viscous and cementitious materials. Early appearances of granular materials can be traced to the Roman Empire in the development of concrete, partially made of aggregates such as sand, coarse stone, or volcanic ash [73] [187]. The durability of concrete is exemplified in the construction of the Pantheon in Rome with its glorious concrete dome, built by Agrippa around 118-125 A.D [6]. The dome spans almost 43.4 meters and has stood for nearly two millennia, requiring only minor repairs. The development of viscous composite construction materials has continued ever since, leading to the discovery of hydraulic lime by John Smeaton in the 1750s [293]. Building efforts continued in search of cementitious materials with better hydraulic capacities until 1824, when bricklayer/inventor Joseph Aspdin developed what is known to today's market as Portland cement [257].

According to the American Concrete Institute, concrete is a mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials [58]. It is considered a viscoelastic material because it exhibits both viscous and elastic characteristics when undergoing deformation. Because of its inherently useful characteristics, including ease of accessibility, processing and handling, concrete is the most widely used material in construction today [308]. Concrete's property tunability has also made it favorable, adapting to different forms and structure types. Throughout history, the scalability of concrete structures was facilitated by its ability to change from a fluid state, where it can fill a mold, to strong, durable, rock-like material, able to withstand structural loads [100][308].

However, the demand for concrete and its widespread use contributes significantly to climate change. Because of its broad availability, low component cost, and ease of preparation, Flatt et al. (2012) clarify that concrete can be considered an ecological material. However, as a result of the volumes of it used concrete globally, the production of Portland cement, concrete's main binder, contributes 5-8% of all global CO2 emissions, the result of the decarbonation of limestone during production [100] [92]. The enormous demand for concrete is primarily responsible for its environmental impact [308]. Finding ways to modify concrete binders so as to be more environmentally friendly is a major objective driving this area of research [100]. Flatt et al. discusses some possible approaches to concrete CO2 emission reduction, including the development of alternative binders, recycling of demolished concrete into new concrete, and the rehabilitation of existing infrastructures [100].

Reinforcement

Traditional concrete has relatively high compressive strength but low tensile strength. Concrete structures that encounter tensile stress need to be reinforced with materials capable of handling this stress. Thus, concrete on its own does not necessarily make a reliable structural material. Reinforced concrete creates a composite material capable of resisting compressive stress, and the reinforcing material resists the tensile stress. Material reinforcement has been an issue since ancient times, and remains a crucial part of the building process for improving material strength.

Historically, hair and straw were used in mortar and mud bricks; since then, alternative materials have been used. Nubian masons used adobe bricks mixed with straw to make them lighter for the construction of lightweight roof structures. The addition of straw to the mixture also provided benefits such as insulation and waterproofing. Although compression-only structures such domes, arches, and vaults do not encounter high levels of tensile stress, shrinkage and thermal changes may develop, requiring a level of material reinforcement. A fiber-reinforced material can be favorable in such conditions, eliminating the need for additional reinforcement. Introducing fibers into concrete can help reduce shrinkage and cracking, while also providing impact resistance and reducing voids, thus increasing concrete's overall tensile strength.

Today, one of the most common reinforcing elements used in concrete construction is steel, formerly known as *rebar*. Joseph Monier, a French gardener, was one of the earliest developers of concrete reinforcement in the form of steel and iron mesh, which he used in the fabrication of flower pots and other items [200]. Monier was granted several patents in concrete reinforcement including one for a technique of placing metal rods in a grid pattern [314] [179] [200]. In the United States, Ernest Ransome patented a system of concrete reinforcement using twisted iron rods in 1884 [245], and was successful in constructing the first reinforced concrete bridge in North America, which remains in San Francisco's Golden Gate Park today [246].

Although material reinforcement has proven to increase tensile strength, a few examples of unenforced concrete structures remain unchanged, including the Pantheon in Rome. Built without reinforcement, it has held the record for 19 centuries as one of the largest and oldest structures made of unenforced concrete [123]. In contrast to dome structures, which gain structural stability through geometry, structures using material reinforcement allow concrete and other brittle materials to be shaped into freeform geometric structures.

Concrete utilizes various forms of reinforcement, including post-tensioning, pre-stressing, and the addition of fibrous materials to the mix. Today, reinforcement materials can be categorized as *internal* and *external*, *passive* or *active* (pre-stressed). Common reinforcement methods include steel rods and wires, fabric, meshes, and fibers. Most of these methods are labor-intensive, time-consuming, and often require high precision. To begin, the concrete construction process requires meticulous planning for the structure or formwork to meet specific, load-bearing criteria. After the planning stage, reinforcement material, such as rebar for example, is cut, bent, and assembled, while ensuring correct placement and fastening in order to maintain the reinforcement's placement once the concrete is poured. Finally, after the concrete is poured, it must be compacted to eliminate air pockets before the mixture begins to harden. The multi-stage process, and the complexity of these tasks make the reinforcement process comprehensive, yet cumbersome.

3D Printing Viscous Materials

Printability is a generic term that refers to the extrudability, pumpability, and buildability of the extruded material [321]. One of the main challenges in large-scale 3D printing are the materials used, which are often thick and deposited in high volumes. During the large-scale 3D printing process, materials are usually deposited through a nozzle, following a robotically-guided toolpath that sequentially creates the designed object or structure trough layered-manufacturing. Because of the nature of the process, 3D printed materials must comply with factors such as high flowability rates and prolonged setting time during the mixing, pumping, and settling after deposition [177][242]. More specifically, fresh viscous and cementitious materials must be sufficiently fluid to be pumpable and extrudable, while being sufficiently strong to support the weight of the subsequently deposited layers [158]. Another crucial challenge facing viscous materials in construction 3D printing is their sensitivity to uncontrolled environmental factors such as temperature variance, humidity, and gravity.

Therefore, materials that may be suitable in lab-scale applications where environments are regulated and controlled, may face challenges in larger-scale 3D printing, especially considering factors such as pumping distance and the quantity of materials transported, stored, and mixed [321].

The structural integrity and the quality of 3D-printed structures is directly influenced by the viscous materials utilized in the printing process. These materials must demonstrate sufficient workability and pumpability, retaining their shape post-extrusion without collapsing under the weight of subsequent layers, as highlighted by Papachristoforou et al. (2018) In large-scale 3D printing, one major challenge is to prepare materials that are compatible with the pumping system and the 3D printing platform [172] [221]. The fluidity, extrudability, pumpability, and buildability of these materials in both their fresh and hardened states must be critically considered [225]. To date, concrete remains the most widely used material, though new developments are being investigated. For instance, Khoshnevis et al. introduced a cementitious composite made of plaster and clay-like substances that is optimized for smooth extrusion in their proprietary CC systems, achieving high surface finish and geometric precision [142]. In addition, Lim et al. formulated a high-performance cementitious mixture for concrete printing that is composed of 54% sand, 36% reactive cementitious compounds and 10% water [169].

In addition to conventional 3D printing materials, researchers have explored sustainable alternatives. Xia and Sanjayan (2016) for instance developed a slag-based geopolymer consisting of slag, a silicate-based activator, and fine sand [317]. On a similar note, Rael et al. (2019) explored large-scale 3D printing using adobe, a material that is entirely sourced from the construction site and has proven, over millennia, to be reliable in construction [241][236][69].

The tunability of deposited viscous materials also allows for the production of varying properties in a single 3D printed product [87]. For instance, the Agua Hoja project, by Neri Oxman and the Mediated Matter Group, is 3D printed with functional gradients varying in water content and material properties across the printed skin of the pavilion. Due to the variation in material layering and mixture properties, new possibilities have emerged, varying the opacity and flexibility of the structure at specified areas of the 3D printed object. The advanced manufacturing workflow, material heterogeneity, and anisotropic structural design have proven to successfully produce structures with high stiffness and durability and low weight [192].

Summary Concepts

Throughout history, various viscous materials have served as crucial building materials in the development of human civilizations. These materials are often combined with granular compounds such as sand, gravel, earth, and clay as a form of reinforcement. The emergence of concrete marked a significant milestone in architectural history, enabling the construction of complex architectural forms. The versatility of concrete, and its ability to be molded into complex shapes makes it a favorable material in construction. Its ability to morph from liquid state to a rock-like solid significantly contributes to the scalability of concrete structures.

Although concrete exhibits exceptional compressive strength, its performance is enhanced when paired with materials that resist tensile forces. This synergy results in reinforced concrete that is able to withstand both, tensile and compressive stress. Historically, reinforcement techniques have evolved, incorporating methods such as pre-stressing, post-tensioning, and the combination of fibrous substances into the concrete mixture. In recent practices, reinforcement can either be internal or external, and either passive or active. Common methods include steel rods, wires, meshes, and fibers.

Large-scale 3D printing applications have further adapted the use of concrete and similar viscous materials. The deposited materials must exhibit adequate workability and pumpability in order to become printable. During the printing process, these materials are sequentially deposited following a robotically-guided toolpath, resulting in structures composed of planar layers. The instability of these materials during their fresh, viscous state presents challenges for constructing overhanging and long-spanning forms. The structural integrity and quality of 3D printed structures are directly influenced by the properties of the employed viscous materials.

The capacity of viscous materials to vary in property tunability within a single 3D printed object introduces new avenues in manufacturing. This includes the development of products with functional and mechanical gradients such as variation in opacity, flexibility, and structural strength as a result of varying mixture compositions. Innovations in manufacturing workflow, material heterogeneity, and anisotropic structural design have demonstrated the ability to produce structures that are not only durable, but also remarkably lightweight.

2.4 Auxiliary Structures

Overview

Concrete forms are generally constructed through pouring or spraying the mixed material during its liquid/wet state into a *formwork* or mold from which the concrete takes its form as the mix sets. Formwork typically consists of temporary molded structures that are used to contain wet concrete until it hardens. Due to the weight of the concrete and the formwork it occupies, the weight of both can require additional support for stabilization, particularly in unsupported conditions such as long spanning forms. Formwork can also be composed of several smaller parts that are assembled together to make a single entity; this entity may also require support to hold its individual parts in place.

Formworks are usually supported by an underlying structure called *falsework* that acts as temporary support. The term also refers to scaffolding, which is used to temporarily support geometry such as arches and vaulted shapes until they are able to support themselves. The terms *formwork* and *falsework* are often confused, since some situations have required falsework to temporarily support formwork containing concrete. Both formwork and falsework play a critical role in constructing concrete or other molded materials in large-scale construction to ensure structural integrity and accuracy of the desired architectural design. Both formwork and falsework have been used since ancient times in different regions of the world.

Although formwork and falsework vary in material and form, both must able to be shaped into different geometric forms that are able to withstand heavy loads without warping or distorting. Lightweight materials are easiest for workers to assemble and reusability minimizes material waste and construction costs.

Formwork can be classified into two categories: *rigid formwork* and *flexible formwork*. Rigid formwork generally involves the use of excessive quantities of material such as timber or metal scaffolding, which can significantly increase construction costs. Rigid formwork also requires intensive labor and construction time. Flexible formwork, on the other hand, provides high degrees of strength and geometric flexibility at lower costs. Flexible formwork includes fabrics, pneumatic structures, and other types of formwork that require less material and are less labor-intensive. Flexible formwork dates back to ancient Roman times, although several crucial developments took place during the 18th and 19th century, emerging from affordable and quality textiles coming out of the Industrial Revolution [305]. Formwork types not only influence the process of construction, but may also affect the design of the buildings they are used to construct. In this section, rigid and flexible formwork types will be discussed, highlighting several projects as a demonstration of formwork's effect on the finished building.

Rigid Formwork

One of the most common methods of rigid formwork construction utilizes timber planks fixed together to construct specific geometric forms. Timber formwork is usually constructed at the building site and generally costs less than other materials such as steel because of its availability across different regions of the world. The weight of timber makes it easier to handle than other materials. Timber formwork also presents the advantage of strength and resistance to moisture over short periods of time, making it an efficient solution for temporary construction.

The use of timber formwork and falsework, especially when constructing complex geometric features, requires a drastic amount of labor and material waste, as shown in **Fig. 2.11**. In the construction of shell structures, dense forests of timber formwork and falsework are required. An example of dense falsework is demonstrated in the shell structures designed by Felix Candela [282]. The design of the shell structures takes advantage of the ruled geometry of the shell. Curvature is achieved through straight lines, which are easily achieved through straight timber members.

Another very common structural system used worldwide is metal, particularly steel and aluminum. In comparison to timber formwork, metal formwork is capable of providing extreme rigidity as well as ease of assembly, disassembly, and erection [164][227] [302]. Metal formwork is also advantageous due to its adaptability to different forms and its ease of

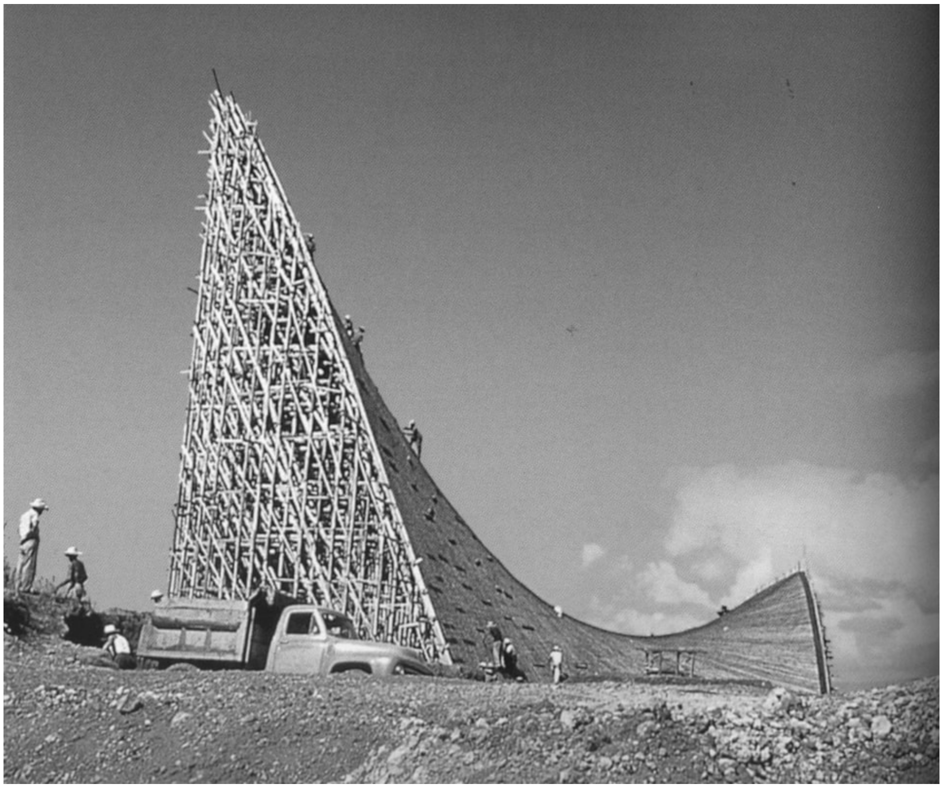

Figure 2.11: The scaffolding needed for the construction of the Palmira Chapel in Cuernavaca, Mexico, in 1959 shows the high material consumption of this process [98].

recycling. The Jubilee Church in Rome is a notable structure in which the three curved walls are made of post-tensioned precast concrete components using steel formwork [47][233]. Aluminum is also a relatively lightweight material adequate for formwork use. Aluminum members are mass-produced in standard sizes, permitting their easy fitting and removal and making them highly efficient [164][274][121]. The Wembley Stadium in London is an example of a large-scale structure built using aluminum formwork [182]. Metal formwork is commonly used today for orthogonal surfaces due to the challenging nature of the material in achieving complex forms. In the construction of orthogonal forms, formwork reusability is also possible.

Earthen formwork refers to the use of natural granular materials such as sand, clay, or earth as temporary formwork for constructing structures such as concrete domes. After the poured concrete has hardened, the earthen formwork is excavated and can be reused. While material reusability and waste mitigation makes this method sustainable, constructing large-scale structures using earthen formwork requires enormous amounts of material. The excavation process is also time- consuming. Notable projects using earthen formwork include the Philips Pavilion for the 1958 Expo in Brussels [37] and the Teshima Art Museum in Japan, Designed by SANAA. The use of earthen formwork in the design of the Teshima Art Museum influenced its geometry, allowing the structure to blend into its surrounding hilly landscape.

Flexible Formwork

The use of fabric as formwork has been popularized throughout the past century. Fabric formwork is a technology that involves the use of structural membranes as the main facing material for concrete molds [305]. Unlike traditional rigid formwork structures, fabric formwork is flexible and can easily be molded into complex surfaces. However, the flexibility of the material presents a new challenge, since it deflects under the weight of the wet concrete. The first appearance of fabric formwork can be attributed to Gustav Lilienthal, who developed a fabric-formed suspended flooring system featuring an impermeable fabric draped over parallel beams [305] [167].

Over the years, fabric formwork has developed beyond its use in construction to embrace the aesthetic possibilities of its textures, as demonstrated by Spanish architect Miguel Fisac [288]. While rigid formwork types require assembly, fabric formwork requires tensioning before materials can be applied. Tensioning is achieved through various methods. Mendez et al. (2019) introduced a method using an external cable-net system for constructing thin shells [88]. In this approach, the fabric spans the distance between cables, while being tensioned from stiff boundary beams, .

More recently, CNC knitting has been used to develop stay-in-place knitted formwork. The KnitCandela project by Zaha Hadid Architects in collaboration with ETH, Zürich uses a knitted fabric that has been pre-stressed into the desired shape and is then sprayed with thin layers of high-strength paste until it has reached a self-supporting stiff state **(Fig. 2.12)** [232]. Another method of tensioning uses air pressure to create a pneumatically inflated fabric formwork. This method was developed by Dante Bini in the 20th century for the construction of shell structures [34].

In 1942, Wallace Neff used inflatable domes as formwork to produce concrete bubble structures [208]. The process uses a cement gun that sprays materials onto the inflated structure in thin layers until the form is able to support itself. Neff's solution presented a low-cost method capable of rapidly erecting concrete structures while reducing material usage and labor. Neff described the developed homes as "beautiful flowing lines and curves that come into being without effort. The absolute absence of girders, columns and jigsaw trusses startles the imagination" [305]. The use of inflatable pneumatic domes and shell structures has become more common.

Cable-net structures consist of cable networks and supporting frames; the interactions between them form structures in equilibrium states [211]. In recent decades, cable-net structures have been popularized in architecture and construction for their cost-effectiveness, light weight, long span, easy handling, and aesthetic values [210]. Combined with fabric, cable-net structures are made into cable-net formwork. The process is enabled through tensioning the cable-net structure to a boundary timber frame or series of beams, while fabric is laid on

Figure 2.12: KnitCandela, a sinuous concrete shell built on an ultra-lightweight knitted formwork [232]

top as shuttering. Concrete or other viscous materials are then applied to take the shape of the curved formwork. Cable-net formwork is considered an efficient solution because of the minimal use of materials relative to the size of the produced structures and the amount of labor and time involved. Experiments performed by Veeneendal et al. (2014), demonstrated the use of cable-net systems combined with fabric formwork in the fabrication of thin shell structures [306]. This method has enabled a higher degree of control over applied pre-stresses and a more precise translation between the digital form-finding model and the actual built experiment.

Support Integration in 3D Printing

The various formwork solutions discussed in the previous section play a crucial role in enabling the fabrication of complex structures. These include geometries that span long distances, or feature overhangs. Formwork integration ensures the stability and integrity of the structure until the cast or sprayed material sufficiently cures or hardens. Interestingly, a similar approach is applied in 3D printing processes. Just as conventional formwork temporarily supports physical structures, 3D printing processes often use temporary 3D printed supports to achieve certain geometric features such as voids, long spans, and overhangs. Overhangs in small-scale FDM 3D printing processes are made possible by 3D printed temporary supporting structures [94] [270]. Temporary supports are 3D printed with distinct features such as thin walls or low volume densities which allow them to break off easily. Other approaches to support printing use dual-extrusion capabilities to 3D print supports made of water-soluble Polyvinyl Alcohol (PVA). The use of support structures also varies depending on the types of 3D printers. For example, supports used for SLA 3D printing are made of thin longitudinally-shaped structures that only support contact parts of the printed object. SLS and Binder-Jet printing, on the other hand, use the loose granular materials in the printing bed as temporary supports for overhanging parts. Regardless of the technique used, temporary supporting structures are often needed to achieve complex geometric features. These solutions, however, are only applicable to small-scale applications due to factors such as the low weight and volumes of the printed material and thermal layer adhesion. The thin extrusion width, low deposited material quantity, and rapid cooling of the extruded material all contribute to successful integration of support materials.

Desktop-scale techniques of support integration cannot be easily adapted to large-scale applications. Support integration in large-scale 3D printing remains a key challenge. Because of the ability of materials to rest onto previous layers, most large-scale additive manufacturing processes currently use layered-manufacturing (LM) techniques that do not require the use of support materials. As discussed earlier in this study, this process restricts the design of the 3D printed objects to continuous vertical extrusions.

The ability to achieve multi-dimensional curved forms enables new expressive design possibilities that are typically more expensive, as additional effort is required for correct measurements on the construction site and/or additional costs are required for factory manufacturing [168]. However, additive manufacturing processes on small scales have proven that structures with complex geometry can be manufactured at relatively low costs. While the adoption of 3D printing in construction promises the possibility of 3D printing complex structures and enables new forms of geometry, large-scale 3D printing has mainly been demonstrated through the development of planar structures which are 3D printed through LM [220][139]. Certain geometric features cannot be achieved efficiently through conventional LM processes. For example, 3D printing shell structures using LM result in stair-stepping surface qualities that can only be improved by decreasing the 3D printed layer height, thus drastically slowing down printing time. Substantial amounts of support material are also required in many cases to achieve certain curved forms and complex geometries [163]. Translating the smaller-scale approach of 3D printing supports into larger scales may seem a viable solution, but would generate much larger amounts of waste and increase printing time.

Summary Concepts

The use of formwork and falsework are essential in shaping concrete into various complex forms. While in its wet state, concrete is poured or sprayed into formwork to take its shape until it hardens. This technique dates back to ancient times where concrete is used in the construction of domes, bridges, and arches. The two main formwork categories are: Rigid formwork and flexible formwork.

Rigid formwork includes the use of timber planks, steel, aluminum, and other forms of rigid elements that are fixed together to construct the mold into which concrete is poured. This category of formwork typically uses substantial amounts of material, and requires high economic and labor costs. Timber formwork for example, especially for complex geometries, leads to substantial amounts of waste. This is primarily due to the specialized material processing intended for single-uses and challenges associated with its reusability. Metal formwork on the other hand is commonly used due its adaptability to various complex forms and ease of recyclability.

In contrast to rigid formwork structures, flexible formwork involves the use of structural membranes as concrete molds. Due to its flexibility, fabric formwork can easily be molded into various complex surfaces. While advantageous in terms of economic and labor inefficiency, the flexibility of the material is challenged by the weight of the wet concrete, causing the formwork to deflect. The use of fabric formwork has also expanded to include aesthetic aspects, embracing fabric textures, folds, and creases to be absorbed by the concrete. Recent developments also include CNC knitted formwork that is pre-stressed into the desired shape and sprayed with layers of concrete. Pneumatic structures are another type of flexible formwork that are temporarily inflated and sprayed with concrete. An example of this type of formwork is Wallace Neff's inflatable domes and concrete bubble structures. This formwork type is known for its cost-effectiveness and minimal material usage.

Another notable formwork type is earthen formwork, which uses natural granular materials such as sand, gravel, and clay as temporary formwork to construct dome-like structures. The loose granular materials are excavated after the concrete is poured onto the earthen formwork and can be reused. While sustainable and economical, earthen formwork requires drastic amounts of materials and are intensive in terms of construction time and labor.

The concept of using temporary formwork is commonly used in 3D printing to achieve complex forms. Desktop FDM 3D printers are able to create complex objects with temporary supports for overhangs and long-spanning forms. 3D printed supports are often printed with particular characteristics, allowing them to easily break-off after completion or dissolve. On the other hand, techniques such as binder-jet 3D and SLS 3D printing take advantage of loose granular materials in the printing bed as temporary reusable supports. These techniques are able to produce objects with high geometric complexity due to the nature of the printing process.

While proving effective in small-scale applications, the above-mentioned methods face challenges when scaled up. Due to the significant increase in material consumption and volume, printing temporary supports can produce drastic amounts of waste. While 3D printing can reduce production costs of complex geometries on a small scale, large-scale 3D printing is mostly limited to planar layers and faces difficulties in efficiently creating complex forms. This is mainly due to the difficulty of efficient support integration and the inability to 3D print support structures that require longer printing times and may generate high amounts of waste.

Chapter 3

Methodology

3.1 Overview

Architecture allows us to transform material research and robotic fabrication technologies into tangible, spatial experiences. It also allows us to ask questions regarding scale and implementation. The adoption of 3D printing technology into architecture and construction holds significant promise, as exemplified in the previous chapter through project demonstrations, and the growing interest from construction corporations. However, the mere adoption of 3D printing is not enough. Despite the considerable potential, key challenges that are impeding its full potential remain unresolved. The objective of automating construction and robotizing fabrication processes extends beyond cutting down construction time or reducing the amount of required labor. This adoption fundamentally unlocks novel opportunities that are intrinsic to the nature of the additive process.

The aim of this thesis extends beyond presenting a single solution to the challenge of formwork integration. It strives to present a comprehensive approach that promotes knowledge transfer, fostering further exploration and development. This chapter sets out to establish a methodological framework that serves as a guide for the upcoming experiments, discussed in the following chapters. Working through the development of software and hardware tools, material explorations, robotic fabrication technologies, and large-scale prototypes, the methods proposed in this chapter aim to connect the different areas of research to obtain crucial feedback that can be incorporated from design to realization. Findings on a material and process level can inform the development of tools and fabrication workflows. The interconnectivity between research areas aim to provide new design possibilities and opportunities that may be challenging to realize otherwise.

3.2 Design Limitations and Fabrication Challenges

Due to the nature of extruded viscous materials, 3D printed structures cannot sustain high tensile forces in their wet state and can deform once layer weight accumulates. These factors limit the geometric properties of the designed structures. 3D Printing forms containing overhangs and freeform geometry require temporary supporting structures to hold up wet 3D printed layers until they cure and harden. Like desktop scale 3D printers, this process may require supporting structures or dual-material deposition systems to 3D print a second removable material [169]. This process may generate large amounts of waste materials as well as require more maintenance and complex operational instructions [169].

Gosselin et al. (2016) reviews current additive manufacturing workflows while reporting the main drawbacks of prominent existing systems, which can be summarized as follows [112]:

1. While adapting 3D printing into construction initially aimed to produce complex forms that would have been difficult to realize using conventional processes, the current technology allows for 2.5D printing only.
2. Geometry is limited due to the nature of the process, material properties, and size of the 3D printer platform.
3. 3D printing supporting structures slow the entire printing process.

In addition to these points, it is important to note that design constraints and fabrication challenges are mostly evident in large scale 3D printing platforms, which utilize viscous material deposition. However, the lack of tools that enable the process to reach its maximum potential of producing unrestricted geometric features remains a problem. These challenges demand the development of alternative workflows for support integration and workarounds on the hardware, software, and material levels.

3.3 Study Objectives

To address the design limitations and fabrication challenges associated with large-scale 3D printing, this study focuses on developing workflows to improve the adaptability, scalability, versatility, and efficiency of non-planar 3D printing of viscous materials across scales. It specifically seeks to establish a methodology for integrating different design and fabrication approaches using non-planar robotic deposition of viscous materials. The research is structured around different types of support solutions, highlighting three key strategies: formwork reduction, alternative formwork approaches, and formwork elimination. To assess the practicality of the proposed approach, feasibility studies are performed, examining platform architecture, material choices, and toolpath strategies. The research focus then shifts to developing task-specific processes and toolsets, designed to adapt to varying fabrication setups. These new tools and processes undergo testing, and are compared with conventional methods, as well as against one another. To test the practical application of these developments, medium-to-large prototypes are fabricated. The decision not to commit to one scale only provides a greater degree of flexibility in design and allows for more innovative and experimental approaches to form and structure [32].

Building on the exploration of support integration solutions and non-planar toolpath strategies, as well as their application across scales and contexts, the research sets out to clearly define the following objectives:

1. Investigating innovative approaches to enhance the capabilities of non-planar 3D printing of viscous materials, with the aim of overcoming current limitations.
2. Exploring the intersection of robotic manufacturing, 3D printing, material design, and formwork integration for 3D printed structures.
3. Creating novel software and hardware tools tailored to non-planar 3D printing processes, which can be applied across various materials and scales.
4. Investigating the difficulties associated with developing alternative support structures, minimizing support requirements, or achieving support-free 3D printed structures.
5. Evaluating the added value introduced by the proposed methods through experiments and prototypes, conducted across a range of materials, scales and possible applications.

3.4 Approach

Innovative architecture solutions often start with a question; How can we 3D print wide-spanning structures without using formwork? Can the integration of reinforcement and lost formwork in 3D printing be automated? Can we repurpose construction waste to be used in other construction applications? These questions may be initiated in an open-ended process and may not address a specific architectural application, or solve a particular problem in the beginning [188]. However, they fall under the umbrella of architectural innovation and have the potential to be adapted into large-scale applications. Architecture allows questions to become visible, while experiments provide designers with the opportunity to decide which questions and ideas are worth further development. Through experimentation, digital designs and material explorations, ideas can be transformed into spatial experiences. The journey of transforming ideas into applications commonly involves detours, obstacles, and most importantly, effort from a team of researchers [188].

Prototyping

The methods proposed in this study aspire to connect different areas of research, cooperatively informing one another. First, concepts are validated, and the feasibility of the proposed method is tested through small-scale experiments. In this step, data relevant to the process limitations, opportunities, and challenges is gathered. This step also allows for a filtering of ideas with less potential, so as to decide which tools, materials, and technologies best serve the purpose of the proposed method. The observations and findings from the initial experiments are then used to render the future direction and scale of the subsequent experiments. In this context, knowledge obtained from computer simulations can play a role in informing the design process, which can then raise questions about the required tools. Subsequently, tool developments can then provide a better understanding of the approaches required to arrive at the intended objectives. Conclusively, experiments are conducted not only to answer the proposed questions, but also ask more questions about process improvement, expansion, and scalability.

The above-mentioned stages of multi-scale experimentation can be exemplified by the development process of the non-planar granular 3D printing (NGP) experiment that is discussed in **chapter 6**. The experiment began with the idea of using sand as a material for rapid 3D printing of large-scale complex objects. This idea is not new, and has been undertaken by several design and research projects. Examples include Solar Sinter by Markus Kayser which uses solar power to selectively sinter sand particles [135], and Quake Column by Emerging Objects which exhibits interlocking components made of Binder Jet-3D printed Sand [261]. These approaches, however, showcased only small-scale objects fabricated through time-consuming processes, demonstrating the need for further exploration of faster fabrication techniques.

The first phase of experimentation described in this thesis tested a wide range of binding liquids that can potentially adhere various types of sand particles together, while at the same time providing adequate component durability and load-bearing capacity. Prototypes were created in the form of 10cm sand cubes which were manually injected with binding agents using a syringe. Based on the results from the first experiment, the most successful material samples were used in the next stage. In the second phase, liquid dispensing tools were developed to specifically accommodate the different viscosities of the binding agents. A granular material container was also designed to allow for potential scalability of the proposed method. It is important to note that tools in the earlier stages were versatile, allowing for different materials to be assessed without drastic modifications to the experiment setup. From there, prototype scales gradually increased, while process parameters such as air pressure amounts, printing speed and extrusion rates were fine-tuned. The delineation of the experiment methodology highlights the importance of the initial tests in shaping the direction of the research. The knowledge gained at the initial stages guided the development of tools and approaches to advance the research. **Chapter 6** provides a comprehensive discussion of the experiment's intricacies.

Validating a process through multi-scale experiments is important in both academic research and in industrial operations at companies looking to advance their manufacturing capabilities. In a conversation with vice president of business development at Kreysler Associates, Joshua Zabel on April 15, 2022, Zabel emphasized the significance of multi-scale prototyping in validating innovative fabrication techniques. The interview revolved around the topic of robotic integration into fabrication and construction workflows. Throughout the company's history, experimental processes have played a role in developing new methods for fiberglass construction. Not long ago, Kreysler Associates purchased two large-scale industrial robotic arms to be used for honing and sanding large panels made of glass-fiber reinforced polymers (GFRP). The adapted method of robotic GFRP honing is considered fairly new in the fiberglass construction industry. However, the company was convinced that this process could help increase the quality and efficiency of the fabricated products. Before purchasing the robots, the company performed small-scale experiments to validate the viability of the idea. Zabel stated, "We were anxious about validating the idea that we were going to hone panels using robots, and we have a KUKA at our Green Island location. We realized that before we delve into this, we need to first test out one part. We started with smaller samples and kind of worked our way up bigger and bigger. There were a lot of questions that took a long time to get to where we are now: Are we using sandpaper? or diamonds? or is it metal?" *(J.Zabel, personal interview, April 15, 2022).*

Although experiments in smaller scales can answer many of the questions that arise in an early development stage, unforeseen scalability challenges may still arise. In the case of Kreysler Associates, small scale experiments were performed using the company's available equipment, validating the approach. Zabel stated the following:

"We were convinced that we were going to do all the sanding dry. We had it working on our KUKA robot at our Green Island location, and thought our prototype was big enough to validate the method. When we got going here, and started doing full sized panels, it was not working. It was not consistent. We had tool marks on the panels" *(J.Zabel, personal interview, April 15, 2022).*

This setback led the company to make tool adjustments to the robotic honing process according to the findings, which were not identifiable otherwise.

Scaling Prototypes

Scalability often requires alterations to the process; experiment setups and tools must be upgraded to accommodate larger prototypes and applications. Designing large-scale prototypes and pavilions is an effective way to allow experimental questions to be examined without dealing with legal and economic obstacles that make innovations in architecture challenging [188] [32]. Barry Bergdoll describes architectural pavilions by saying, " Lack of permanence has often been a trampoline for invention. It might thus be possible to trace a history of architecture's leaps into new tasks, new experiences, and new formal, spatial and structural experiments by following the meandering path of pavilions." [32] Large-scale prototyping is also a way to expose unforeseen obstacles. While small to medium-scale experiments can allow designers and researchers to explore new methods and opportunities, they do not address questions related to construction logistics, industrial equipment, and material scalability on the construction site.

3.5 Evaluation

An experiment is defined as an operation or procedure carried out under controlled conditions in order to discover an unknown effect or law, to test or establish a hypothesis, or to illustrate a known law [95]. The experiments in this study are performed primarily to test the validity and efficiency of a proposed fabrication process. More precisely, the setups for all the experiments involve robotic arms as manipulators to perform additive manufacturing tasks to deposit or extrude viscous materials. The proposed experiments do not necessarily aim at replacing conventional fabrication methods, but instead build upon existing methods to unlock opportunities and push technological boundaries. The focus of the experiments is thus not solely on the product being fabricated, but on the process that leads to its fabrication. Thus, products are considered mediums by which a method can be tested to evaluate the performance of the experiment and acknowledge the limitations of the proposed method. By following this approach, the resulting products can then be tracked to better understand their location during the evolution and the continuous development of the proposed method. In this section, the criteria by which experiments can be evaluated are discussed. The evaluation criteria is based on commonly used assessment standards in the analysis of 3D printing processes such as process efficiency, versatility, and scalability.

Printing Time

Additive manufacturing processes are known to be slower than other fabrication techniques [215]. Standard 3D printing processes such as SLA, FDM, and SLS often require 3D models to be processed and prepared before printing. 3D models, regardless of their size, can take hours, if not days, to be completed. Preparation and printing time are key elements in evaluating the efficiency of a method. In this study, the proposed method of Non-planar Granular 3D Printing, for example, is compared to similar methods that use powder materials such as Binder Jet 3D printing. The assessment of both methods is on the time required in the production of similar objects using the same material.

Waste-Reduction

Generally, 3D printing can be considered a very material-efficient and sustainable manufacturing technology. The process offers the possibility of depositing materials only where they are structurally or functionally needed, thereby eliminating waste generation and mitigating material off-cuts. This is a significant advantage over most most subtractive manufacturing processes, where generated material waste is a common issue. Furthermore, it offers the opportunity to extrude recycled or bio-based raw materials, which can further reduce the embodied carbon footprint of objects produced in this way. However, as already indicated in earlier chapters, the 3D printing process commonly requires objects to be manufactured in sequential layers, leading to challenges related to overhangs that require temporary supporting structures [161] [289]. In conventional 3D printing processes, temporary support structures are often printed, and can be removed or chemically dissolved after printing. This process can lead to extreme material waste, especially in large-scale applications where the amount of support material required can exceed the volume of the 3D printed object. Methods have been developed to save cost by 3D printing supports using a different materials such as Polyvinyl Alcohol (PVA) that can dissolve in water. Other methods which have been discussed in **Chapter 2** aim at completely eliminating the need for supporting structures. These processes include freeform 3D printing of lattice structures that directly deposit materials in 3-dimensional space [132] [277]. **Chapter 5** thoroughly discusses a novel method of conformal 3D printing onto bending-active formwork aims at reducing the amount of support material used. The method not only reduces the amount of material used, but aims to incorporate the bending-active strips as stay-in-place formwork that produces zero waste. In the context of this study, experiments are evaluated based on their efficiency in utilizing materials. Efficacy of the method can also be measured by weighing the products and the materials used throughout the production process.

Material Versatility

Most 3D printing technologies today require specialized materials to operate. Materials are sometimes produced only by the manufacturers of the 3D printers employed, which may affect the cost of production. One way to compare and evaluate 3D printing methods is by examining the number of materials a technology can support. SLA printing, for example, is limited to photopolymers that are cured using UV light. In contrast, FDM processes have the advantage of allowing for a wider range of materials that may vary in physical, optical, and mechanical properties. This evaluation criteria may encourage the development of processes that can support a wide range of materials and recycled waste.

Within the scope of this study, the materials employed in each experiment are discussed in their corresponding chapter. This is intended to illustrate the ability of the proposed methods in taking advantage of commonly available materials or repurposing waste products from other industries, setting them apart from conventional 3D printing methods.

Scalability

Process scalability is an important criterion for evaluating a 3D printing process, particularly in architectural design applications. The ability to produce large-scale objects through a particular 3D printing technique does not necessarily make it efficiently scalable. Standard 3D printing processes such as SLS and SLA are capable of producing large-scale objects, but at extremely high costs, financial or time expenditure. Evaluating the scalability of the process can be directly associated with other factors such as process limitations, material availability, production time, and cost. Scalability may not always refer to changes associated with size; structures composed of multiple parts may also require increased complexity and production time.

One or more of the above-mentioned evaluation criteria is used as a starting point to assess the proposed experiments in the following chapters. Comparing proposed methods to available 3D printing techniques provides a better understanding of the technology's limitations and opportunities. In application of this strategy, the experiments may expand on existing techniques to develop them further, or potentially explore alternative strategies. Throughout the development process, experiments are evaluated not only by comparison to existing techniques, but also to earlier versions of the experiment itself.

3.6 Development Projects

Across the world, research teams have conducted studies on the implications of digital fabrication for climate change, pointing towards a sustainable future that is assisted by additive manufacturing technologies [203]. Increased interest in adopting digital fabrication into construction has been influenced by cost and time saving opportunities, as well as by environmental goals to use material wisely and reduce waste [49].

In response to the above-mentioned challenges, this study proposes three experiment categories which address challenges related to support integration. The conducted studies identify the design space of large-scale 3D printing, covering support reduction, alternative support integration, and support elimination. The proposed methodology is tailored for 3D printing workflows that utilize viscous and cementitious materials. In each area of classification, experiments result in products of varying scales. The three proposed methods share the common goal of innovating more sustainable and efficient fabrication workflows that are adaptable to diverse environmental conditions [189].

Support Reduction

3D printing of cantilevers and unsupported forms using viscous and cementitious materials requires complex formwork solutions that are often labor intensive, costly, and consume large amounts of materials that eventually go to waste. **Chapter 5** proposes a new method to produce formwork that can be embedded into the finished product suggesting solutions that both environmentally and economically efficient. The proposed method can potentially free large-scale construction from the need for costly and wasteful formwork.

Alternative Supports

Chapter 6 discusses a method of alternative support integration. The aim of this experimental design approach is to overcome some of the current limitations of 3D printing through the utility of viscous materials and to expand the spectrum of possibilities such as scalability, material variation, and support integration. The studies are accompanied by tool developments and evaluation procedures for the proposed methods.

Support Elimination

Chapter 7 presents a series of experiments that aim to study the potential of 3D printing compression-dominated geometric forms using viscous and cementitious materials without the requirement for support integration in order to limit the amount of wasted materials and reduce the cost of fabrication. The challenge here is to identify material and process limitations that are specific to viscous extrusion and to explore approaches that lead to the admissible geometric features within the design space. The study also considers the development of software and hardware tools that assist in the design, simulation, and fabrication of such forms.

Chapter 4

Beyond Planarity: Designing with G-CODE

4.1 Overview

Most additive manufacturing processes share common operational principles, regardless of the materials being printed or their platform architecture. These processes often begin with creating a 3D digital model using CAD software. During this stage, the designed objects must adhere to specific criteria, such as containing no gaps or overlapping mesh faces, and are generally exported in the Standard Triangle Language (STL) format. These models are then imported into a slicing software that aligns with the chosen 3D printing technique to be prepared for printing. Slicing software can either be proprietary to the 3D printer in use or versatile enough to support various platforms. Slicing software has two primary functions: first, to set the key printing parameters of the printed object and second, to convert the parameters into machine readable G-CODE, instructing the 3D printer movements to facilitate the chosen parameters.

Printing parameters include wall thickness, the infill density of solid objects, and the height of the printed layers. This is particularly important in layered manufacturing (LM) processes, where parameters significantly affect the quality of the printed object. Temporary support structures are also generated at this stage of pre-printing. Parameters such as support contact points, density, and material are selected in preparation for 3D printing.

Once the parameters are confirmed, the slicing software exports the file in G-CODE format, which includes a list of instruction lines for the 3D printer to follow. These lines of code are mainly composed of commands instructing the machine to move to a specific location within the printer volume at a given speed while extruding a certain amount of material. An example of this can be found in **Fig. 4.1**.

Although the conventional LM process is widely used and adapted to various 3D printing platforms and CAD software, it presents limitations. These limitations are particularly evident when dealing with complex geometries such as lattice structures, extrusions with

```
G90 ; absolute positioning
M82 ; absolute extrusion
M106 S0 ; set fan to zero speed
M190 S65 ; set bed temperature
G28 ; auto-homing
M104 S250 ; set extruder hot end temperature
G29 ; bed leveling
M109 S250 ; wait until hot end reaches temperature
G0 X3 Y3 Z0 E0 F200 ; move to starting point
G92 E0 ; reset extruder current position to zero
G1 X3 Y9 Z0 E0.16 F2000 ; move to the first point of the print path
G1 X5 Y11 Z0 E0.85 ; move to the second point of the print path
G1 X13 Y11 Z0 E1.04 ; move to the third point of the print path
G1 X15 Y9 Z0 E1.82 ; move to the fourth point of the print path
G1 X15 Y2 Z0 E2.53 ; move to the fifth point of the print path
G1 X11 Y2 Z0 E2.72 ; move to the sixth point of the print path
G1 X11 Y5 Z0 E3.41 ; move to the seventh point of the print path
G1 X7 Y5 Z0 E4.13 ; move to the eighth point of the print path
G1 X7 Y2 Z0 E4.82 ; move to the ninth point of the print path
G1 X3 Y2 Z0 E5.57 ; move to the tenth, and last point of the print path
G92 E0 ; reset extruder current position to zero
G1 E-6.00 F1500 ; retract extrusion
M107 ; turn off fan
M104 S0 ; turn off hot end heater
M140 S0 ; turn off bed heater
M84 ; turn off motors
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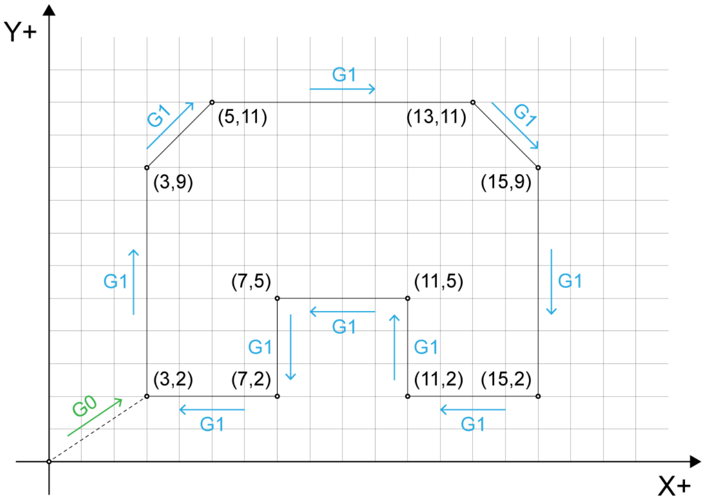


Figure 4.1: An example of a typical G-CODE file with command lines, accompanied by a diagram illustrating these commands.

varying extrusion thicknesses and printing speeds, and non-conventional 3D printing applications that are not layer-based. This conventional approach also requires transitioning through multiple software platforms before the actual 3D printing takes place, leading to redundancy when dealing with large files and complex geometry. Additionally, achieving precise machine control – including managing movement speeds, variable extrusion rates, and base surface shapes, – proves to be extremely challenging.

Recent years have witnessed a rise in research projects exploring non-conventional 3D printing techniques through custom extruder designs and toolpath planning [217] [125] [118] [119] [62]. Molloy et al. (2017) demonstrate objects with tactile, visual, and expressive qualities achieved by non-conventional toolpath design [194]. The studies showcase surface textures and geometries possible only through non-planar material extrusion. Mueller et al. (2014) use a conventional 3D printer to print wireframe models by extruding filaments directly in 3D space [204]. The method can enable printing speeds up to 10 times faster than conventional approaches. Another study draws inspiration from the spinning behaviors of insects, instructing the 3D printer to extrude filaments along spatial curves [325]. While most non-conventional approaches to 3D printing utilize industrial robotic arms that are typically programmed using custom toolpaths, these approaches are often challenging when it comes to conventional desktop 3D printers and other affordable plastic extrusion platforms.

This chapter introduces a collection of software tools that are designed to enable designers to convert polylines, curves, and points, all commonly used in the Rhinoceros 3D and Grasshopper CAD environments, directly into machine-readable G-CODE. The workflow allows for the encoding of machine parameters into the design workflow, eliminating the need for additional slicing software. This approach allows 3D printers to operate along cus-

$$E = \frac{\mathit{Layer\ Height} \cdot \mathit{Extrusion\ Width} \cdot \mathit{Curve\ Length} \cdot \mathit{Extrusion\ Multiplier}}{\mathit{sqr}\left(\frac{\mathit{Filament\ Diameter}}{2}\right) \cdot \pi}$$

Figure 4.2: Formula for calculating the extrusion value in the G-CODE.

tom, user-defined toolpaths, offering complete control over machine positions, speeds, and extrusion rates. The proposed software tools can fully utilize the degrees of freedom offered by 3D printers, contributing to the affordability and accessibility of non-conventional 3D printing techniques. The main objective of this study is to democratize non-conventional 3D printing methods, making them accessible at the desktop 3D printer level rather than restricting them to expensive platforms such as industrial robotic arms.

The discussion of custom toolpath planning and G-CODE design is strategically placed in this chapter, prior to the introduction of the experiments in the following chapters. This order of topics is critical because the 3D printing methods explored in **Chapters 5** through **7** either partially utilize the tools discussed in this chapter, or follow a similar approach to toolpath planning and design. Given that the non-planar 3D printing workflow serves as a foundation for this thesis, all the proposed methods and experiments discussed in the subsequent chapters are designed using custom toolpath strategies.

4.2 Caterpillar

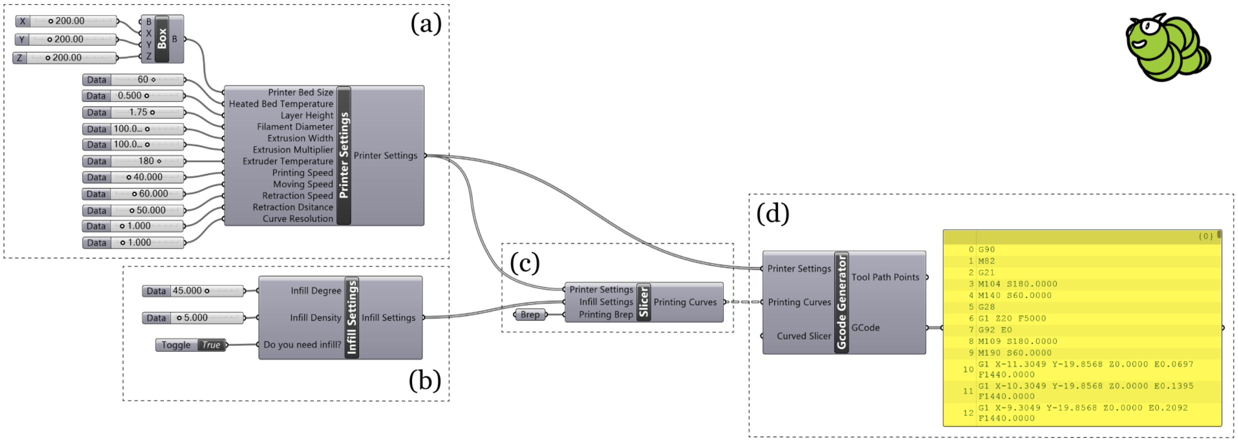
Overview

Aiming to integrate non-conventional 3D printing and toolpath design capabilities into commonly used software environments, the *Caterpillar* plugin is developed to enhance the versatility and control of 3D printers and CNC machines [326]. Caterpillar components function within the *Rhinoceros 3D* and *Grasshopper* environments, streamlining the workflow by eliminating the need for multiple software applications or the transfer of data between programs. *Caterpillar* offers a set of software tools that are compatible with various 3D printers and machines that operate on G-CODE. This following section delineates the plugin's features, explaining the core components and demonstrating their potential through experimentation. This project was developed at the University of California, Berkeley under the supervision of Professor Kyle Steinfeld. A detailed list of contributors for the Caterpillar project is available in the credits section of this thesis for further reference.

Navigating the Interface

The core components of *Caterpillar* fall under four main sections: Platform settings, toolpath geometry, G-CODE generation, and simulation. The software's adaptability to various platforms necessitates adjustments to the default 3D printer settings so that they align with the parameters of the platform in use. Users then proceed to define the 3D printed toolpaths, which can be input in the form of curves, planes, or points. Notably, *Caterpillar* also supports conventional 3D printing methods, allowing users to input 3D models and access slicing software functionalities. The final step in the workflow is the conversion of toolpaths into G-CODE exported in the form of text, which can directly be uploaded to the 3D printer.

Additionally, the software suite includes a tab containing supplementary components for enhanced user convenience. These include a 3D printing simulation visualizer and a component that converts G-CODE text into curve toolpaths. This feature is particularly convenient for reverse-engineering tasks, modifying G-CODE files, and transitioning the same geometry between different 3D printing platforms.



```
 0 G90
 1 M82
 2 G21
 3 M104 S180.0000
 4 M140 S60.0000
 5 G28
 6 G1 Z20 F5000
 7 G92 E0
 8 M109 S180.0000
 9 M190 S60.0000
10 G1 X-11.3049 Y-19.8568 Z0.0000 E0.0697
   F1440.0000
11 G1 X-10.3049 Y-19.8568 Z0.0000 E0.1395
   F1440.0000
12 G1 X-9.3049 Y-19.8568 Z0.0000 E0.2092
   F1440.0000
```

Figure 4.3: The main components and workflow of the Caterpillar plugin for Grasshopper: (a) printer settings, (b) infill settings, (c) slicing component, and (d) G-CODE generator.

Platform Settings

3D printers vary in dimension, platform architecture, printing speeds, and materials. Some platforms may also include additional elements such as a heated *build-platform*, cooling fans, and a heated extruder. These characteristics are crucial for generating G-CODE files that are suitable for the specific 3D printing platform in use. **Fig. 4.3 (a)** illustrates the twelve different input parameters that make up the settings component in the *Caterpillar* plugin. The component comes with default parameters that are designed to be compatible with a

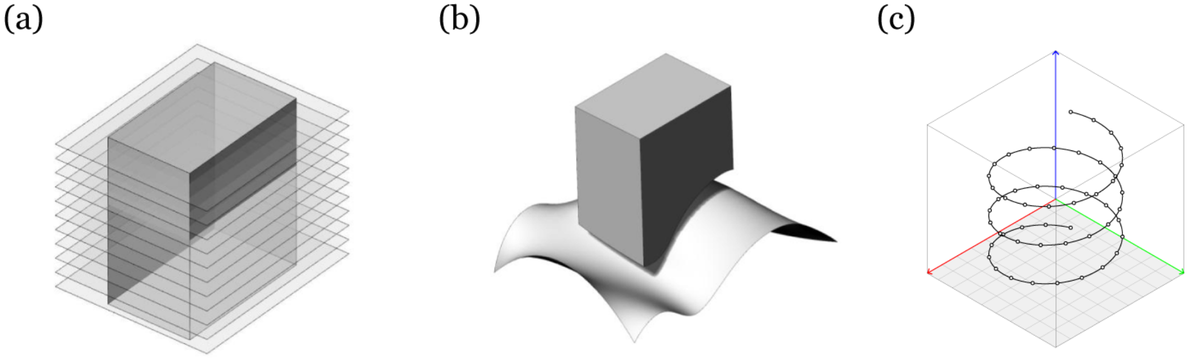


Figure 4.4: The three main methods of creating custom toolpaths in Caterpillar: (a) planar slicing, (b) non-planar curved slicing, and (c) user-defined toolpaths.

wide range of 3D printers. However, users have the flexibility to adjust each parameter to suit their platform requirements or to achieve specific non-conventional 3D printing objectives.

Additionally, it is important to note that certain parameters in the settings component can accept a range of values, rather than a single, fixed figure. This feature presents a significant advantage over traditional slicing methods. Features such as printing speed or extrusion rate, for example, can accept a list of values, allowing them to vary throughout the 3D printing process. This capability enables users to achieve a higher degree of control over the machine's parameters at precise locations. Such flexibility enhances the potential for innovative approaches to non-conventional 3D printing.

The settings tab also contains an *Infill Settings* component, particularly useful for importing 3D models rather than toolpath curves. Similar in functionality to standard slicing software, the *Infill Settings* component offers a diverse selection of infill patterns. Additionally, it allows users to define the infill density of the printed object.

Toolpath Design

Caterpillar is fundamentally built around components that allow users to generate 3D printable toolpaths within CAD environments, employing three different methods, illustrated in **Fig. 4.4**. The first approach adopts traditional planar slicing functions that are similar to most slicing software. The second method introduces curved slicing, enabling the user to 3D print objects onto curved surfaces or substrates. This process makes use of the underlying surface topology for slicing the 3D model. Finally, the third method allows users to define their own toolpaths with complete freedom. In this method, users can use curves or a series of three-dimensional points to define the printing trajectory.

In the first method of planar slicing, users are required to input a closed mesh. The 3D model is sliced into planar cross sections that are separated by a user-defined layer height. This method also requires the use of the infill settings component in order to specify the density of the 3D printed model. While this method closely aligns with conventional functionalities of standard slicing software, its integration within the Rhinoceros and Grasshopper environments offers a notable convenience.

A distinct feature of the Caterpillar plugin is the ability to slice 3D models using curved planes or surfaces. This feature is specifically designed to generate toolpaths that can be printed onto pre-existing objects or surfaces, allowing them to conform to the substrate's topology. In this workflow, users provide both a 3D model of the substrate object and the 3D model to be printed, ensuring that the two models intersect. The software then uses the intersecting profile to define the topology of the 3D printing toolpath. Moreover, the infill settings component includes a boolean switch that enables the users to choose between planar and non-planar slicing. When non-planar slicing is selected, the infill pattern is generated in alignment with the non-planar toolpath cross sections, resulting in conformal infill patterns. This method expands creative possibilities, allowing users to print onto pre-existing objects by first 3D modelling or 3D scanning them, then generating toolpaths for 3D printing directly onto the objects. It is important to note that accurate placement of the object onto the 3D printer's build-plate is crucial for accurate printing and surface adhesion.

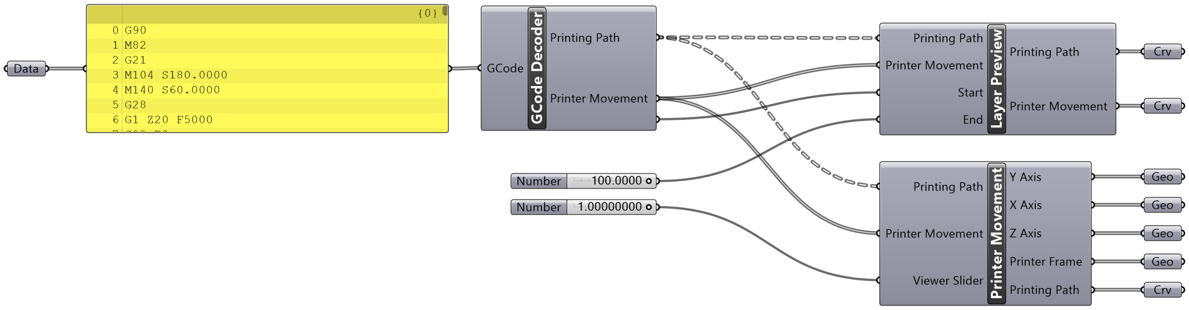
To prevent collisions during the 3D printing process, the curved slicing component calculates the highest point of the substrate model and establishes a clearance distance at the beginning and end of the 3D printing process. Despite this precaution, collisions between the 3D printer's nozzle and the base object may still occur, primarily when dealing with complex base geometries. To address this, *Caterpillar* includes a visualization component that enables users to preview the printing process and simulate potential collisions that may occur during printing.

The most flexible toolpath generation method in *Caterpillar* allows users to define their own custom toolpaths, offering considerable flexibility. Users can import curves or a series of points to represent the printed toolpath that the 3D printer will trace. Notably, the imported curves are not restricted to being planar or arranged from bottom to top. Unlike conventional slicing software workflows, the imported data is not organized based on height or spatial positioning relative to the build-plate. Instead, users are required to import the toolpath data in their preferred sequence and orientation, taking into consideration the directionality of the imported geometry. This approach provides users with complete freedom to design unconventional toolpaths and explore innovative printing techniques.

Curves to G-CODE

When curves are imported to the *Caterpillar* G-CODE converter, they are segmented into a series of points by the software. This segmentation takes into consideration the curvature degrees of the imported curves; areas with higher curvature receive a denser distribution of points, while straight sections contain fewer points. This approach preserves the resolution of the original curve while reducing the amount of points and file size.

Lines of G-CODE include X, Y, and Z values that represent the spatial coordinates in movement commands, as illustrated in **Fig. 4.1**. These values correspond to the coordinates of the points derived from the imported curves. Additionally, the same G-CODE lines include values of extrusion and speed, represented with the letters 'E' and 'F', followed by a numerical value representing the amount of each. The extrusion value is calculated based on various platform settings that include layer height, filament diameter, extrusion width, and extrusion multiplier. The calculated extrusion value indicates the amount of extruded material from one point to the next. The method of calculating the extrusion value is detailed in the formula presented in **Fig. 4.2**. Once the X, Y, Z, and E values are present, a speed variable (F) is gathered from the speed input parameter in the platform settings component and is applied to every line of G-CODE.



```
{0}
0 G90
1 M82
2 G21
3 M104 S180.0000
4 M140 S60.0000
5 G28
6 G1 Z20 F5000
```

Figure 4.5: The G-CODE decoder component offered by caterpillar enables users to convert any G-CODE file back into curves.

For a G-CODE file to be executed by a 3D printer, a series of commands must by inserted into the beginning and the end of the file. These lines of G-CODE are commonly referred to as *start* and *end* commands. These commands are platform specific, and may vary across different machine types. Starting commands often include instructions for initializing the 3D printer, such as homing all axes, preheating the extruder and build-plate, and activating the cooling fans. End commands perform functions that conclude the 3D printing process, ensuring that once the 3D printing process is completed, and movement commands are executed, the extruder returns back to its home position. End commands also include instructions for deactivating the heaters and fans, bringing them back to their default state. **Fig. 4.1** illustrates an example of a typical G-CODE file that contains start commands, movement commands, and end commands, and is ready to be executed by the 3D printer.

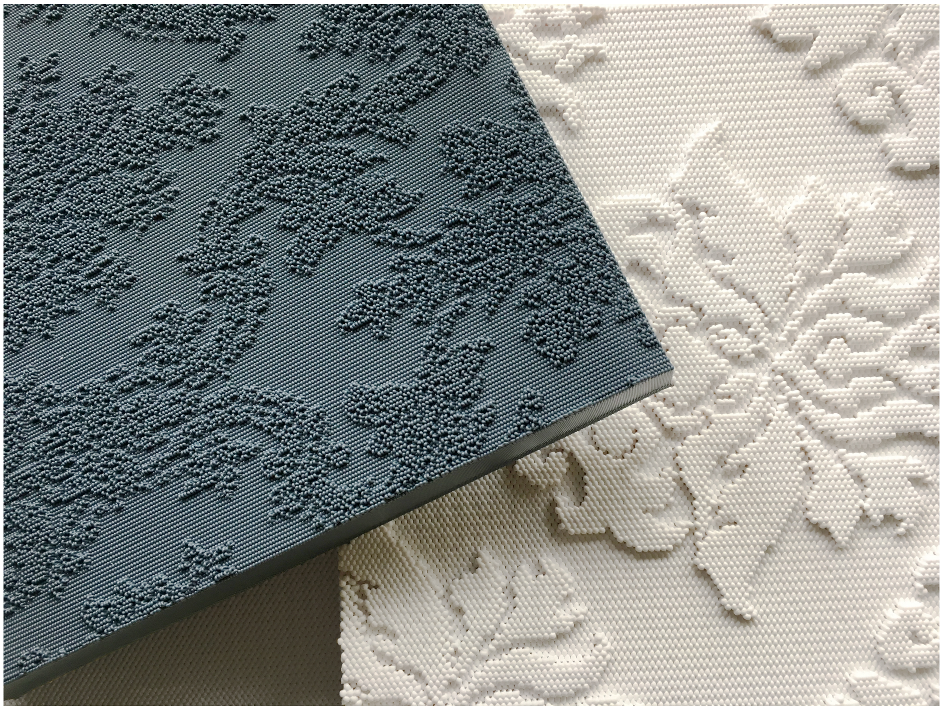


Figure 4.6: Textural expressions in 3D printed plastic achieved through the Caterpillar plugin [237].

Extra Features

The *Caterpillar* plugin also incorporates features that enhance user experience. A notable addition is a visualization component, interpreting the user-defined settings and the generated G-CODE file to simulate the 3D printing process. This simulation is controlled by the user through a slider, that allows the user to visualize the entire printing process. The plugin also includes a *G-CODE Decoder* component. This tool is designed to reverse-convert G-CODE files back into curve geometry and serves multiple purposes. For instance, it allows for the analysis of the generated G-CODE files, identifying potential errors before the files are sent to the 3D printer. It also allows for the adaptation of the same G-CODE file for use with different printing platforms, ensuring compatibility with the platform settings.

4.3 Potterware

Overview

In an effort to democratize non-conventional 3D printing and designing 3D printable toolpaths, Potterware is a software application, developed by Emerging Objects, that specifically targets users without extensive modeling and computational design skills, allowing them to produce objects with high geometric and textural complexity.

CAD software often involve a learning curve, particularly for modeling complex designs and textures. Modeled objects must meet certain characteristics and tolerances in order to be 3D printable. In contrast, Potterware is accessible to a broad audience, catering to enthusiasts who may not possess any prior modeling experience. The application's user-friendly interface is equipped with parametric sliders that simplify the design process, allowing users to create hundreds of printable designs within minutes **(Fig. 4.7)**.

Potterware aims to transcend traditional 3D CAD software and the conventional approach to 3D modeling and printing. It allows users to redefine the boundaries of printed objects, creating novel expressions in 3D printed clay. This innovation is rooted in the unique characteristics of the material's plasticity, responsiveness to gravity and machine parameters. Clay's forgiving nature makes it an ideal material for experimentation, as it can be easily recycled and reused.

The software also enables a seamless transition to various CAD tools and 3D printing platforms. Users of Potterware are able to export their designed artifacts in various file formats. Moreover, the geometry created in Potterware can be downloaded as G-CODE files that are compatible with a broad range of commonly-used ceramic 3D printers. This compatibility significantly simplifies the process of moving from design to production.

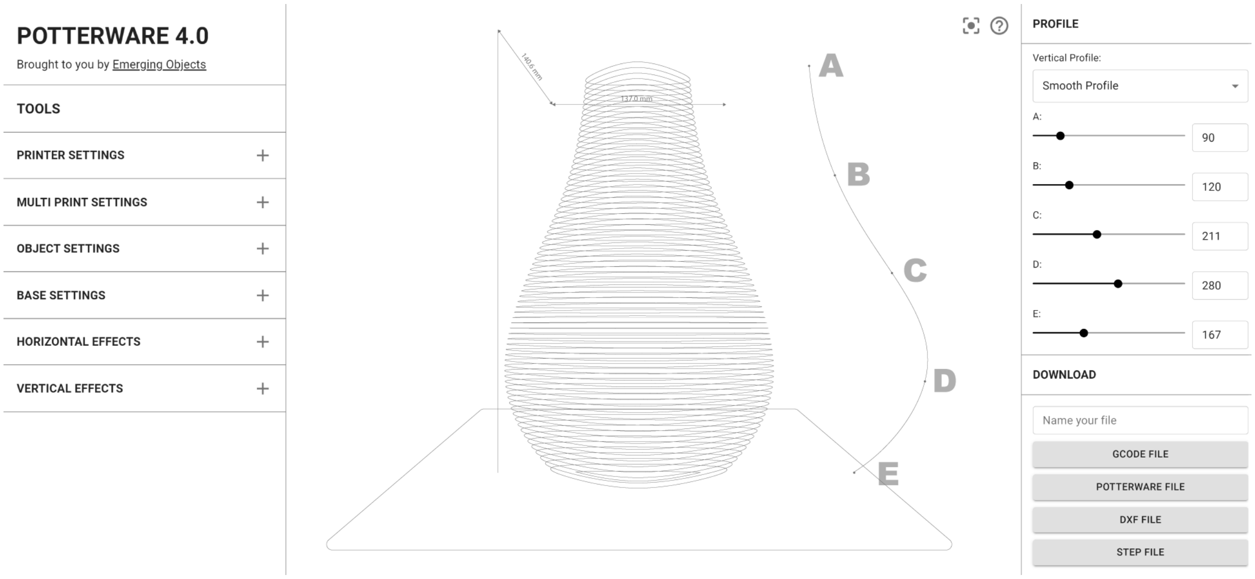
Potterware was developed alongside a team of designers and researchers, under the supervision of Professor Ronald Rael, at Emerging Objects [212]. A detailed list of contributors for the Potterware project is available in the credits section of this thesis for further reference.

Settings and Platform Compatibility

Potterware demonstrates broad compatibility across a wide range of common ceramic 3D printers in the market. The software enables users to select their specific 3D printer model from a list of pre-configured settings. Selecting the type of 3D printer to use ensures that printing parameters such as printing speed, material extrusion amount, build-plate dimensions, and format of the exported G-CODE are compatible with the user's platform.

Different 3D printing platform structures operate under several types of coordinate systems. For instance, polar 3D printers such the 3D Potter SCARA and the Delta WASP [111] [234] [310], typically locate the origin of the coordinate system at the center of the build plate. In contrast, Cartesian 3D printers such as the Lutum 3D or the 3D Potter 10 Pro locate the printer's origin at one of the build-plate's corners. The location of the origin is an important factor in the way the G-CODE is structured for every platform. Incorrectly selecting the printer settings in Potterware can lead to printing problems such as under-extrusion, or over-extension of the 3D printer's axes.

The extrusion mechanisms in various types of clay 3D printers can differ significantly. Some clay 3D printers use compressed-air extrusion systems utilizing wet clay bodies [171] while others rely on direct motorized extrusion [234]. These variations in the extrusion mechanism directly influence the quantity of clay extruded throughout the printing process.



Vertical Profile: Smooth Profile

A: 90

B: 120

C: 211

D: 280

E: 167

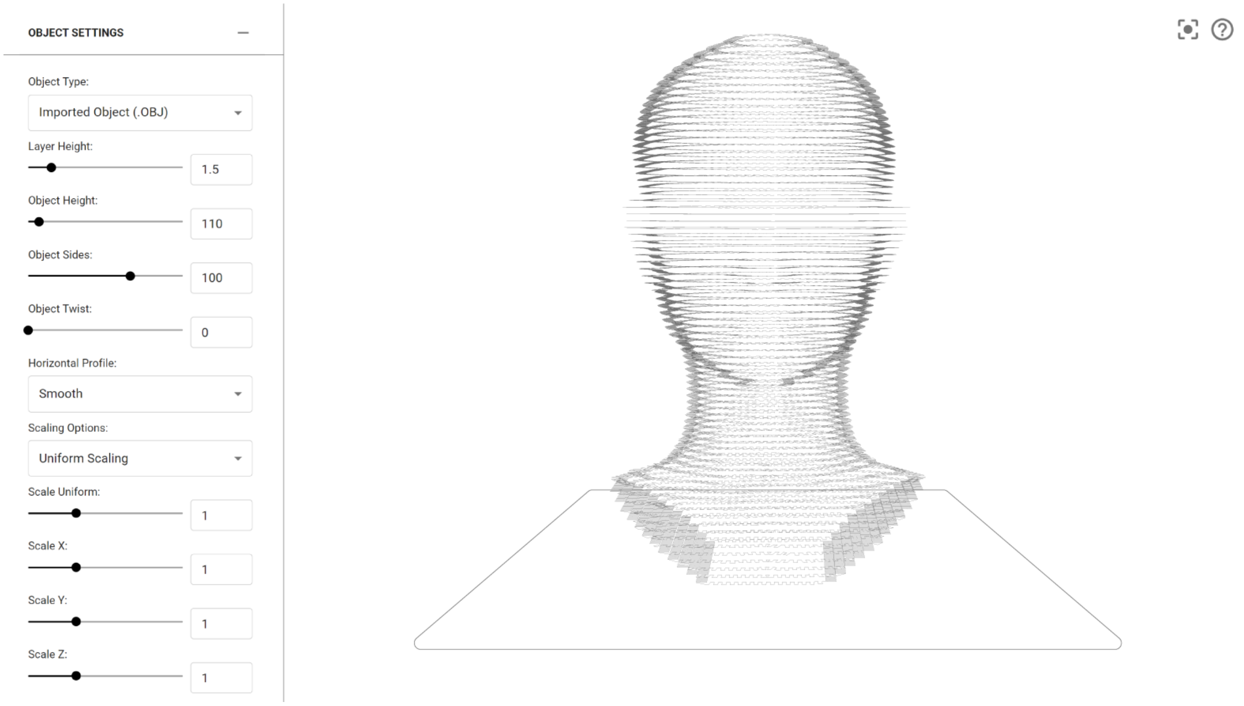
Figure 4.7: The Potterware intuitive interface is designed to cater to non-designers and beginners with limited 3D modeling experience. The interface mainly consists of object profile sliders for shaping the 3D object, a series of tabs for applying effects and textures to the design, and tab to download the final G-CODE [212].

Consequently, this affects the extrusion rate (E value) in the G-CODE, which becomes a critical factor in the printing process, emphasizing the importance of selecting suitable 3D printer parameters. Platform selection also affects the formatting and settings of the G-CODE file. When a particular 3D printer is selected, the starting and ending G-CODE commands are changed to align with the 3D printer's requirements.

Object Geometry

Potterware features two principal approaches to initiating object design. The first approach allows users to import 3D models, created through various 3D modeling software. This approach provides users with a certain level of geometric manipulation through transformative functions and the ability to apply diverse surface textures to the imported model **(Fig. 4.8)**. The second approach uses a Potterware object from which users design cylindrical forms from the ground up. Here, the object's profile is depicted in the form of a curve, whose control points can be manipulated using sliders. Users are also able to choose between an angular or a smooth profile, which affects whether the control points are interpolated either smoothly or through a rigid polyline. The profile curve is an intuitive tool that functions like a hand shaping pottery on a wheel.

Additionally, users are able to specify features such as object height, size, and other ge-



OBJECT SETTINGS

Object Type: Imported Object (.OBJ)

Layer Height: 1.5

Object Height: 110

Object Sides: 100

Object Twist: 0

Horizontal Profile: Smooth

Scaling Options: Uniform Scaling

Scale Uniform: 1

Scale X: 1

Scale Y: 1

Scale Z: 1

Figure 4.8: Potterware users can import any mesh geometry and utilize the software's full range of features to modify the 3D model [212].

ometric characteristics. Regardless of the chosen approach, objects can also be manipulated through various other features offered by Potterware, including twisting commands, and the use of images as bump maps on the object's surface.

Textures and Effects

In Potterware, users are able to apply horizontal or vertical effects, which are considered design tools that can produce a formal or textural expressions onto the designed object. Horizontal effects modify the object toolpath along the X and Y axes, introducing intrusions, extrusions, or bumps on the initially smooth cross-sections as shown in **Fig. 4.9 (c)**. This manipulation is achieved by selecting a mathematical wave type from a preset library. Applying a horizontal effect transforms each layer to conform to the selected wave profile, resulting in a textured surface. Users have the ability to further manipulate these effects by adjusting parameters like wave amplitude (determining the extent of extrusion from the object's body), the frequency of the wave, and the wave's repetition pattern. Moreover, users can apply global transformation effects such as incrementally rotating every layer and designating specific areas on the object for the effects to occur, enabling the creation of targeted gradients.

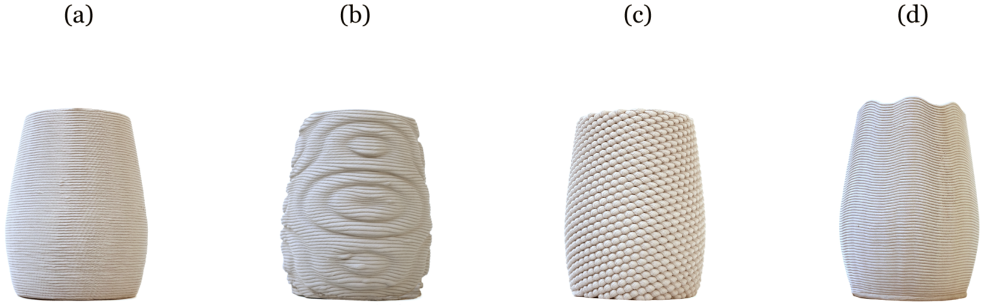


Figure 4.9: Demonstration of the various Potterware effects that can be applied to objects. (a) original geometry, (b) image-based bump maps, (c) horizontal effects, and (d) horizontal effects.

Vertical effects use a similar approach of selecting wave types from a preset library but extend beyond texturing to influence the off-plane movement of the 3D printer **(Fig. 4.9 (d)**. Here, users can define upper and lower profiles, allowing layers to gradually morph between a starting and ending curve. This feature enables users to create non-planar toolpaths at specific sections of the object. However, careful attention is required when adjusting the amplitude of the vertical effects. Excessively increasing the amplitude may lead to nozzle and toolpath collisions or result in compressed layers if the specified layer height is low.

Exporting G-CODE

Upon finalizing the design of the Potterware object, users must download the G-CODE file in order to execute the designed toolpath. Potterware facilitates this by offering several formats for downloading the toolpath file. The first is G-CODE format, which is tailored to align with the specific 3D printing platform selected by the user in the settings tab. By selecting the 3D printer, the generated G-CODE file will conform to the 3D printer's requirements.

The software also supports exporting files in STEP or DXF file formats. These formats contain the designed toolpath in the form of curves, and is compatible with various CAD software. This level of flexibility ensures that users can seamlessly integrate their designs into different software and hardware systems.

Conclusion

Potterware is an innovative application that empowers users, regardless of their prior experience in 3D modeling or 3D printing software. It simplifies the process of creating complex geometric objects to slider adjustments through an intuitive platform interface. The software offers users the opportunity to effortlessly explore advanced modeling features such as texture mapping, toolpath pattern generation, geometric transformations, and non-planar 3D printing. Such functionalities typically demand a substantial understanding of 3D modeling tools and skills to craft custom G-CODE. With Potterware, these complex features are made accessible, effectively democratizing the process, which significantly lowers the barrier to entry for ceramic 3D printing, and, most importantly, opens up new creative possibilities.

Chapter 5

Conformal 3D Printing using Bending-Active Formwork

5.1 Overview

Emerging large-scale 3D printing technologies have demonstrated great potential for reducing the carbon footprint in building environments. Nevertheless, challenges remain with the use of thick and cementitious materials such as concrete and adobe. Layered Manufacturing (LM) techniques are not efficient for constructing curved forms, as they produce a stair-stepping effect that is visible in large scales and can affect the surface quality and mechanical properties of the 3D printed geometry. LM workflows also cannot handle unsupported parts such as overhangs and bridging structures. In contrast, constructing long spanning or curved forms requires substantial amounts of formwork, creating significant waste. Over the years, strategies for formwork reduction have been sought, and recent studies reveal the feasibility of constructing thin concrete shells using elastic formwork made of prestressed textiles and cable nets [304][231]. This approach enables the creation of double-curved tensile structures onto which concrete can be sprayed or manually applied. By altering support conditions, these tensile structures are transformed into compression shells. A notable key limitation of this process is the requirement of extremely stiff edge beams. The process is also constrained to designing *anticlastic* forms.

This study proposes using a bending-active formwork as a material-efficient substrate for conformal 3D printing. This pioneering method exploits the advantages of bending-active structures, enabling the simple fabrication of structurally advantageous curved geometries. The research focuses on adapting the 3D printing process to construct wide-spanning roof structures like vaulted ceilings, domes, and freeform shells using planar components. The advantage of this method is that the 3D printed layers can directly follow the curved substrate geometry, which acts as a lightweight and load-bearing auxiliary structure. This method can dramatically reduce fabrication complexity and material waste, as the bending-active formwork enables printing over long spans with very little extruded material. This method also significantly reduces the amount of support materials required to achieve multi-axis curvature using viscous and cementitious materials.

To conform to the curved formwork, multi-axis robotic extrusion must be integrated into the 3D printing process to ensure the precise and even deposition of materials onto the bending-active formwork. The innovation in this context extends beyond material development for construction 3D printing. It includes the strategic integration of robotic fabrication and the efficient use of formwork elements. This unique design approach takes advantage of the high elasticity of these materials, forming a robust structure by precisely bending and interlinking multiple strips together. Additionally, this study introduces a groundbreaking concept in which the bending-active structure serves as both lost formwork and external reinforcement, increasing the tensile strength of the concrete structure and resulting in thinner and more resilient designs.

This chapter discusses prior uses of bending-active structures and examines their potential application as reusable or lost formwork. The chapter also presents a series of thoughtful experiments and outlines specific challenges related to formwork registration, toolpath generation, and robotic fabrication of full-scale prototypes. The key challenges in adapting additive manufacturing processes to formwork geometry, both in terms of hardware and software, are discussed in detail.

The chapter concludes with a summary of the main findings and presents an outlook on possible future research directions. The potential impact of this novel methodology includes significant material savings in wide-spanning and roof structures and floor slabs – a critical area of research for reducing CO_2 emissions and material waste. By introducing innovative solutions for the challenges of architectural-scale 3D printing, this chapter contributes to advancing the capabilities and opportunities of this emerging technology within the construction sector and aligning with the critical goal of reducing embodied carbon in the built environment.

5.2 Introduction

Concrete, the most widely used construction material on the globe, is valued for its structural capabilities, affordability, availability, and longevity. One of concrete's key advantages is also its malleability during its liquid state, being castable into almost any geometric form. However, the construction of concrete formwork is labor intensive, expensive, and generates large amounts of waste. Moreover, formwork costs increase dramatically during the construction of curved forms that deviate from standard, rectilinear volumes. Awareness has also grown regarding the negative effects of cement production on the environment, including the substantial CO_2 emissions and water consumption associated with producing concrete in mass quantities.

As the global demand for housing increases, construction continues uninterrupted, employing conventional construction processes that are slow, expensive, and wasteful. Considering the urgency of the issue, a comprehensive approach to construction is required that

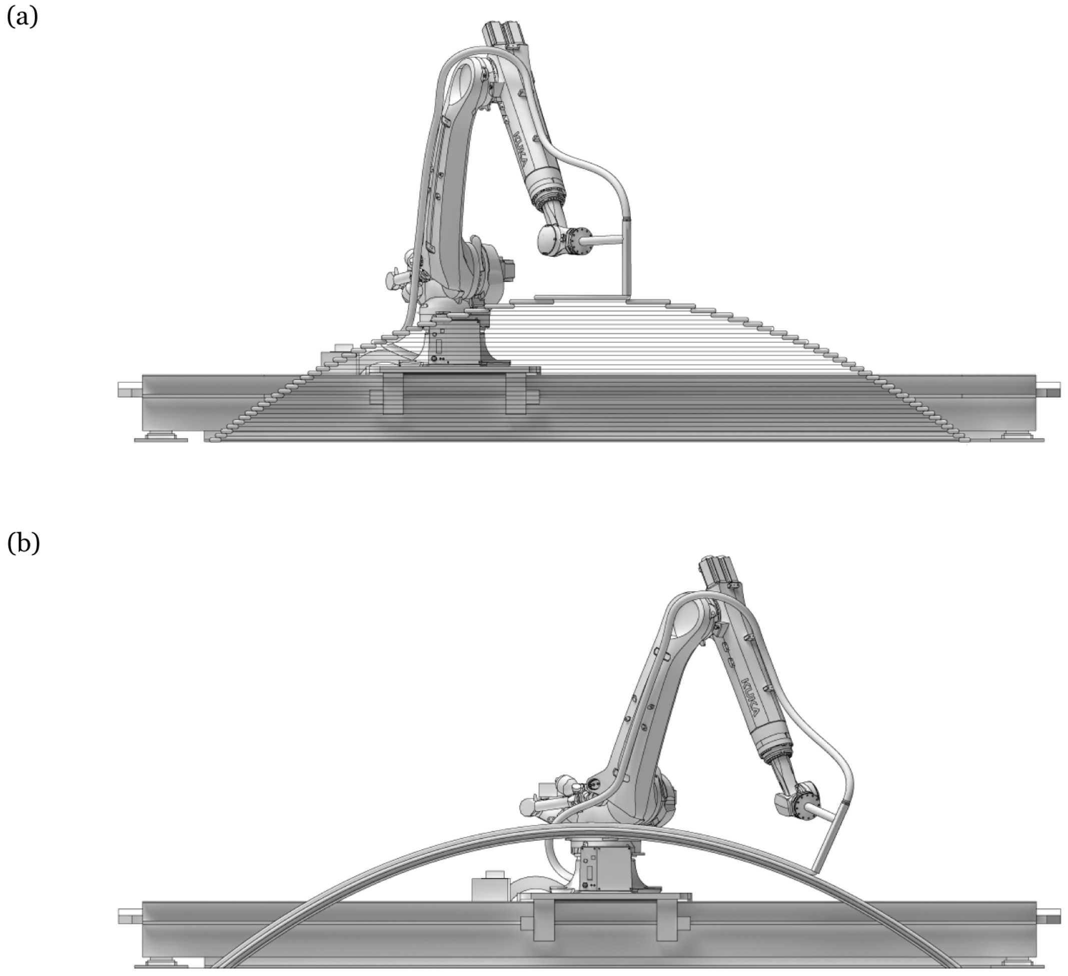


Figure 5.1: Printing curved geometries with planar 3D printing (a) requires excessive support material and results in a staircase effect. In comparison, conformal 3D printing on a bending-active formwork (b) can dramatically reduce material consumption, but requires a multi-axis printing platform to align the nozzle normal to the base geometry.

goes beyond enhancing concrete's sustainability; developing low-cement mixtures or bio-based concretes is not enough to deal with the problem. Instead, an effort to rethink how buildings are designed, materialized, and constructed is required.

For research purposes, addressing the problem of sustainable concrete construction from a structural perspective involves acknowledging that concrete building elements are often not material efficient. Some structures made of concrete material are not geometrically efficient; many are bulkier than they need to be. In other instances, concrete is simply used for architectural applications where other materials would have been lighter, cheaper and, in most cases, more sustainable. This inefficiency is largely due to the standardization of formwork and the conventional geometries often employed in the construction of concrete structures such as slabs, walls, columns, and mass foundations.

An effective method for reducing material usage, is the adoption of compression-dominant structures such as domes, vaults, shells, and gridshells, made from masonry and timber. These three-dimensional forms are capable of spanning distances comparable to, or even higher than those covered by bending-dominant plate structures, while significantly reducing material consumption. Notable examples include the highly efficient thin-shell structures designed by architects and engineers such as Heinz Isler, Felix Candela, and Eduardo Torroja [148] [54][297][45] [232]. However, the construction of these structures necessitates a considerable amount of formwork and falsework, requiring extensive labor. These lightweight concrete structures were primarily constructed in the period between the 1950s and 1970s, when labor costs were relatively low. Since that time, the adoption of this approach has almost halted due to the rise in labor and material costs, and as a result of the growing awareness of material consumption. Recently, however, interest in such construction methods has resurged, utilizing computational technology to enable intricate freeform design through fabrication approaches that are efficient, demonstrated by architects and designers such as Zaha Hadid, and the Block Research Group [231].

This trend coincides with advancements in generative and digital fabrication technologies, including 3D printing of concrete, adobe, and clay. Depositing materials only where required increases efficiency and reduces waste. Some of the most recent large-scale implementations, including 3D printed walls and hollow bridge components, have showcased the potential for constructing lightweight concrete structures. However, most of these projects primarily utilized layered manufacturing and the vertical construction of small to medium-scale components. While these approaches are steps in the right direction, challenges remain for overhanging and long-spanning structures such as shells, and gridshells. The primary difficulty in building these shapes arises from the need for a substantial amount of supporting structures during the 3D printing process.

Large-scale 3D printing is emerging as a significant innovation in the field of automated construction and offers a vital pathway towards minimizing CO_2 emissions. The technology represents a method, capable of lessening environmental concerns in the construction sector. Large-scale 3D printing also streamlines the constructing process by reducing construction time, reliance on high labor costs, and energy intensive construction techniques. To further contribute to lowering carbon emissions, the process also takes advantage of materials such as low-cement concrete or concrete made from recycled construction waste.

5.3 Motivation

The integration of bending-active structures in the development of lightweight roofing systems through robotic 3D printing represents a logical and efficient approach, taking advantage of the simple construction process of bending-active structures. Characterized by their simplicity in construction, initially planar strips or plates are elastically bent and fixed together, forming curved forms. Such a structure is robust enough to support the weight of 3D printed concrete layers, enabling the construction of efficient compressive shells.

Traditional formwork structures are generally rigid and heavy, designed to precisely shape the final product. In contrast, the use of lightweight, flexible formwork can deform under heavy loads, which is a crucial factor to consider during the printing process. Therefore, the application of concrete onto the formwork requires careful placement so as to evenly distribute the weight across the formwork geometry. These considerations require the development of new design tools and printing processes that can address the unique challenges of 3D printing onto flexible formwork.

The question of whether to use the bending-active structure as a reusable formwork or a stay-in-place formwork remains open. Using it as reusable formwork offers the advantage of constructing the support structure only once, leading to economic advantages in the construction of multiple identical roof structures. On the other hand, using the bending-active structure as permanent formwork could foster synergy between the two materials, potentially forming a hybrid material. For example, coupling bending-active *Carbon Fiber Reinforced Polymer (CFRP)* strips with overlying 3D printed concrete layers could form a highly effective hybrid shell, where the formwork serves as structural reinforcement. This approach would amalgamate the compressive strength of concrete and the tensile strength of CFRP. However, this construction method and its application in the design of wide-spanning roof structures is only in its infancy, and requires further exploration.

5.4 Proposed Fabrication Method

This research responds to the above-mentioned limitations by presenting a method for printing lightweight curved roof structures that span long distances, yet does not require immense amounts of formwork. The proposed method of 3D printing onto bending-active formwork could potentially be applied in pre-fabrication construction processes, where modular structures are printed off-site, and subsequently transported and assembled, as shown in **Fig. 5.2 (b)**. This approach takes advantage of regulated factory environments, where the formwork can be accurately measured for even material placement. Additionally, the workflow has the potential to adapt to on-site 3D printing workflows, taking advantage of the ease of assembly, and the reduced material amount and cost **(Fig. 5.2 (a))**. Both ap-

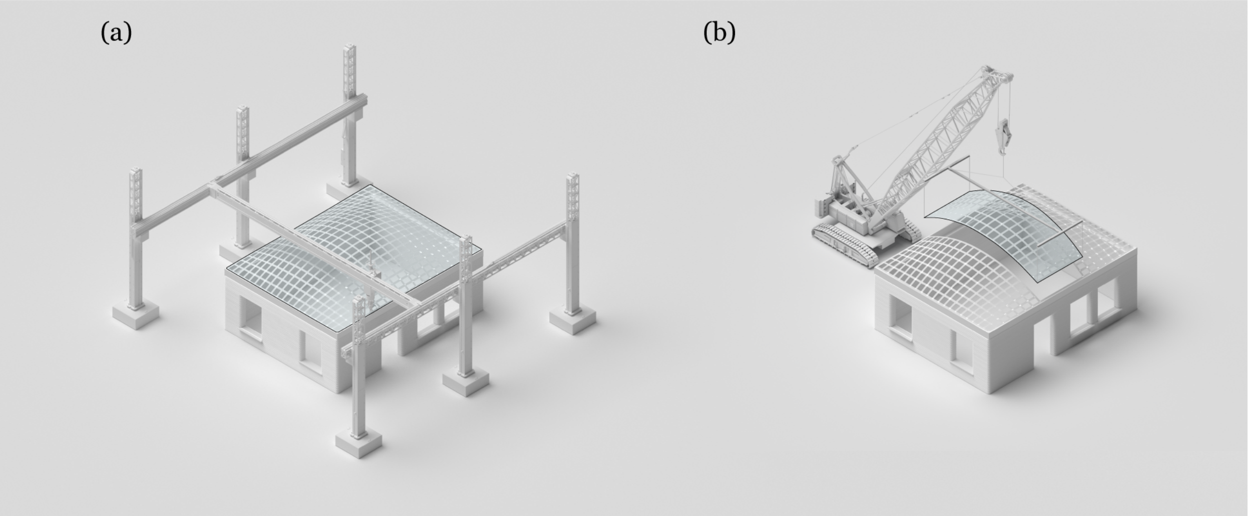


Figure 5.2: Vision for a new construction process of wide-spanning roof structures. (a) 3D printing onto a gridshell formwork structure directly on the construction site. (b) The gridshell formwork being prefabricated and printed on off-site and then lifted onto the 3D printed building walls by a crane.

proaches share common challenges such as formwork registration and accuracy, structural integrity, and workflow optimization. To provide a more detailed understanding of the proposed approach, this section provides an in-depth understanding of the two core components that make up the proposed method: *bending-active formwork*, and *conformal 3D printing*.

Bending-active Formwork

Bending-active structures are defined by Lienhard et al. (2014) as structural systems that use curved beam or shell elements which initially are in a straight or planar configuration and achieve their geometry through elastic deformation [165] [146] [166] [267] [155]. Recent work has successfully demonstrated the value of bending-active structures in various architectural applications ranging from pavilions to kinetic facades [166] [269] [155] [44]. Bending-active structures can offer a cost-efficient alternative to conventional construction methods, particularly when manufacturing curved geometries. The idea of using an elastically bent structure as formwork is not entirely new; it has been applied before, for example in the context of minimal scaffolds for masonry [138]. Recent research has investigated the interesting phenomenon that bending-active structures, although built of highly flexible materials, can sometimes support loads much greater than their own weight. For example, Cuvillier et al., used a combination of textile and bending-active formwork to cast a concrete shell [63]. Here, the concrete layer served as a bracing system for the lost bending-active formwork. Schleicher and Herrmann [268] pushed this idea further, designing a hybrid gridshell with a bending-active formwork made of 1.2 mm thin carbon fiber strips supporting a 15 mm thin concrete layer. The resulting hybrid gridshell showed an astonishing resistance and was able to withstand a vertical load of 5.6 kN. Perhaps the most interesting finding of this study, however, was the observation that when concrete was applied sequentially to the formwork, in this case one strip at a time, the concrete layers applied first had time to cure and bond with the formwork and helped strengthen it, allowing the formwork to carry more load as more material was applied. Although this project was built entirely by hand, this observation is particularly interesting for the concept of 3D printing on bending-active formwork proposed here, as the material can be placed in a more targeted manner and the print path design provides more control over how much material is applied where and when.

Conformal 3D Printing

As discussed in **Chapter 2**, *Conformal 3D printing* refers to a method of non-planar 3D printing in which materials are placed onto a freeform surface or substrate [16]. This approach has the potential to 3D print materials onto non-planar formwork and supporting structures, enabling wide-spanning and overhanging structural forms. This study proposes the use of *bending-active* structures that not only reduce the amount of material used, but are adaptable to different curvature degrees, possibly achieving a variety of geometric properties.

3D printing onto bending-active formwork can significantly reduce the amount of support material required to achieve multi-axis curvature using viscous and cementitious materials. The proposed method requires the use of a 6-axis industrial robotic arm, capable of orienting the extrusion nozzle along the normals of the surface or substrate **(Fig. 5.1 (b))**. In contrast to conventional methods that print in planar layers, toolpaths in conformal 3D printing workflows are mainly determined by the complexity and base surface topology that changes as the robotic platform travels along the surface thrust lines while maintaining a fixed offset distance. The success of the method can then be evaluated according to the accuracy of the material distribution onto the freeform surface [16].

On a technical level, conformal 3D printing comes with a number of challenges that make successful application of this method more complicated. For a start, it is necessary to have precise knowledge of the target surface, not only the basic geometry used for the digital design of the formwork, but also its exact dimensions after assembly and construction. Second, the 3D printer must be able to reach all locations on the formwork, which can be achieved either by using a larger platform or by integrating additional axes of motion. Finally, the extruder must ideally be kept perpendicular to the curved surface of the formwork during the printing process to ensure optimal print quality.

5.5 Comparative Case Studies

Non-planar 3D printing methods are often not supported by conventional 3D printing software solutions, specifically in terms of non-planar slicing and path generation, and therefore,

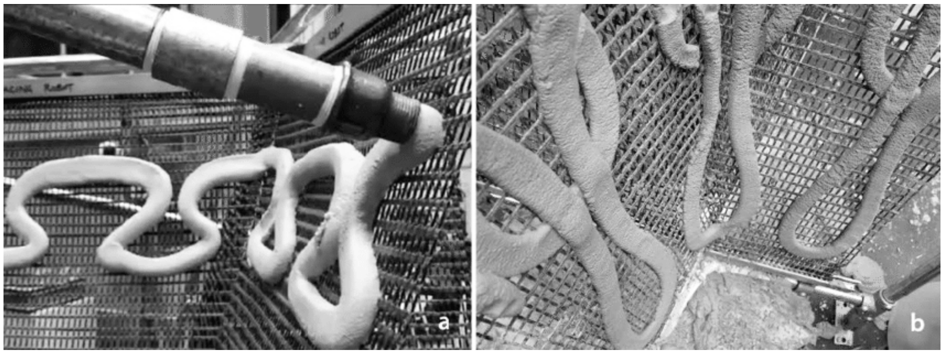


Figure 5.3: Sparse Concrete Reinforcement in Meshworks. Robotic 3D printing onto non-planar mesh formwork [25].

demand more complex toolpath generation techniques [324]. In this process, it is important to take into consideration not only the 3D printed object itself, but also the surface or substrate onto which the object is being printed. In order to ensure precise 3D printing and exact alignment of the formwork with the robotic platform executing the 3D printing task, the formwork needs to be accurately registered. Various methods can be employed for formwork registration, including reference point registration, constructing the substrate formwork using the same robotic platform, or digitally modeling the built formwork using 3D scanners or other techniques to digitize the physical formwork. Consequently, this area of research demands the development of versatile tools that are capable of accommodating a wide range of geometric features. This section presents different approaches to conformal 3D printing, with a focus on their processes, as well as an examination of some of their advantages and disadvantages.

Sparse Concrete Reinforcement in Meshworks

Ayres et al. presented a novel construction method of robotic conformal 3D printing named *Sparse Concrete Reinforcement In Meshwork*s (SCRIM) [25]. The hybrid method integrates conformal robotic concrete 3D printing with supportive mesh structures to produce complex lightweight concrete structures, as shown in **Fig. 5.3**. The base mesh also acts as a reinforcement material, merging aspects of fabric formwork with tailored reinforcement techniques. SCRIM is comparable to other techniques that use stationary reinforcement such as spraying, as presented by Neudecker et al. (2016) or by pouring concrete [209] [259] [118]. However, SCRIM selectively deposits materials with higher precision amounts, providing a higher degree of control over the 3D printed geometry.

The SCRIM method was tested in two experiments. The first experiment used a carbon fiber reinforced polymer textile to construct curved structures in the form of a tapered half cone and a curved quarter pipe. Two mesh types were tested varying in size according to the spaces between the metal wires. The mesh was tied to a timber surface to support it and hold it in shape. The aim of the experiment was to test the viability of the method and obtain a better understanding of its limitations. Concrete was applied to the mesh using an industrial robotic arm and a concrete pump, extruding concrete through a 40mm nozzle. During the experiment, concrete fell through the large-spaced mesh structure in areas with increased curvature, indicating that the concrete was not able to resist the bending moment and shear stresses in the wider-spaced mesh cells. Some of the challenges pertaining to material instability can be approached through adjustments in the material mixture. A stiffer mixture with fiber reinforcement may provide more material stability, but may also cause cracking and tearing in the extrusion. On the other hand, the experiment using a tighter mesh provided better support for the extruded concrete. However, irregularities during the assembly of the tight mesh caused mismatching to the digital model, indicating that the process requires additional tools for position calibration and translation between the digital and physical models. Despite the imprecision of the calibrated physical formwork, the SCRIM method has shown that printing on curved mesh formwork is plausible, even in forms with high curvature conditions.

The second experiment aimed at testing the scalability of the SCRIM method and increasing the spatial complexity of the formwork. Two intersecting vertical mesh walls were constructed in directions perpendicular to one another. Both walls were held using an aluminum frame on the top and bottom edges. The deposition of concrete also was performed using a 6-axis robotic arm in a knit-like, self-intersecting, continuous toolpath pattern. The experiment used higher speeds to counter mesh deflection. However, as more materials were added, the distance between the nozzle and mesh increased as a result of the local deflection under the applied self-weight of the material. The second experiment showed that heavy material deposition may cause deflection, especially in partially supported mesh structures, which in return causes inconsistency in material deposition and adhesion rates. Both experiments demonstrated great potential of the SCRIM method not only in reducing the amount of used formwork, but in providing a viable solution for reinforcement integration, an area that remains one of the key challenges to large-scale 3D printing using viscous materials.

Sub-Additive Manufacturing

Battaglia et al. (2019) at Cornell University also presented a method of conformal 3D printing termed *Sub-additive Manufacturing*, utilizing mechanically shaped granular aggregates as a reusable support structure [28]. The method aims at producing doubly curved arched concrete structures by replacing traditional formwork and falsework with curved granular formwork to reduce 3D printing speed and material use. Sub-additive manufacturing employs principles of land forming to create temporary curved formwork made of granular materials **(Fig. 5.4)**. The molds are made using a CNC gantry which is able to achieve different curved forms in a fraction of the time required in typical mold construction processes.

A series of experiments was conducted to test the viability of the proposed method. First, a gantry platform was used to perform initial tests pertaining to allowable degrees of cur-

Figure 5.4: Conformal 3D printing onto reusable granular formwork [28].

vature, extrusion thicknesses, and layer heights. Single line extrusions were first performed to determine the curvature degree by which the material maintains its stability while being applied to the granular formwork. 1-5mm gravel was used as granular formwork for its course geometry, able to achieve high angles of repose. The experiment showed evidence of shifting in the granular materials as the curvature reached 40 degrees. The verification process was conducted using a LIDAR 3D scanner to compare the accuracy of the digital 3D model with that of the printed material. The initial experiment also proved that the first layer of the deposited concrete material will absorb some of the gravel, providing some stability to the layers.

Battaglia et al. (2019) explains that the method requires the 3D printed concrete to be reinforced, so multiple methods were tested. Although the material used in the experiments contained nylon fibers, it may have not been enough to address layer-to-layer discontinuity. Therefore, the team tested several methods of embedding a flexible steel chain link, mesh, long strand pins, and various fibers to add additional strength. The initial tests showed the feasibility of integrating reinforcement mid-print and post-print.

Once the viability of the proposed process was established, the team tested the method in constructing Arch geometry prototypes of varying toolpath densities and sizes. The gantry-style 3D printer was replaced with a 6-axis robotic arm, achieving additional degrees of freedom, capable of orienting the nozzle to the direction of the conformal extrusion. In contrast to the vertically oriented nozzle used in the gantry-style printer, the robotic arm proved to achieve layer height consistency across the entire prototype.

The proposed method has proven to be advantageous on a multitude of levels. Speed and process efficiency are dramatically increased relative to the complex geometry achieved by the process. Typically, the construction of doubly curved forms requires larger amounts of formwork, which is wasted, whereas the sub-additive method enables formwork re-usability. However, the proposed workflow of using a single platform for reshaping the mold, and the 3D printing of the concrete may be challenging when the method is tested on larger scales. Controlling larger amounts of coarse granular materials in this context can be problematic.

5.6 Research Objectives

Driven by the outlined motivation, based on the proposed fabrication method, and inspired by insightful case studies, the research aims for this first experiment are as follows. The research first, aims to develop a complete method for 3D printing lightweight structures that span long distances, most importantly without being constrained by conventional layered-manufacturing approaches that currently limit large-scale 3D printing to vertical extrusions. In this research, an important objective is to evaluate the feasibility of the proposed method through a multifaceted approach, primarily focusing on physical prototyping across scales. The initial phase centers on understanding the limitations of the method on a smaller, more manageable scale. This entails using materials that closely replicate those employed in larger-scale prototypes, allowing researchers to gauge potential challenges inherent in upscaling the technology. Concurrently, efforts are made to develop a comprehensive workflow to ensure effective application of the proposed method. This includes the creation of software models that simulate the 3D printed forms and their structural capabilities. The development of efficient software and hardware tools for streamlining the toolpath generation process is another key objective of this research. These tools are crucial to ensuring a smooth transition from physical to digital models. Another research objective is to determine the most efficient and reliable method for formwork calibration and localization adaptable to various different geometric forms and auxiliary structure types. In order to achieve desired structural and mechanical specifications, calibration and formwork registration are critical components in ensuring consistent layer deposition. To achieve this objective, the research will investigate different calibration and formwork registration techniques and evaluate their reliability and accuracy.

Project Goals

While the research objectives of this proposal outline a clear direction, they introduce a multifaceted challenge that can only be addressed through the integration of various research domains. This research aims for an interdisciplinary knowledge exchange, bringing together four distinct yet complimentary three areas: geometric and structural design, digital fabrication and robotic construction, and full-scale prototyping and production.

Geometric and Structural Design

Based on the hypothesis that long-span structures can be 3D printed with minimal formwork, three main aspects related to geometric and structural design are investigated. Firstly, the research explores the design possibilities for 3D printed roofs using bending-active formwork, taking into consideration the geometrical, structural, and fabrication-related constraints. Secondly, it analyzes the structural integrity and material efficiency of various formwork configurations and shell geometries. Finally, the research aims to investigate how to scale the proposed method from digital models to smaller-scale prototypes to large structures. To achieve all these objectives, parametric design and structural analysis tools must also be developed.

Digital Fabrication and Robotic Construction

A main goal of this research is to advance the fabrication process of bending-active structures, either as reusable or disposable formwork for concrete 3D printing. This goal involves developing innovative methods for conformal 3D printing onto flexible formwork, using a multi-axis robotic setup. To address these challenges, the research focuses on refining the fabrication method of bending-active structures, improving the assembly and fastening of bent strips to facilitate robotic 3D printing.

Additionally, specialized toolpath design tools must be developed. This involves a custom software approach that accommodates the unique conformal toolpaths dictated by the formwork topology, diverging from standard, horizontal layering techniques. The research also focuses on developing workflows for simplified CAD/CAM data exchange. This involves creating routines that seamlessly convert design data from CAD software into G-CODE that is readable by robotic platforms. This systematic approach enhances the efficiency and accuracy of the overall process.

Prototyping and Full-Scale Production

In the initial phase, the research focuses on fabricating various specimens and partial prototypes to conduct material and structural feasibility studies. The research then shifts to the construction of a full-scale prototype of a hybrid shell, followed by a thorough validation of its structural performance. To realize these goals, small mock-ups are developed using a robotic arm to print on both straight and curved formwork strips. Following these initial tests, the construction of a full-scale technology demonstrator is developed, showcasing the practical application and integration of the research findings.

5.7 Experiments

In order to test the feasibility of the proposed fabrication method, two prototypical experiments are conducted and discussed with respect to key aspects of the experimental setup, toolpath design, formwork registration, and printing process.

A detailed list of contributors for the work presented in this chapter is available in the credits section of the thesis for further reference.

Experiment 1

Experiment Setup

The objective of the first series of experiments is to identify the main challenges and limitations of the proposed fabrication method using very basic curved shapes and printing scenarios. This simplified approach primarily considers the behavior of the bending-active formwork during 3D printing when material is applied and evaluates its ability to support the load of the 3D-printed concrete. For the first test, the formwork was made by bending individual strips into different curvatures, as shown in **Fig 5.5 (a)**. Each strip consists of two layers of 3 mm plywood, measuring 2000 mm in length and 100 mm in width. After bending and mounting the strips to a timber frame, their height at mid-span measures 222 mm, 305 mm and 375 mm. The second test follows the same approach and measurements, except that the formwork consists of three longitudinal strips held together by six transverse strips, as shown in **Fig. 5.5 (b)**. The distance between the longitudinal strips is kept at 10 cm, and all the strips were bolted together after bending to form a curved gridshell. This simplified gridshell is then mounted on a timber frame to keep its supports at a fixed distance from each other. On both types of bending-active formwork, the concrete was 3D printed in two layers, each measuring 15 mm high, with four extrusion passes for each strip. For this purpose, the experimental setup requires a concrete mixer and pumping system, as well as a robotic platform to control the orientation of the nozzle during the printing process. An IMER Small 50 pumping system and a KUKA KR 16-2 were employed in this experiment. The printing material used in this experiment is Sikacrete®-752 3D.

Toolpath Design

The 3D printed toolpath is designed in two phases, first as accurate 3-dimensional curves, using the Rhinoceros and Grasshopper CAD software. The curves are then projected onto a curved surface, which served as a close representation of the constructed strip. After the formwork was accurately registered, a more accurate surface is modeled, onto which the toolpaths are projected. This step ensured precise alignment and surface conformity between the formwork and the print layers.

To determine best material deposition and dimensional accuracy, all strips used in this experiment were divided into four 3D printed passes, taking into account the nozzle width of 20 mm and the width of the strips of 100 mm. To facilitate this, the central isocurve of each strip is automatically offset in both directions. The distance between the print layers is then established by offsetting the projected toolpaths again by a distance corresponding to the extrusion thickness of 30 mm.

Figure 5.5: To test the concept of conformal 3D printing on a bending-active formwork, a series of small-scale experiments were conducted. (a) shows configurations with one strip, while (b) demonstrates a configuration with a grid of multiple strips.

The three-strip formwork presented a number of additional challenges that required special attention. First, the intersecting strips require a modified offsetting and joining procedure to ensure that the printed concrete covers the entire strip surface. The printing sequence in this design started with the printing of the toolpath of the center strip, followed by the successive printing of the adjacent strips from both sides. This approach is chosen to ensure that the weight of the printed concrete is evenly applied across the formwork. Balanced weight distribution reduces the risk of asymmetric loading and local or global buckling.

Formwork Registration

An essential prerequisite for designing toolpaths for conformal 3D printing is the registration of the formwork itself. This step is crucial as it precisely locates the built formwork in 3D space and enables its subsequent digital recreation. To simply perform this registration process in the first set of experiments, a sharp touch probe is screwed to the extrusion nozzle of the robot and moved to several locations on the surface of the formwork where the coordinates of the tool were recorded. These data points are then used to digitally reconstruct the formwork, creating a substrate onto which conformal toolpaths could be projected.

Printing Process

To start the printing process, the required amounts of cement and water were precisely measured and mixed thoroughly. After loading the concrete mixture into the pump, the robotic arm began executing the programmed toolpath. Calibrations for the one-strip and three-strip prototypes proved successful as the distance between the print nozzle and the formwork remained uniform throughout the printing process. This uniformity is reflected in the proper adhesion of the material to the formwork and in the constant width of the print paths and layers. This proved that the digital model exactly matches the actual built formwork.

Discussion

The consistent results of these tests confirmed the procedures for registering the formwork and demonstrated the feasibility of the proposed fabrication method. However, these tests also revealed some difficulties, especially in the manual, labor-intensive preparation phase before printing . The registration process, while effective, is time consuming and involves several steps, especially for formwork designs with multiple crossing members. The complexity of these steps increases rapidly with more sophisticated formwork geometries and strip patterns. Although the manual registration process used has proven to be effective, the experiment has shown that a more efficient and faster alternative is needed to scale this approach. In addition, the computational design approach for generating toolpaths, particularly for intersecting cross-members, calls for further optimization and a streamlined workflow to facilitate conformal 3D printing on a bending-active formwork. Finally, these initial tests motivated further studies that investigated in more detail the structural behavior of the hybrid cross-section and the effects of the strip pattern arrangement on the structural performance of the gridshells [320] [319].

Experiment 2

Experiment Setup

The second experiment builds on the previous results but applies the same method to the fabrication of a full-scale prototype. The objective here is to build a wide-span hybrid gridshell with a length of 4.6 meters and a width of 2 meters. To elevate the gridshell from the ground and facilitate its mobility, it is placed on two EURO-pallets fitted with custom-made bulkheads. These end plates were designed to accommodate the strips of the gridshell and provide structural support during and after the fabrication process. To ensure that these supports do not slip under the weight of the structure, they were connected together with wooden slats as tension members. Since the scale of the second experiment exceeded the capabilities of the robot and pumping equipment used in the first experiment, the research team partnered with the company Print 4D to utilize their facilities located in Prague, Czech Republic. Their setup has the advantage of using a larger industrial robot (KUKA KR 210 R3100) on a longer linear track (KUKA KL 1500/3), which significantly increases the reach of the 3D printing platform and ensures that the concrete can be applied at every location on the surface of the gridshell, as shown in **Fig. 5.6 (a)**, and **Fig. 5.6 (b)**. In comparison, the pumping system was also significantly upgraded to a MAI Multimix 3D concrete pump, which allowed for automatic mixing and continuous printing of very uniform concrete mixtures

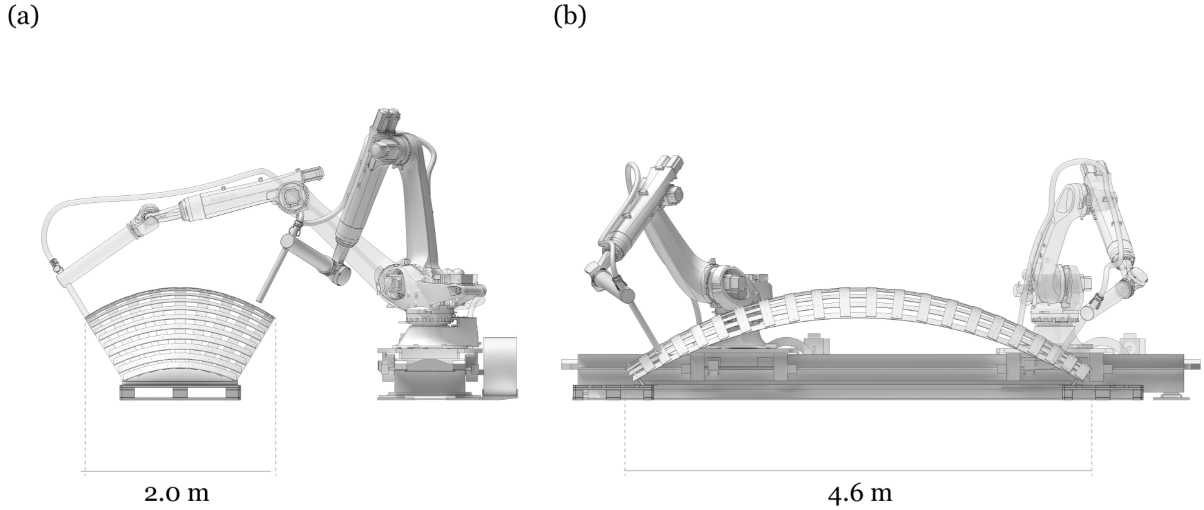


Figure 5.6: To ensure the reachability of the printing platform at all locations and to align the nozzle normal to the bending-active formwork, the team opted for a 6-axis industrial robot standing on a linear motion track that gives the system a 7th axis.

(Sikacrete®-752 3D). Aside from being fully automated, this pumping system is tailored for longer-running 3D printing workflows and provides the reliability needed for large-scale printing operations.

The bending-active formwork in this test consists of nine longitudinal strips and 22 transverse strips. The longitudinal strips were made of 100 mm wide and 15 mm thin spruce boards and the transverse strips were made of 100 mm wide and 6 mm thin plywood strips. The gridshell is held together by 198 M6 bolts.

Toolpath Design

To efficiently design toolpaths for complex gridshell and full-scale prototypes, which by their nature have an increased number of intersecting strips, a computational method for toolpath generation was developed. Here, user-defined skeleton graphs derived from the center isocurves of each strip are used as the basis for constructing toolpaths through offsets and layering, as shown in **Fig. 5.8**. Once the skeleton graph is defined, the user can specify the number of printing passes on the strip as well as the distance between the toolpath curves. All curves are then automatically connected to form continuous toolpaths, resolving any problems with overlaps or intersections. This process greatly simplifies toolpath design and the definition of the print sequence, enabling rapid adjustments and real-time visualization of complex, overlapping toolpath curves through an intuitive design framework.

Figure 5.7: The finished bending-active formwork was made of 9 longitudinal and 22 transverse timber strips and fitted with fiducial markers to facilitate registration of the exact formwork geometry.

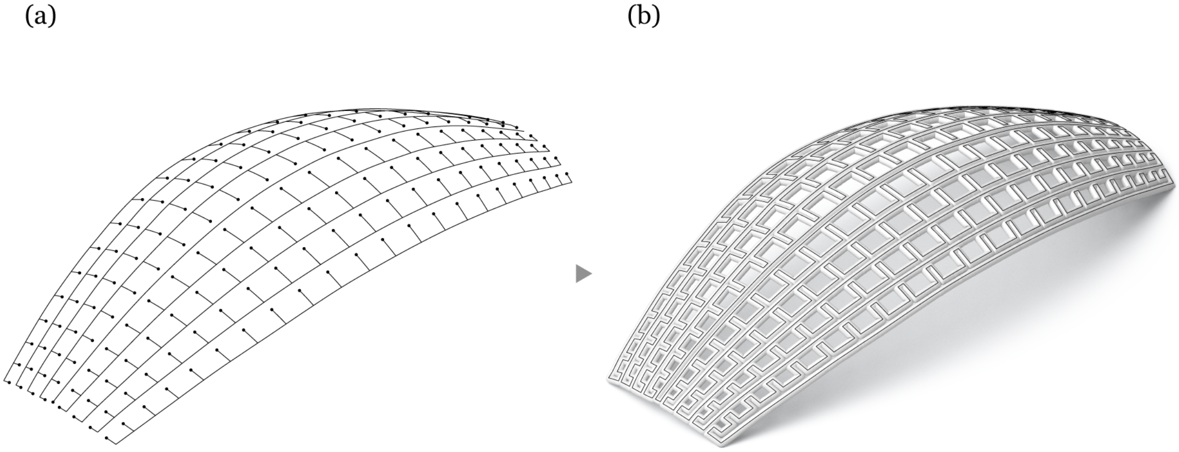


Figure 5.8: (a) Using a skeletal graph containing isocurves from each strip as input for toolpath design. (b) Conversion of the graph into a multi-layer toolpath with user-defined widths, and simultaneously resolving intersecting members.

Formwork Registration

Given the challenges in upscaling the workflow used in the first experiment, this experiment explored two alternative methods for formwork registration that proved to be more time efficient. The first utilizes high-resolution 3D scanning, while the other employs visual positioning using *fiducial ArUco markers*. Both methods aim to speed up the process while maintaining the accuracy required to match the geometry of the formwork during conformal 3D printing. The advantages and limitations of each method are discussed in more detail below.

3D Scanning

The first method for formwork registration used an EinScan HX handheld 3D scanner that combines blue LED light with a blue laser. With this hybrid configuration, the 3D scanner delivers reliable results even when scanning reflective surfaces or under poor ambient light conditions. Its compact size and portability make it especially suitable for scanning large objects. To improve the alignment capabilities of the 3D scanner, reflective tracking markers were glued to various areas of the formwork surface before starting the scanning process. Scanning of the built formwork is required to create an accurate digital model that can be used as a substrate for projecting the toolpaths onto the geometry of the actually built formwork. Omitting this step can lead to an uncontrolled offset between the formwork and the toolpath, resulting in significant printing imperfections. To capture the actual shape of the formwork, the scanner was moved over it manually and its geometry is registered as a point cloud, as shown in **Fig. 5.9 (a)**. The collected data was then converted into a mesh model suitable for toolpath projection **(Fig. 5.9 (b) (c))**. The resulting 3D scan has proven to be exceptionally accurate, capturing even small details such as the fasteners that hold the strips together. Furthermore, this scanning method is also very reliable, as evidenced by the successful projection onto the resulting mesh and the execution of the toolpath during printing. However, it should be noted that the process involved several steps that are currently carried out manually rather than being automated: from initial preparation before scanning, point cloud data collection, mesh conversion and cleaning, to importing the resulting mesh into the software environment used for toolpath design and robot simulation. Despite being a multi-step process, this method has successfully demonstrated a high level of accuracy, making it a reliable approach for formwork registration in large-scale conformal 3D printing applications.

Camera Vision

The second method of formwork registration is based on visual positioning using fiducial ArUco markers, measuring 5x5 cm as a reference **(Fig. 5.10)**. Here, a ZED 2 stereo camera equipped with an Inertial Measurement Unit (IMU) is used. The IMU sensor enables real-time tracking of the camera's position and orientation in 3D space, allowing the camera to be attached to the robotic arm as it traverses the formwork. In this approach, the OpenCV

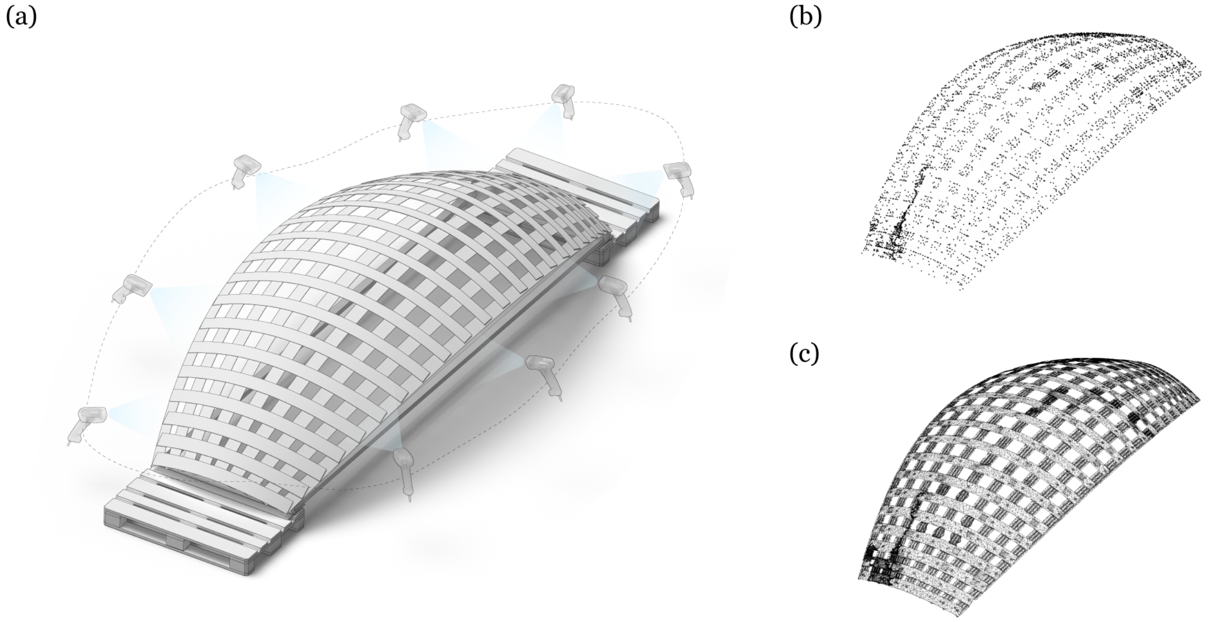


Figure 5.9: The formwork is scanned with a portable 3D scanner (a), which generates a point cloud (b), which is then processed into an accurate 3D mesh that serves as the basis for the projection of the toolpaths (c).

library is used in conjunction with the Stereolabs ZED SDK to acquire spatial data. The method includes three key functions. The first is responsible for calculating the position of the stereo camera within the world frame, while the second detects the spatial orientation of the ArUco markers. The third and final function is for real-time position estimation. It captures data from the stereo camera, identifies ArUco markers and estimates their orientations. The method also includes error tolerance values that act as filters to minimize computational errors and improve the accuracy of the method. As the stereo camera was moved over the formwork, the positions and orientations of the fiducial markers are captured and recorded in a comma-separated values (CSV) file. The recorded data was then used as the basis for reconstructing a digital version of the gridshell's skeleton graph by plotting and connecting the recorded points, resulting in a digital surface that can be used as a substrate for toolpath projection. After testing the vision-based pose estimation method, it has been found that the process can occasionally produce duplicate points or slight inaccuracies due to noise and poor ambient conditions. However, since the formwork consists mainly of strips that can be easily described as a skeletal graph model, this method has proven to be sufficiently reliable for recreating the surface geometry. Comparing the two techniques, this vision-based approach stands out to be a simple, fast, and reliable method of formwork registration, especially for

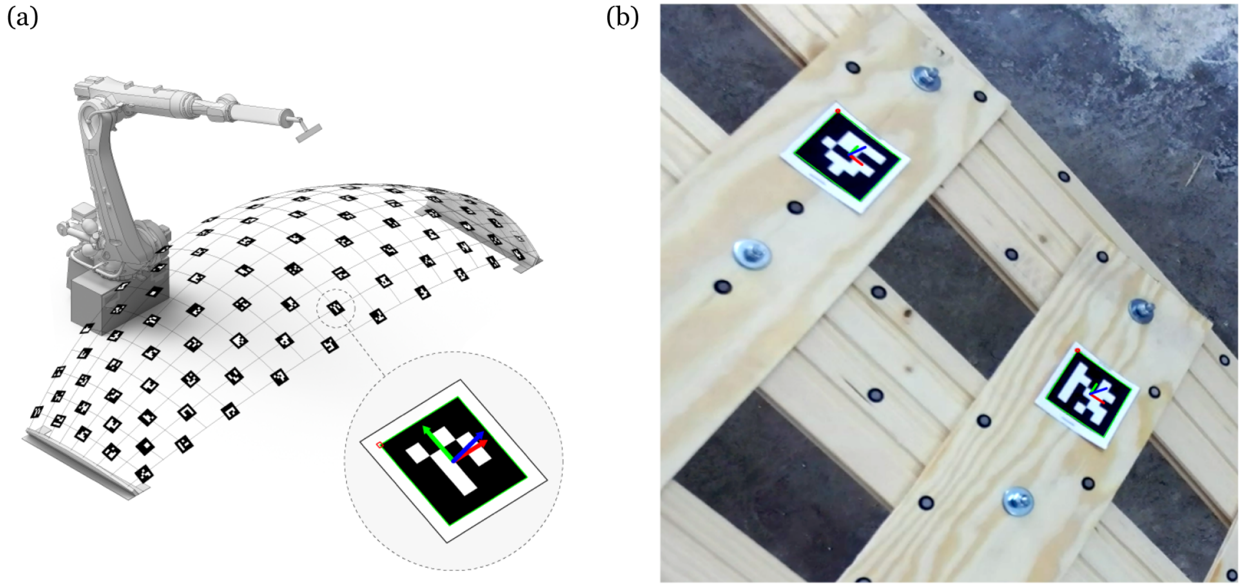


Figure 5.10: The second method for formwork registration uses a ZED 2 stereo camera and ArUco markers for a vision-based position estimation process. The stereo camera accurately identifies the position and orientation of the markers in 3D space, which are used to digitally recreate the formwork.

formwork consisting of smooth curves that do not require detailed geometric registration.

Printing Process

Following the registration of the formwork, the robotic toolpath was projected onto the digitally created substrate surface and used for conformal 3D printing. In a first step, the MAI concrete pump was activated to mix the material with high consistency and continuity throughout the entire printing duration. **Fig. 5.11** shows the uniform deposition of concrete layers on the bending-active formwork. The toolpath in this experiment is designed to apply three consecutive layers of concrete to the formwork to complete the process.

The fabrication of this prototype unfortunately failed after 3D printing the third layer, when the bolts securing the formwork strips to the bulkhead tore out, causing the support conditions to change and the gridshell to fail under the load. This mistake could have been easily avoided by either selecting a more suitable material for the bulkhead and connection, to withstand higher forces, or by slowing down the printing process or even pausing printing after the first layers to give each layer more time to cure and to make the bond between the formwork and the concrete, as well as the applied concrete layers themselves, stronger and more load-bearing. Nevertheless, the formwork in this experiment was able to support the weight of 500 kg of concrete even before the material had fully cured.

Figure 5.11: Conformal 3D printing process on bending-active formwork in action. The multi-axis printing platform ensures that the concrete is distributed evenly with a constant layer height and that the nozzle maintains a normal orientation to the formwork.

Discussion

Despite the unfortunate outcome of the printing process, this experiment has successfully demonstrated that both 3D scanning and the use of a stereo camera are reliable methods for formwork registration and that in principle, the proposed fabrication method of conformal 3D printing on bending-active formwork can work. 3D scanning has proven to be a more accurate technique for capturing highly detailed geometry regardless of ambient conditions. However, it is a multi-step process that requires manual post-processing or should ideally be automated in the future. In comparison, the vision-based pose estimation is less accurate, but has turned out to be a sufficiently reliable alternative for this type of scale and geometry, making it a fast and straightforward method for formwork registration. Therefore, choosing one method over another depends on the requirements and geometry of the formwork.

5.8 Conclusion

The research in this chapter renders the possibility of significantly reducing waste during the construction process and enables the fabrication of long-span roof structures using 3D printing. The proposed fabrication method was subjected to a rigorous validation process that began with small-scale experiments examining single-strip and three-strip configurations.

Figure 5.12: Multiple layers of concrete are 3D printed onto a lost, bending-active formwork to create a wide-span, material-efficient hybrid gridshell.

This first experiment is a crucial step in verifying the feasibility of the proposed method while bringing to light some of the challenges, limitations, and areas that require further improvement. The valuable lessons learned from this experiment prompted the development of tools and workflows to address the challenges associated with formwork registration and toolpath planning.

Building on these results, the second experiment demonstrated the application of the proposed fabrication method in the context of a full-scale hybrid gridshell prototype. In this experiment, a computational workflow is first developed to overcome the complicated challenge of intersecting strips within the gridshell and to facilitate the modeling process of the toolpaths. Second, two methods for formwork registration are investigated: 3D scanning and vision-based position estimation. Both methods have shown their respective strengths and limitations, which are influenced by factors such as the required formwork resolution, the formwork scale, and the environment in which the formwork is located. While 3D scanning has been shown to produce a high-resolution model, vision-based position estimation has been sufficient to achieve the desired accuracy in the context of this study. This is primarily due to the simple curvature of the gridshell, which does not require extensive geometric details. Through this iterative approach, the research has evolved from concept to practical implementation, illustrating the feasibility and potential implementation of the proposed fabrication method for using bending-active formwork in conformal 3D printing of roofs and gridshell structures.

Chapter 6

Non-Planar Granular 3D Printing

6.1 Overview

Most existing approaches to 3D printing are layer-based, regardless of the scale they operate in, and the type of 3D printing process they employ. Among these technologies, powder-based 3D printing stands out to offer benefits such as eliminating 3D printed support requirements, and the ability to achieve high printing resolution. Despite these advantages, the process remains challenged by the conventional approach to file preparation and slicing, as discussed in **Chapters 2** and **4**. The current reliance on layer-based 3D printing is a significant limitation, obstructing powder-based technologies from reaching their full potential.

To address these challenges, this research introduces an innovative additive manufacturing technique called *Non-Planar Granular Printing (NGP).* NGP is a scalable method that is faster and more adaptable than traditional 3D printing techniques. The method is based on the selective deposition of a liquid binder into a granular particle volume to fabricate 3-dimensional objects. Like other 3D printing methods, NGP can use a CAD 3D model and conventional slicing software to produce a robotic toolpath following a desired height and width. However, by moving the extruder's dispensing tip freely within the granular particle volume, the method has the advantages of being able to 3D print objects in a non-planar fashion. In contrast to conventional methods, this process does not necessarily follow a layer-based approach, but instead allows for rapid fabrication of vertical, spatial, or freeform extrusions that would normally require the printing of additional supports in conventional 3D printing processes [51]. Owing to this capability, the NGP technique significantly reduces printing duration and enables the production of certain geometric forms that would be very cumbersome or time-consuming to produce using conventional 3D printing processes.

NGP builds upon traditional powder-based additive manufacturing techniques. The use of powders and granular materials provides an advantage in printing components of high complexity and geometric freedom, obviating the need for external support integration or for 3D printing temporary breakaway structures. Particles in the build-volume remain loose until a binding liquid is selectively applied, causing the particles to bond together, forming parts of the 3D printed object. The surrounding loose particles in the container temporarily support the weight of the wet particles during their curing period. This allows for complex geometric forms to be achieved without the need to 3d print supporting structures or generate any material waste. Upon the completion of the printing process, the remaining loose particles can be re-used in the same process repetitively.

Due to the highly customizable nature of the NGP process, this technology capitalizes on the use of abundant waste materials for 3D printing. Almost any material that can be broken down into granular or powder form is compatible with the NGP method. This capability broadens the range of materials applicable to 3D printing, presenting a significant improvement in material efficiency. Conventional powder-based processes lack the material versatility and are challenged by high costs and long printing times. These limitations, in addition to the volume dimensions of conventional powder-based 3D printing techniques, make them inadequate for process scalability and adaptation for large-scale 3D printing applications. Rather than confining the printing process with standard, three-axis gantry systems, NGP integrates multi-axis robotic extrusion with flexible build-volumes, and employs a diverse material palette to enable printing at various scales using a variety of materials. This integration significantly enhances 3D printing speeds, process scalability, and material diversity while also enabling geometric forms that are difficult to fabricate using conventional approaches. Another primary benefit of NGP is its ability to rapidly produce complex, support-free geometry with embedded functional gradients and varying thicknesses.

This chapter investigates the primary NGP technology components while detailing a series of benchmark experiments. These experiments address specific technological capabilities related to printing speeds, extrusion thickness variation, multi-material printing, and process scalability. The chapter also reviews similar 3D printing approaches that utilize multi-axis robotic extrusion and reusable support materials, offering a comprehensive understanding of NGP's position amongst other 3D printing techniques.

The study concludes with a summary of the key findings and a projection of prospective avenues for future research. The approach discussed in this chapter demonstrates the potential to substantially improve material usage and reduce 3D printing durations across various scales and applications. By offering groundbreaking improvements, this research marks an important step forward in expanding the potential and application of this technology within the 3D printing field.

6.2 Introduction

Various 3D printing techniques, each grounded in a distinct production workflow, offer unique advantages and limitations. These methods of production influence fabrication speed, production cost, quality of printed objects, and material selection. An essential factor in this consideration is the object's geometric complexity. Additive manufacturing is widely recognized for its ability to produce complex, intricate designs at reduced costs. Compared to traditional methods that often require costly molds and involve laborious, multi-stage processes, additive manufacturing stands out in this regard, offering a simpler transition from design to production. Moreover, different additive manufacturing processes adopt different strategies to produce complex geometric features such as overhangs, intricate lattice structures, and unsupported forms. These strategies may include printing temporary support structures or using auxiliary materials to support printed forms during production. While some of these strategies can be advantageous, they often come with their own set of drawbacks, mainly in terms of material waste and production cost. The fabrication of unsupported forms or large objects tends to increase the amount of required support structures. A significant issue in this context is that printed support materials are typically non-reusable. Consequently, as the complexity and scale of the printed object increases, there is a corresponding increase in material waste. This relationship highlights some of the current drawbacks of additive manufacturing technologies, suggesting significant potential for advancements in process efficiency and sustainability.

A primary challenge in most current 3D printing technologies is scalability, limited by factors such as build-volume, material availability and production cost. The size of 3D printed objects often depends on the dimensions of the 3D printing platform, necessitating increased machine sizes for larger 3D printed objects. Typically, the extrusion system and the build-platform are integrated into a single 3D printing machine, precluding separation or customization of either systems to accommodate varying object dimensions. As a result, objects exceeding the printer's volume are commonly segmented into smaller parts in order to fit the machine's allowable volume.

However, 3D printing platforms utilizing industrial robotic arms offer a degree of flexibility. While these systems are limited by the reach of the robotic arm, reachability can be extended by incorporating additional axes, such as linear rails or tracks. In such setups, the dimensions of the printing platform are more adaptable, as the robot is able to print on any surface, not only those within the confines of a machine. The separation of the extrusion system from the build-platform provides a level of customizability, addressing some of the constraints related to object scalability.

Moreover, many additive manufacturing technologies are restricted to materials offered by the machine manufacturer, materials that are specifically engineered to meet certain requirements. These materials predominantly include thermoplastics, composites, thermosets, ceramics and metals. However, many common industries generate substantial waste materials that have the potential to be taken advantage of for 3D printing. For example, construction development processes often involve demolishing existing sidewalks, driveways, and foundations, leaving construction workers and contractors to deal with huge amounts of concrete waste [134]. The recycling of concrete can typically be accomplished by crushing and pulverizing it using industrial equipment such as grinders, shredders, and granulators [134]. Plastic, which is used in an enormous number of household products, is another area of waste [264]. The recycling process of plastic waste typically involves shredding and repurposing into other plastic products [313]. In addition, huge amounts of rubber waste are produced annually, most of which are from vehicle tires [134]. The recycling process of rubber also involves shredding the material into smaller parts and repurposing them into other object forms. Additionally, wood waste is commonly generated in the form of sawdust or small wooden chips that are used in the production of particle boards. Smaller pieces of recycled wood are also used as abrasive media for sandblasting and paint removal applications. The availability of these waste materials points towards a significant area for potential development in terms of sustainability and resource efficiency in additive manufacturing.

Binder Jet 3D printing processes use materials that are in granular or in powder form. In this process, liquid binders are jetted through a cartridge onto very thin layers of powdered materials that are incrementally re-filled and sequentially constructed, capable of achieving objects of high geometric complexity and resolution [198]. Advantages of BinderJet 3D printing include the possibility of printing non-supported forms without the need to 3D print temporary supporting structures. The loose powder material fills the printing volume, becoming a temporary supporting structure for the bonded particles. After dispensing the binding liquid at particular locations within the volume, the bed moves lower, and an additional layer of powder fills the print bed for the next printed layer. Although this technology produces minimal waste, it lacks the versatility of materials used in other forms of 3D printing and is relatively slow due to the need to print the thin layers required for fine. Therefore, the scalability of such technology is limited by printing speed and volume and may increase platform costs. However, the effectiveness of binder jet 3D printing processes could be enhanced if granular waste materials could be used in the printing process. Key enhancements to the current technology also include increasing the dimensions of the build-volume and accelerating the speed of production. Such advancements hold the potential to adapt powder-based printing techniques to large-scale production. 3D printing at the architectural scale seeks technological efficiency capable of constructing without geometric restrictions at high speeds while being less dependent on fine resolutions at the micro-scale. By coupling the speed and versatility of industrial robotic arms with the powder-based printing process, this study presents one possibility for 3D printing complex components at high rates and with unprecedented material and geometric freedom.

	Fused Deposition Modeling (FDM)	Stereolithography (SLA)	Selective Laser Sintering (SLS)	Binder Jet	Non-Planar Granular 3D Printing	Rapid Liquid Printing (RLP)
Printing Speed	Slow-Moderate [216] [143]	Slow-Moderate [99]	Moderate [53]	Moderate [207]	Fast	Fast [119]
Materials	Thermoplastics, Biothermoplastics, Polymeric composites, Biopolymeric composites, Metals [Titanium, Copper, Aluminum] [132] [244] [191] [76] [159] [230] [50]	Thermosets (Photopolymers), Biothermoplastics (gelatins, hyaluronic acids), Thermoplastics (Polyethylene Glycols) [74] [205] [175]	Thermoplastics synthetic polyamides) ThermosetsMetals Ceramics [151] [170] [254] [12]	Ceramics, Metals, Composites, Thermoplastic Biopolymers [198] [275] [81]	**Binding Material:** Thermoplastics, Thermosets, Biopolymers (Hydrogels)* **Granular Material:** Ceramics (Sand, Glass), Biopolymers (lignocellulose)*, Metals, Thermoplastics	Elastomers (Urethane Rubber, Silicone) Thermoplastics, Metals [119]
Material State	Solid (pre-extrusion), Viscous (during extrusion) [132]	Viscous [127]	Solid (granular)	Solid (granular), Viscous (Binder) [327] [84]	Solid (granular), Viscous (Binder)	Viscous [119]
Support Type	3D printed supports (Same as 3D printed Material) [132]	3D printed supports (Same as 3D printed Material) [132]	Non-Printed Granular Support [132] [101]	Non-Printed Granular Support [132] [327]	Non-Printed Granular Support	Non-Printed Granular Support (Biopolymers, Hydrogels) [119]
Build Volume	Limited by Printer Dimensions [162]	Limited by Printer Dimensions [162]	Limited by Printer Dimensions [162]	Limited by Printer Dimensions [162]	Independently customizable, Modular	Independently customizable [119]
Cost Per Volume	Low [101]	High	Moderate [101]	Moderate - High	Low	Low [119]

Table 6.1: A comparative summary of some key characteristics of 3D printing technologies, highlighting common specifications that are present in the Non-Planar Granular Printing method [68]

6.3 Motivation

Powder-based 3D printing methods are widely recognized for their exceptional capabilities in fabricating high-quality, intricate structures. The essence of powder-based processes lies in their use of loose, granular materials that not only serve as the 3D printed material, but also function as a temporary supporting medium for the 3D printed parts. This feature presents a remarkable advantage for powder-based 3D printing processes in terms of material efficiency. Because the loose, granular materials can be recycled and reintegrated back into the printing process, material wastage is minimized, promoting an efficient production cycle.

Despite these advantages, current 3D printing technologies based on granular materials and powders are not without limitations. One of the primary constraints is the volumetric limitation of 3D printing platforms, restricting the dimensions of printable objects and potentially obstructing the scalability of the technology. Additionally, the range of materials compatible with this printing technique is relatively narrow, mainly confined to a select group of powders. This limitation hinders design versatility and material properties, which also impedes the broader application of this technology across industries.

These challenges set the stage for this study's pursuit to refine 3D printing technologies based on granular materials. The study investigates a series of questions. What if this technology could be dissected to individually enhance its critical components: the extrusion system, the material palette, the build-platform, and the robotic control mechanism? How would the development of these components improve the overall capabilities of granular-based 3d printing techniques? What if the developed system were capable of utilizing waste materials from other industries, which already undergo recycling processes like crushing and granulating? Finally, what if the developed technology could enable the construction of large-scale products, thereby broadening the horizons of 3D printing applications?

To overcome the aforementioned challenges, a comprehensive approach must address certain aspects of the technology. First, there is an opportunity to expand the current material palette to consider materials that are prevalent in existing large-scale production. Emphasis could be placed on incorporating recycled materials such as crushed glass, recycled metals, stone, and sawdust. Since these materials are already being processed into fine powders in the recycling process, their integration into the 3D printing would not be difficult. There is also room for improvement on the level of binding materials. The current binders used in powder-based 3D printing processes could be improved or replaced with new binder types that are compatible with the new granular materials. Exploring alternative binders such as biomaterials presents another promising avenue. This approach not only aligns with sustainable construction practices, but also expands the material possibilities within the 3D printing domain.

Moreover, developments of the extrusion system might enable the use of various binding materials and provide precise control over the quantities of extruder binders. This could lead to the ability to vary extrusion thicknesses throughout the printing process, and handle complex binding liquids that require mixing or temperature regulation. Isolating the extrusion system from the printing platform has the potential to enable this level of control.

In terms of the 3D printing build-volume, there is potential to break-free from the dimensional constraints of the 3D printer. By separating the build-volume from the 3D printing platform, it becomes feasible to customize build-platforms of any shape or size, enhancing process scalability. Lastly, the introduction of multi-axis robotic control, replacing the traditional 3-axis mechanism, opens up new possibilities for precision and control. This advancement could enable the rapid production of complex geometries, and not only improve the 3D printing speed but also enhance the mechanical properties of printed objects.

In summary, considerable potential exists for enhancing aspects of powder-based 3D printing technologies. One important benefit is the widening of the spectrum of materials that are currently used in 3D printing, potentially enabling the creation of objects with embedded functional and mechanical properties. This means objects could be designed to be stronger in certain areas but flexible in others, or could exhibit properties such as opacity, thickness, and roughness. Such prospects drive the research presented in this chapter. Exploring these possibilities will require tool developments on the hardware and software levels, a challenge that this research also aims to address.

6.4 Research Objectives

The objective of this research is to develop and assess a novel method for non-planar 3D printing that prioritizes speed, customizability, material efficiency, and scalability. A fundamental aspect of this research is not only the introduction of a new method, but an evaluation of its practicality, constraints, and possibilities.

Additionally, the study seeks to outline the technological limitations of this method on the design and process levels. Given that the NGP method is new and untested, comprehensive considerations of the entire design to fabrication workflow are essential to ensure its accessibility and potential applicability within the 3D printing domain. Furthermore, this study involves a thorough performance evaluation of the NGP technology, comparing it to existing technologies and comparing the new developments with previous prototypes and experiments on the hardware and software levels. Feasibility testing is a critical part of this study, encompassing a focus on materials, equipment, process, and scalability. This iterative testing aims to refine the technology at every stage, filtering out the most promising approaches. In this process, the findings in one domain are expected to influence other aspects of the research. For example, material feasibility studies can influence the design of hardware and software tools, as well as toolpath strategies. This integrative approach ensures the ultimate success of the proposed printing method.

Goals

The overarching research question for the following experiments section is to better understand how the NGP method enables the fabrication of digitally designed shapes into physical objects and to what extent this manufacturing process depends on the design workflow, technical specifications of the 3D printing platform, and materials used. It is important to study these factors in more detail and introduce performance metrics for their evaluation because all three aspects have significant impact on the design freedom, precision, and accuracy of the manufactured parts.

On the manufacturing process level, a main goal of this research is to establish a 3D printing process that aligns with and subsequently surpasses the capabilities of current 3D printing technologies. This involves every phase of the process, from the design of the object to file preparation, system operation, production, and post-production. The aim is to then holistically evaluate and develop the NGP technology further by considering all these elements.

At the technical level, the focus is on fabricating appropriate tools to ensure the efficient operation of the method. First, this involves developing software workflows that are tailored to this technology, as well as advancing hardware components. Considering that the NGP technology utilizes an industrial robotic arm as a control platform, hardware developments include the fabrication of specialized end-effectors, extrusion systems, and build-platform solutions, ensuring that each of these components enhances the technological capabilities in line with the overarching research goals.

The final area of focus is material experimentation. A significant focus is placed on identifying compatible materials and their requirements, achieved through rigorous material sampling and analysis. The objective here is to test various granular substrates and liquid binding materials, identifying those best suited for this technology while exploring both their potential and limitations. The research aims to reveal new materials that have not been previously utilized in 3D printing, setting the stage for future explorations and other compatible materials.

6.5 Proposed Fabrication Method

The proposed Non-Planar Granular 3D printing (NGP) method shares some of the advantages of powder-based 3D printing processes, and aims to overcome some of their limitations and challenges. Similar powder-based processes, the NGP technique uses the load-bearing capacity of the surrounding medium as a temporary support to enable free-form 3D printing without being limited to certain geometric features or relying on material adhesion during printing. The NGP technology is based on an industrial robotic arm that drives a long and slender nozzle through a volume of coarse granular material ($\sim 200\mu m$ - 600 μm or bigger) and selectively injects a liquid resin to bond particles together and to create a three-dimensional object, as shown in **Fig. 6.1** and **Fig. 6.2.** Until the binding agent cures, the dry particles surrounding the 3D printed object provide temporary support. This allows designers to create freeform objects without having to 3D print support structures or integrate auxiliary scaffolding, as is the case with most other 3D printing technologies. After curing, the 3D printed object can be pulled out of the volume. Like its technological counterparts, the loose granular material in NGP that is left in the container can also be recycled and reused without producing any waste. However, a key advantage of NGP over other processes is that the granules can vary in size, shape, and physical properties, which significantly expands the range of acceptable materials and lowers production costs by enabling the use of recycled waste from other industrial processes that has already been processed through shredding and pelletizing. Another important advantage of NGP technology is that it offers the ability to fine-tune the material throughout the 3D printing process. Thanks to the interchangeability of the used granular materials, and the precise control of the liquid flow and the tunability of platform parameters such as speed and nozzle diameter, the printed objects can vary in resolution, extrusion thickness and material properties.

Technical Setup

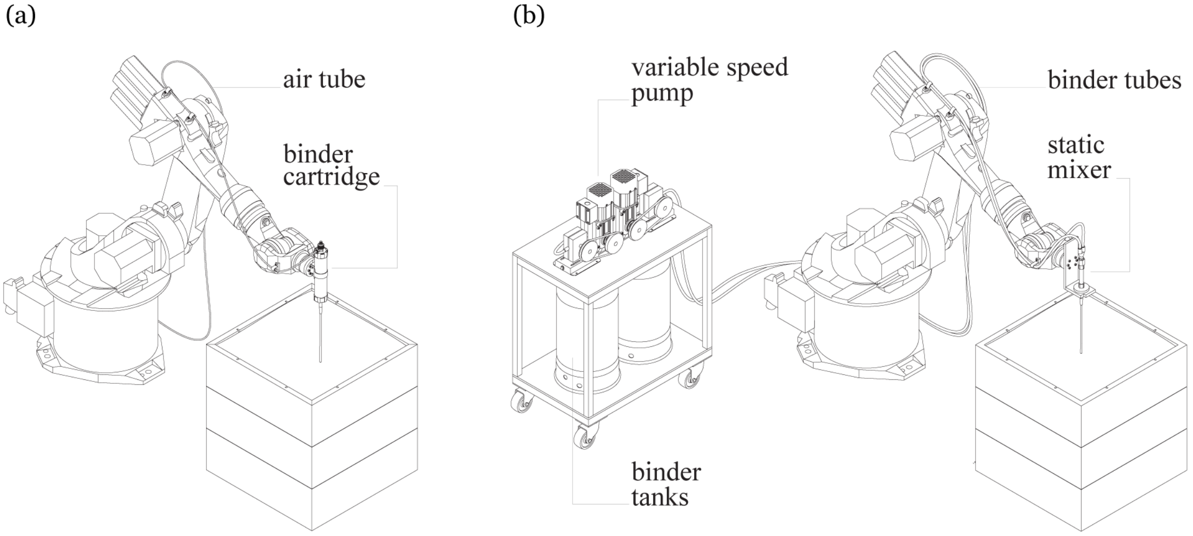


Figure 6.1: Two technical solutions have been developed for NGP printing. (a) one consists of a pneumatically operated cartridge system containing 20 oz. of liquid binder. (b) the other allows extrusion of larger quantities and consists of two separate tanks and variable speed pumps feeding a mixing nozzle at the end effector [68].

The technical setup of the NGP platform consists of a conventional industrial robot arm (KUKA KR16-2) as well as a custom-made resin dispensing system and a build tank containing the granulate material, see **Fig. 6.1 and Fig. 6.2** [67][68]. Although the NGP printing process does not depend on a complicated robot and could be done with a simpler gantry system or a Scara robot, a 6-axis machine is chosen because it allows free movement and orientation of the end effector and is limited only by the robot's kinematics and reach. The attached dispensing system is determined by the design of the nozzle and resin supply

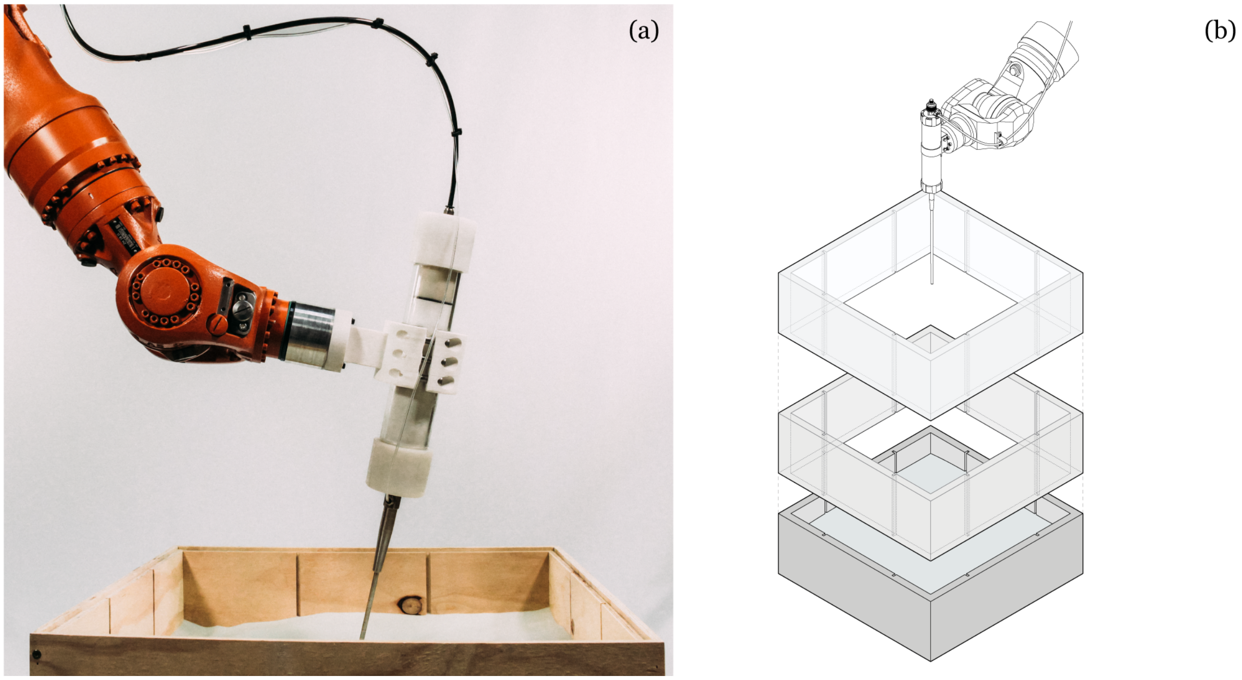


Figure 6.2: A custom-made modular container system for holding the granular material was developed for the NGP process. To print, the robot moves the end effector into the volume and injects a liquid binder into the granules along a predefined toolpath. After curing, the particles bond together resulting in a 3D-printed part. The remaining loose granulate can be reused for future prints [68].

pump. Finally, the build tank is designed as a modular container that can hold a variety of materials and is adjustable in size to accommodate prints at different scales. In this setup, the resin dispensing system and the build tank are specifically designed for the NGP printing process. The NGP process uses a two-part liquid binder that is stored in a tank or cartridge, mixed, and then selectively distributed through the robotic platform along the planned toolpath. During this process, the liquid flows through a long, thin stainless-steel nozzle that injects the binder deep into the volume of the granular material.

Two different types of dispensing systems are developed and tested as part of this study. The first is a simpler cartridge system, as shown in **Fig. 6.1 (a)**. Here, the binder is filled into a cartridge and pressed down to the stainless-steel nozzle by a pneumatically operated piston. The thickness of the extrusion depends on the level of pressure driving the piston and the speed of movement of the robot platform. A digital compressed air regulator determines the pressure required to extrude the liquid binder. By varying the air pressure selectively over the entire tool path, adjustable extrusion thicknesses can be achieved. This dispensing system is mainly suitable for small applications limited by the size of the cartridge and the amount of liquid binder it can hold.

Fig. 6.1 (b) shows the second, more complex dispensing system used in this study. This system is developed to increase the capacity of the liquid binder beyond the small volumes of the cartridges, an advantage when printing larger objects. Here, the two-part liquid binder is stored separately from the end effector in special pressurized tanks. The tanks use air to feed the two-part resin to a high-capacity, variable-speed gear pump that delivers the liquid material through vinyl tubing to a static mixer that is part of the stainless-steel nozzle at the end effector of the robot. A special feature of this NGP system is that the flow rate of the gear pump is variable and can be easily adjusted to achieve either different mixing ratios and viscosities or to process different types of binders, from conventional polyester and epoxy resins to more or less sustainable liquid binders and biomaterials. This feature offers a great opportunity to improve the printing process at the binder level, as well.

Another fundamental part of the technical setup for Non-Planar Granular 3D Printing (NGP) is the stainless-steel dispensing nozzle. The system is equipped with a nozzle measuring 20 cm in length and an outer diameter of 7 mm. The length of the nozzle is an important factor, as it determines how deep the dispensing nozzle of the printer can penetrate into the volume of the granular particles. To further control the thickness of the extrusion, the nozzle is threaded so that tips of various sizes and inner diameters can be screwed onto it. During the printing process, the nozzle is pulled through the volume of granular particles, following the predetermined toolpath. Depending on the material used, the granulate can cause a deflection of the nozzle, especially with coarser particles or in deeper areas of the volume, where the material cannot evade the nozzle as easily.

The last element of the NGP setup is a custom-made build tank that contains the granular material. The stackable container system is designed to be modular from the ground up, thereby addressing a common limitation of many 3D printing processes where the size of the printed object is constrained by the build volume of the printer. While the modular container system is still limited by the reach of the robotic arm, it allows the carrying of both, smaller and larger quantities of granules, as well as permitting the positioning of varying quantities of material at different heights. This feature makes it possible to create a bounding box around the object to be printed and to minimize the amount of material required. The height of each stackable container is determined by the length of the output nozzle, in this case 20 cm. Therefore, larger 3D-printed objects are enclosed in several containers of the same height. This allows the binding liquid to be injected within a 20 cm section. In this case, where the 3D-printed object exceeds the volume of a single container, additional containers can be stacked and filled with granules without having to interrupt the printing process. Since the containers can be filled with any type of granulate and the size and shape of the containers can be varied depending on the robotic platform or material used, this modular container system also allows the tailoring of the printing process at the material level.

Materials

One of the main advantages of the NGP process is the wide range of granular materials it is able to use. These can have a variety of sizes and properties, from fine powders in the nanometer range to a conglomerate of coarser particles in the centimeter scale [90]. Apart from the particle size, the granules can vary in weight, optical properties such as opacity, or geometric characteristics such as sphericity and surface roughness. The flexibility of the printing process proposed in this study in accepting a wide range of granules even opens the door to a previously untapped source: waste materials. This includes materials that are already recycled into particles by shredding, crushing, granulating, and pelletizing.

When selecting suitable materials for NGP, it is particularly important to pay attention to certain material properties, as these can greatly influence the success rate of the process. Aspects of the particles such as the shape, size and surface roughness directly affect not only the accuracy of the 3D print, but also the resistance experienced by the nozzle as it moves through the volume. In general, particles with smooth and spherical shapes have a higher success rate because they have a higher flowability rate and can roll towards one another. In comparison, coarse particles with irregular geometry have higher packing density, and the resulting higher particle friction causes strong resistance to the movement of the 3D printing nozzle. In the experiments conducted and discussed in the following section of this study, various granular materials are tested and classified. While most granules were successful, some performed better than others.

In addition to the granular material, the other defining element in the NGP process is the liquid compound used to bond the particles together along a specific toolpath. Choosing a suitable binder plays an important role in the success of the printing process and its adaptability to a wide range of granules, as well as the resulting accuracy, durability and resolution of the 3D print.

Fortunately, binders are commonly used in other powder-based and granular casting and 3D printing processes, so a wide range of binders exist that can be adapted to the NGP process. Sivarupan et al. (2021) lists a selection of liquid binders traditionally used in casting processes, such as Silica (SiO2), Zirconia (ZrO2), and Olivine, as well as commercially available liquid binders used in binder-jet 3D printing applications, such as. e.g. Furan (based on chemically cured furfuryl alcohol), HHP binders (acid-cured phenolic resin) and other inorganic binders (water-based, alkali-silicate binders) [283][214]. Over the course of this study, the use of industrial adhesives has been investigated, including thermosetting polymers, which have proven to be particularly successful. In contrast, bio resins have proven to be less effective, resulting in fragile, inaccurate prints.

6.6 Comparative Case Studies

Each 3D printing technologies has its own advantages and disadvantages. As shown in **Table 6.1**, different technologies offer varying production speeds, material palettes, and size limitations. These factors directly influence the suitability of a certain technology to specific applications. For example, Fused Deposition Modeling (FDM) is commonly used for prototyping and experimental applications, where the manufacturing speed and low cost are most important. In contrast, Stereolithography (SLA) or Selective Laser Sintering (SLS) may be ideal for producing highly complex geometric features that require smooth surface textures.

Table 6.1 provides a loose comparison between various 3D printing technologies, listing some of the key specifications that must be considered in the comparison process. The aim of this table is to position NGP within the spectrum of available technologies and to highlight its advantages and disadvantages compared to primary 3D printing processes.

Table 6.1 highlights some of the common features that have proven to be advantageous in various 3D printing technologies and are adapted in the NGP process. One of the key drawbacks in many 3D printing technologies is their limited build platform dimensions, which is often restricted to the size of the machine. Therefore, the size of the 3D printed object is constrained by the dimensions of the build volume. Technologies such as NGP and Rapid Liquid Printing (RLP) overcome this limitation by separating the build volume from the extrusion platform, as described in more detail in the following sections of this chapter. In so doing, the build volume can be tailored depending upon the desired object scale, offering a higher degree of platform flexibility.

NGP also takes advantage of granular support integration into the 3D printing process. Using 3D printed support structures can be time consuming, wasteful, and sometimes limit the complexity of the 3D printed object. Technologies that use granular support structures benefit from reducing printing time and opening up geometric possibilities that often require 3D-printed supports and sometimes labor-intensive post-processing.

Granular Materials

Granular materials in 3D printing are not entirely uncommon and are used in processes such as binder-jet 3D printing or selective laser sintering (SLS) **(Table 6.1)** [152][198][160] . In both processes, a fine layer of powder ($\sim 25\mu m - 150\mu m$ or smaller) is either sprayed, glued, or sintered with a laser beam to create a thin two-dimensional layer of a 3D object [190]. Incrementally, more powder layers are applied, and the binding/sintering process is repeated until all the layers that make up the three-dimensional object are completed. Binder jet 3D printing, among other additive manufacturing technologies, has the advantage of producing complex isotropic components using a wide variety of materials. This is made possible by the load-bearing capacity of the loose, unadhered powder particles, which temporarily fill all the cavities and unsupported geometric elements until the printing process is completed. The Oakland-based practice Emerging Objects, for example, has demonstrated architectural possibilities through binder-jet 3D-printed cladding and artifacts made of various recycled materials, including Portland cement, salt, sugar, tea, and rubber [239][102][238][255]. However, the process still faces the challenges inherent in layer-based manufacturing and in object size restrictions that are common to most 3D printing methods, leading to long printing time

(Table 6.1). This is evident throughout Emerging Objects' work, where large components are often broken down into smaller parts that can fit within the allowable volume of the 3D printing machine and that can be printed simultaneously on multiple machines to save time.

Rapid Liquid Printing

In contrast to layer-by-layer manufacturing and the sequential breakdown of objects into 2D layers, efforts have been made toward achieving free-form 3D printing without auxiliary structures. In such non-planar 3D printing processes, the platform is instructed to move simultaneously in the X, Y and Z axes to freely deposit materials without relying on the previous layer. By eliminating support structures, free-form 3D printing can increase printing speed while reducing the amount of material used. A notable approach to non-planar 3D printing that is fast, versatile, and scalable has been previously demonstrated by MIT's Self-Assembly Lab named Rapid Liquid Printing (RLP) [101][119][126]. Hajash et al. (2017) explain that this process uses a pneumatic extruder supported by a robotic arm to inject liquid composite materials into a tank filled with a granular gel. Here, the granular gel acts as a reusable support medium that temporarily carries the extruded liquid until it cures [119]. The versatility of the platform makes it possible to extrude various liquid materials in single or multiple parts. Hajash et al. (2017) explored various material options, including urethane rubber and plastics, and discussed the possibility of extruding materials such as foams, plastics, and even concrete. This research team also considered the potential for scalability by increasing the size of the container holding the granular gel and increasing the reach of the robotic arm for large-scale printing. One of the most notable advantages of the RLP system is the ability to print objects quickly and freely without being limited to printing in incremental, flat layers. With the ability to extrude materials in all three dimensions within the granular gel, the system enables the production of complex geometric features that would normally require support structures. However, one of the limitations of RLP is the extrusion thickness, which is limited by the load-bearing capacity of the gel. When 3D printing materials that are dense or heavy, problems can occur, such as inaccuracies that arise from the displacement of the printed object.

RLP has impressively demonstrated a new take on non-planar 3D printing, introducing an innovative reusable support material. This technology was a great inspiration for the NGP technology , which is extensively discussed in this chapter. Currently, RLP is restricted to using liquid-based materials for both, support and extrusion. Building on this foundation, NGP seeks to expand the application of RLP's principles to granular materials, aiming to broaden the scope and utility of this 3D printing approach

6.7 Experiments

In this section, a series of experiments were conducted to help identify the specific opportunities and challenges associated with the Non-Planar Granular 3D printing (NGP) process.

These tests are designed to answer questions related to acceptable geometries, possible materials, scalability of the process, potential applications, and the effects of toolpath planning on the physical properties of the printed object. Each of the experiments presented in this section has a similar general workflow that can be divided into the following phases: preparation, printing, and post-processing. The experiments themselves are then discussed in terms of objectives, design workflow, technical setup, materials, printing, and results. A detailed list of contributors for the work presented in this chapter is available in the credits section of the thesis for further reference.

Preparation, Printing, and Post-Printing

The experiments presented in this chapter were performed using a KUKA industrial robot. The toolpaths that make up the 3D-printed objects were programmed using KUKA Robotic Language (KRL) and were designed within the CAD software Rhinoceros and the built-in parametric modeling tool Grasshopper [184]. The generated shapes were then converted into non-planar print paths via KUKA—prc, a plugin that enables the simulation of robot movement and the export of KRL files [41].

Before the printing process can begin, both the granular, and the binding materials must be prepared to ensure a smooth, uninterrupted process. These can be, for example, homogeneous mixtures of granules with the same material and the same particle size or inhomogeneous mixtures of granules with different materials and/or particle sizes. This freedom in material selection is possible as long as the granular materials in use are carefully sieved to ensure that they are free of large chunks or other unwanted pieces that could obstruct the toolpath or cause collisions with the dispensing nozzle. The granular material can then be filled into the modular build tank. The preparation of the liquid binder, on the other hand, depends on the product used. For instance, 2-part resins can either be premixed and filled into a cartridge dispenser or filled into two separate tanks and mixed together with the custom-made pumping system for large-volume binder delivery.

Once the materials are ready, the NGP printing can be initiated by running the robot program. The parameters that control the toolpath as well as the movement speeds and extrusion rates during this process are embedded in the program. This program can also include commands that manage air pressure for binder extrusion, as well as ways to control a solenoid valve that turns the pressure on and off where the toolpaths need to begin or end. Once printing is complete, a post-printing procedure ensures the safe removal of the 3D-printed objects and proper maintenance of the equipment for future use. Before the printed parts can be removed from the build tank, users must wait until the liquid binder has cured. Depending on the binder, the duration of curing may vary. After curing, the loose granules can be removed by opening the drain plugs at the bottom of the modular build tanks. The loose material can be emptied into containers for reuse and for the production of future 3D-printed parts. Once the build volume is empty, the printed objects can be collected. Unlike other 3D printing processes, NGP does not require the removal of supports or post-printing processes such as UV curing, heating or other finishing techniques.

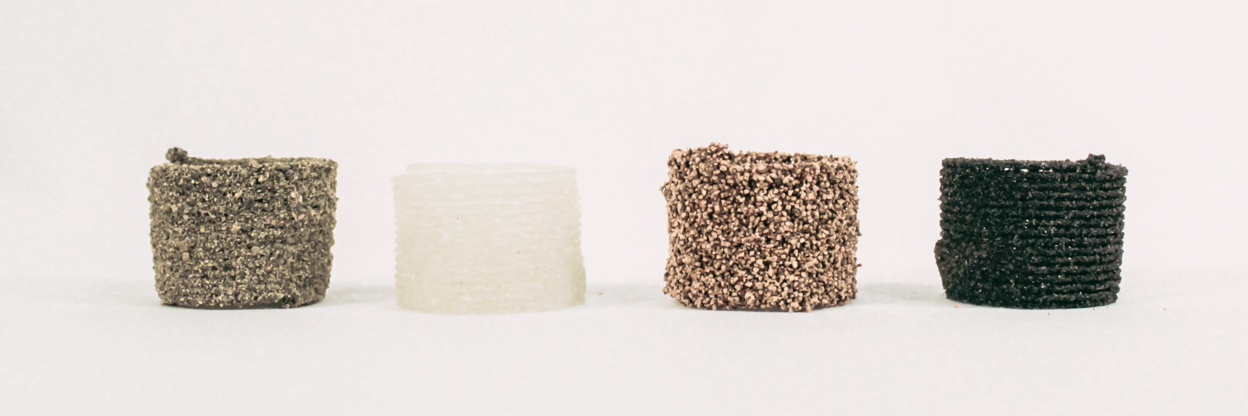


Figure 6.3: 3D printed granular material samples including sand, glass beads, walnut shell, and aluminum-oxide.

Initial feasibility tests

To investigate the feasibility and versatility of the newly developed Non-Planar Granular 3D printing (NGP) method, a series of benchmark tests and practical experiments have been conducted. First, preliminary material tests were conducted to identify the most suitable properties of granular materials. The granular materials explored in this study are fine sand, glass beads, walnut shells, aluminum oxide, sawdust, and steel beads **(Fig. 6.3)**. A two-part epoxy resin was used as a binder, as the early tests confirmed its efficacy in adhering various granular materials, making it a suitable choice for a standardized liquid binder across all test samples. In these tests, a syringe was used to dispense small amounts of liquid binder onto specific areas of each granular material. The binder was then left to dry before the samples were evaluated.

These initial tests showed that coarse particles ($\sim 850\mu m$) allowed the binder fluid to seep into the gaps between the particles, resulting in inaccurate toolpath results. In contrast, materials with small particles ($\sim 50\mu m$) showed low binder absorption, granular clustering, and highly saturated areas. Granules between $200\mu m$ and $600\mu m$ performed best in the tests, showing good binder absorption and strong particle binding.

A second feasibility test has been conducted by 3D printing cylindrical test samples using each of the granular materials. The test uses a conventional layer-based technique to 3D print a cylinder measuring 8 cm high, and 5 cm in diameter. Prior to printing, each granular material is separately filled into a cubical container measuring 15 cm x 15 cm x 15 cm. This container size ensures an amount of granular material sufficient to construct the cylindrical sample. To maintain consistency throughout the samples, an identical toolpath was used to print each cylinder. This approach ensures that any differences in the printed geometry can be attributed to the material itself, rather than to variations in the printing process. After all of the samples have been printed, they were left in the build-volume for the liquid binder to cure.

The outcomes of the tests revealed that the extracted cylinders were not uniform. This variation in geometry indicates that the mass and shape of the particles play an important role in the printing precision. Homogeneous mixtures with particles of the same size, surface smoothness, and higher sphericity (i.e. glass beads), provide the dispensing nozzle with an easier travel path which results in higher toolpath accuracy. However, these characteristics tend to produce prints with lower strength after curing.

The tests also revealed that particles with high mass and coarse surface structure, such as steel beads and aluminum oxide particles, create higher friction with the dispensing nozzle, causing it to be deflected in deeper areas of the particle volume, as shown in **Fig. 6.3**, resulting in toolpath inaccuracy. However, the non-uniformity in particle geometry tends to produce stronger prints with better material bonding.

The test findings indicate that when granular materials are characterized by a coarse surface structure or higher mass, an alternative approach may be necessary. A potential strategy suggests using smaller quantities of granular materials in the build-volume. This can then be incrementally increased during the 3D printing process, ensuring that the dispensing nozzle resists fewer granular materials as it travels through the volume. These challenges have prompted the development of an innovative nozzle design that is aimed at minimizing friction between the nozzle and the particles. Details of the nozzle design are elaborated in the following section of this study.

Air-Sleeve Nozzle

Nozzle bending and deflection can cause an undesirable mismatch between the toolpath of the designed object and the resulting printed geometry, as shown in **Fig. 6.3**. To overcome this obstacle and reduce the risk of toolpath inaccuracy, a novel air-sleeve nozzle design is developed, shown in **Fig. 6.4**. Here, the nozzle consists of two stainless steel cylinders inserted into each other. The inner tube carries the binder fluid to the nozzle tip and the outer tube encapsulates the inner tube and nozzle tip. The outer tube is equipped with an air inlet and perforated in the lower parts of the nozzle. Air can flow between the two tubes and out through the perforations, moving up along the nozzle as it escapes through the perforations and through the surrounding granular material. The rising air creates an air sleeve around the stainless-steel nozzle, clearing the path for the moving nozzle by loosening the surrounding granules and reducing the contact area between the nozzle and the particles in the volume.

In this development process, two distinct versions of the nozzle were fabricated and evaluated. The initial version features a perforated outer sleeve extending the entire length of the nozzle, as shown in **Fig. 6.5 (a).** However, testing this design indicated that a significant amount of air was escaping from the upper perforations in the sleeve, thus failing to reach the lower areas where most nozzle deflection occurs. Consequently, the nozzle design was revised, incorporating fewer perforations, strategically located at the lower part of the nozzle. Additionally, a small scoop was added to encapsulate the perforations, channeling

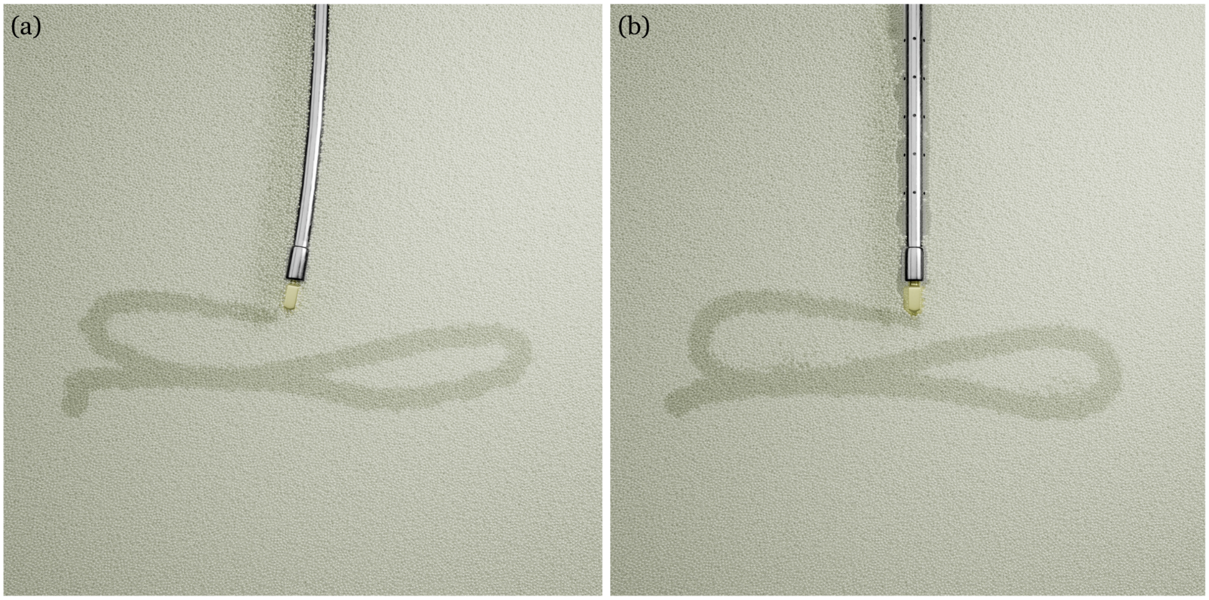


Figure 6.4: As the nozzle moves through the build volume, distortion of the toolpath can occur due to particle friction (a). To solve this issue, the authors have developed a distributive air-sleeve nozzle (b) that experiences less friction during the printing process and provides higher accuracy [68].

the escaping air upwards as it exits the perforations. This modification aims to reduce the turbulence caused by the escaping air, thereby preventing interference with the wet binding material of the printed toolpath. As shown is **Fig. 6.5 (b)**, the second design creates an air sleeve surrounding the stainless-steel nozzle, with air escaping upwards. This sleeve serves as a barrier between the nozzle and the granular material, clearing the path for the moving nozzle and reduce friction and nozzle deflection.

Experiment 1: Toolpath Limitations

Following the preliminary tests and the insights gained regarding the most suitable materials and equipment, the NGP method is further evaluated in a series of experiments. The objective of the first experiment, discussed in this section, is to determine the limits and best practices in toolpath design. Since the NGP process does not require objects to be printed in successive planar layers, it is important to understand the capabilities and limitations of the process, as well as the effects the toolpath design has on the physical qualities of the printed parts. In conventional 3D printing workflows, objects are often printed from the bottom up, avoiding any form of toolpath collisions. In contrast, NGP enables free-form 3D printing capabilities that can lead to intersections and therefore requires further planning to

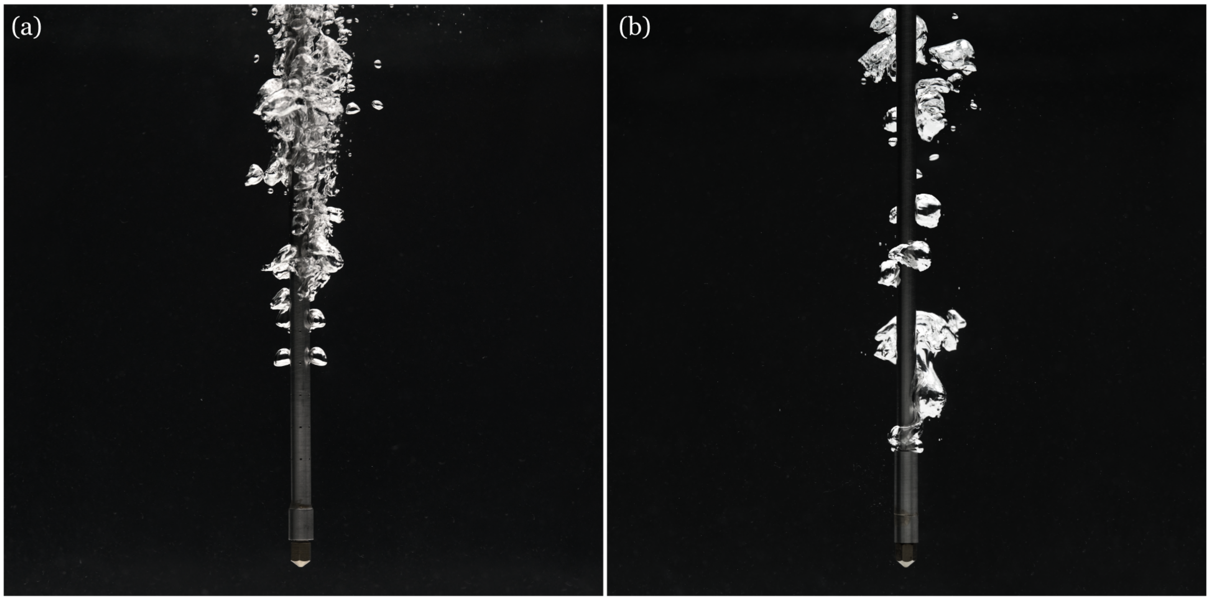


Figure 6.5: Two versions of the air-sleeve nozzle were developed and tested in a water tank to examine the rising air flow. In the first design (a), the perforations along the entire outer nozzle sleeve causes air to escape before reaching the lower sections of the nozzle where it is most needed. This version also requires higher air supply causing undesired turbulence. Therefore, the nozzle is developed further to only include perforations in the lower ends of the nozzle (b). As the air escapes the perforations, a small scoop forces the air to travel upwards, resulting in an evenly distributed air-sleeve around the nozzle.

avoid self-collision of the toolpath.

Three tests are performed in which the speed of the robot and the flow rate are kept constant while different toolpaths are printed. The technical setup of this experiment is designed in such a way that the three tests can be carried out by printing into three volumes with the same granular material. Each volume is contained in a modular build tank measuring 30 cm x 30 cm x 30 cm, made of 2 cm thick plywood sheets. All three containers are filled with fine glass beads ($\sim 400 \mu m$). The height of the containers is determined by the length of the stainless-steel nozzle used, which is 25 cm long and can thus reach most parts of the build tank. In addition, the nozzle features a tip with a 3 mm inner diameter. The binder for this experiment comes from a 12 oz. cartridge mounted onto the robot's end effector.

Glass beads were chosen as the material for this experiment because preliminary tests have shown that their smooth, spherical shape and small particle size (200 μm to 500 μm) lead to high binder absorption, which in turn ensures high print resolution. For the liquid binder in this test, a 2-part epoxy resin with a mixing ratio of 1:1 was used. The binder has

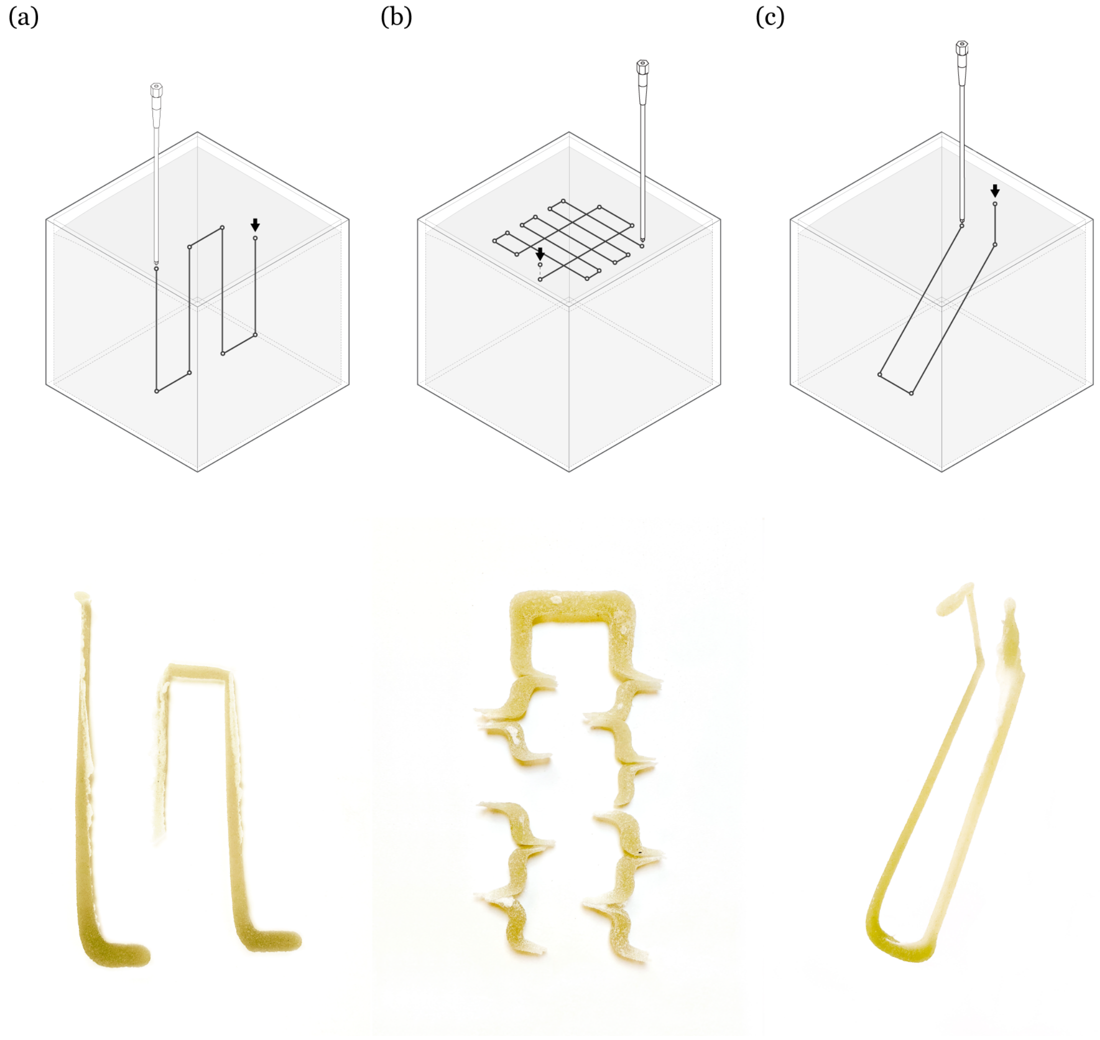


Figure 6.6: The first experiment explores the limits of toolpath design by (a) testing vertical toolpath movements , (b) lateral toolpath collisions , (c) and diagonal toolpath movements [68].

a working time of one hour and a curing time of 6 hours.

Three test prints were performed. In the first, the robot was programmed to drive the dispensing nozzle in a square wave through the granular volume, as illustrated in **Fig. 6.6 (a)**. Here the nozzle moves in straight lines down to the bottom of the container, then to the side and up again. This toolpath is repeated twice. The aim of this particular test is to determine whether the second pass and subsequent collision of the nozzle with the wet binder from the first pass would have a negative impact on the printed object. The second test, shown in

Fig. 6.6 (b), is intended to determine the effects of lateral collisions between the nozzle and the wet binder of the previous passes. For this purpose, the nozzle is moved 3 cm below the surface of the volume, drawing an open rectangle. The robot is then programmed to drive the dispenser in a crisscrossing motion through the wet binder of the previous pass. Finally, **Fig. 6.6 (c)** shows the third test, comparing the print quality of the vertical toolpaths of the previous test with a toolpath moving diagonally through the granular material. Here, the nozzle follows a 45° angle as it travels through the volume.

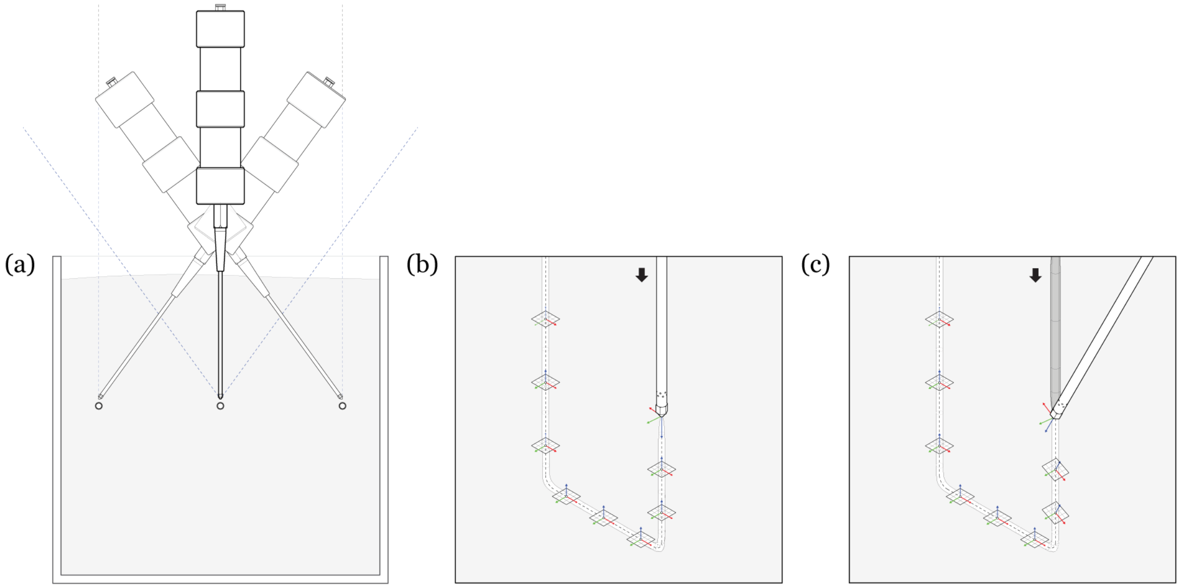


Figure 6.7: Utilizing the degrees of freedom offered by industrial robotic arms, the dispensing nozzle can be tilted in order to avoid toolpath collisions (a). This challenge is particularly present in straight downward movements when the toolpath plane normals are aligned with the tool-tip normal vector (b). To resolve this problem, the toolpath planes can be reoriented in order to avoid collisions with the dispensing nozzle (c) [68].

From the first tests in **Fig. 6.6 (a)**, it can be concluded that vertical movements of the dispenser through the volume can lead to uneven and interrupted extrusions. This likely occurs because the nozzle collides with the wet binder from the first pass aligned in exactly the same direction it uses for the second pass. A closer look at the 3D-printed object also shows that straight downward motions produce discontinuities in the print, while straight upward motions result in continuous but uneven extrusions with varying thickness along the path. Also noteworthy is the fact that the horizontal portions of the print, where the nozzle was not aligned with the tool path but oriented perpendicularly to it, showed no irregularities, and the extrusion was smooth and uninterrupted. A look at the second test print in **Fig. 6.6 (b)** shows that crossing tool paths in the horizontal direction can also have a negative effect on extrusion quality. Here, the self-intersecting path caused the extrusion to shift, resulting in inaccuracies, uneven thicknesses, and splitting. Finally, the third test print, shown in **Fig. 6.6 (c)**, reveals that diagonal paths produce the most accurate and consistent extrusions. Both downward and upward motions resulted in similarly good extrusion thicknesses across the entire toolpath.

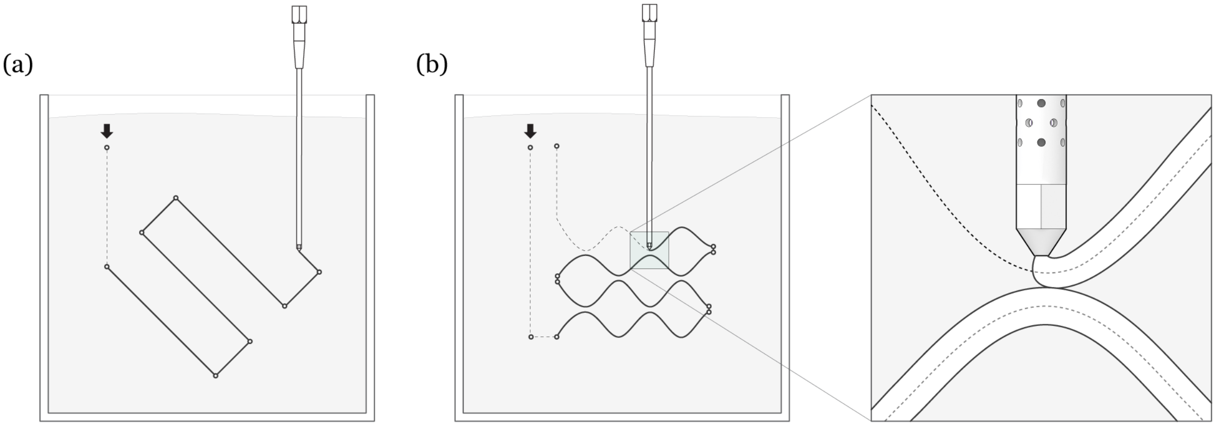


Figure 6.8: Strategies for avoiding self-intersecting and colliding toolpath segments include object reorientation within the build volume (a), and offsetting toolpaths by a distance that is equal to the width of the extrusion [68].

From the observations of the three performed tests, it can be concluded that toolpaths with horizontal and diagonal movements and nozzle orientations that are not congruent with the toolpath provide the most accurate and consistent print results. One of the biggest challenges are downward traveling toolpaths. **Fig. 6.7 (b)** shows that when the Z-axes of both the toolpath planes and the tool tip are aligned, the extruded binder collides with the nozzle, causing the print to fail. To overcome this limitation, **Fig. 6.7 (a)** shows that the nozzle can be tilted away from the vertical segments of the toolpath, taking advantage of the additional degrees of freedom offered by the industrial robotic arm. Tilting the nozzle away ensures that self-collisions are avoided throughout the toolpath. To provide the most accurate and consistent print results, nozzle reorientation can be used throughout the printing process in areas where nozzle collision avoidance is required. **Fig. 6.7 (c)**, for example, illustrates how toolpath planes are only reoriented in downward traveling motions, where self-collisions may occur. To identify areas of potential collision, toolpaths should go through a collision-checking process that highlights toolpath planes where the normals are aligned with the world Z coordinate.

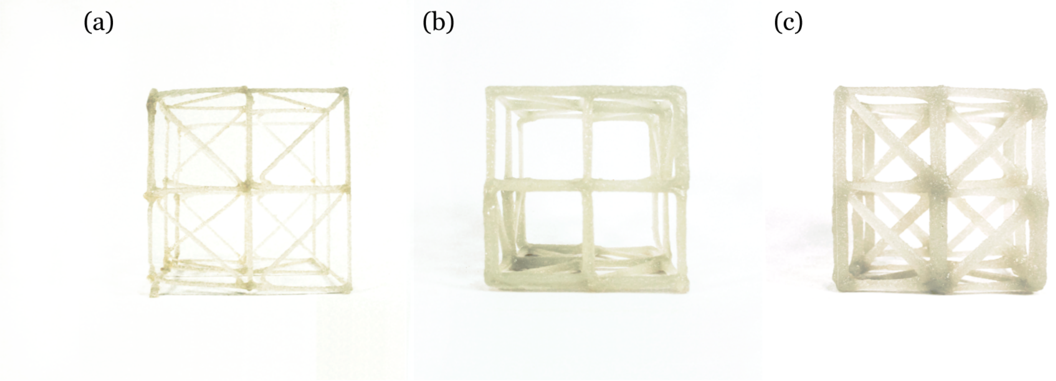


Figure 6.9: The second experiment investigates the relationships between robot speed and extrusion thickness by printing the same lattice cube at different speed settings. (a) printed at 0.4 m/s gives a 3 mm thick extrusion, (b) printed at 0.1 m/s gives an 8 mm thick extrusion, (c) printed at 0.025 m/s gives a 12 mm thick extrusion [68].

Although the nozzle reorientation strategy resolves many of the toolpath obstructions, it is limited by the toolpath depth and the size of the build volume. As shown in **Fig. 6.7 (a)**, different areas within the build volume can be reached by tilting the dispensing nozzle. However, excessive tilting of the dispenser may cause collisions between the dispenser and the build volume frame or the granular material bed.

A different approach to resolving nozzle and toolpath alignment is to reorient the 3D printed object instead of the dispensing nozzle. As shown in **Fig. 6.8 (a)**, straight-down toolpath motions are avoided by tilting the object at a 45-degree angle. By so doing, the vertical lines in the toolpath are tilted so that the nozzle can be vertically aligned with the Z-vector of the world coordinate system without colliding with the toolpath. Another notable challenge in toolpath planning for NGP occurs at the intersections where toolpaths cross. As shown in **Fig. 6.6 (b)**, horizontal crossing through the printed extrusion may cause the wet binder to smear or split. Therefore, the order of printing and the distance between toolpath segments must be carefully planned. In **Fig. 6.8 (b)**, segments of the toolpath are offset by a distance equal to the thickness of the extrusion. This allows the different segments to adhere to one another once the binder is absorbed by the particles in the build volume. Therefore, by offsetting the toolpath segments, the moving nozzle no longer collides with the wet extrusions, thus avoiding smearing, splitting, and delamination.

Experiment 2: Thickness Variation

Building on the findings of the previous experiment, the second experiment investigates the relationship between nozzle speed and extrusion quality and the extent to which these parameters affect the properties of the 3D-printed object. Again, three tests were performed with the same setup, using glass beads as the granular material. This time the geometry was kept constant throughout the three tests, while the robotic motion speed varied during the printing process. The nozzle used for these tests is 25 cm long and has an inner diameter of 3 mm.

In all three tests, the robotic arm was programmed to print a cubic lattice structure measuring 15 cm x 15 cm x 15 cm. The lattice geometry consists of four cells with diagonal cross members in four of its faces. To avoid irregularities in the print caused by the vertical movement of the nozzle, as studied in the first experiment, the shape of the lattice cube was rotated so that it sits diagonally in the build tank. In addition, the lattice cube is designed to be printed in a single continuous toolpath that starts from the lower levels of the build tank and moves upward to avoid self-collisions. Each cube was printed in the same sized build tank, but the speed of the nozzle as it moves through the granules was reduced from print to print. For the first test, shown in **Fig. 6.9 (a)**, the robot speed was set to 0.4 m/s. For the second test print, shown in **Fig. 6.9 (b)**, the robot speed is lowered to 0.1 m/s and for the last test, as seen in **Fig. 6.9 (c)**, the robot speed is further reduced to 0.025 m/s.

After curing, the prints were carefully removed from the build tanks and compared with each other. It became immediately clear that the speed at which the robot follows the toolpath plays a crucial role in the thickness of the extrusion. The members of the first printed lattice cube, in which the robot moved the fastest, were the thinnest and weakest, with a diameter of only 3 mm. In the second test, the slower speed of the robot resulted in stronger member sizes of 8 mm in diameter. And in the third test, with the slowest robot movement, the diameter of the members was 12 mm, which resulted in a very sturdy print. This increase in extrusion thickness in response to robot speed is significant and must be taken into account at an early stage when using this printing technology. However, it demonstrates the unique potential of the NGP process to create objects with very different physical properties and stiffness gradients by simply changing the speed settings in the toolpath programming.

Experiment 3: Material Variation

In the third experiment, key promises of the NGP process are explored, including its ability to print with a wide variety of materials, thus enabling the exploitation of endless material sources from industrial processes already available in granular form. To test this hypothesis, several test objects were printed, keeping the geometry and machine settings constant, while filling the build tank with different materials in particles of varying shape, size, mass, and density **(Fig. 6.10)**. Four build tanks were used in this experiment, measuring 30 cm x 30 cm x 30 cm, and filled with different materials. Three of them were filled with a homogeneous material, either glass beads, sand or walnut shells. One container was filled with a mixture of materials in which walnut shells are layered with glass beads.

Glass beads, sand and walnut shells were chosen as materials for this experiment because they are widely available as waste products from manufacturing processes and are already

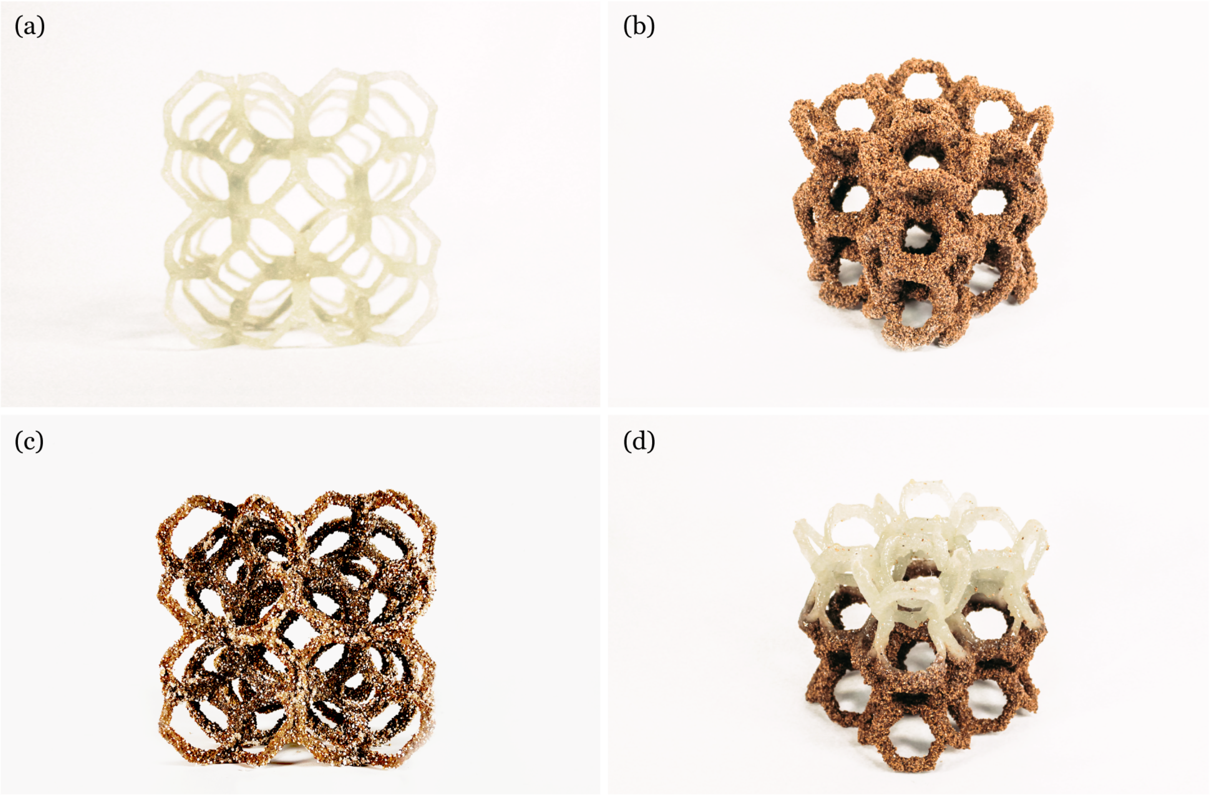


Figure 6.10: The third experiment investigates the flexibility of the NGP process when printing the same geometry from different materials. These prints were made from (a) glass beads, (b) walnut shell, (c) sand, and (d) a combination of glass beads and walnut shell [68].

used in other industries involved in, for example, surface preparation and sandblasting. In the context of this study, however, these materials present an additional interesting challenge because they differ in several characteristics. Glass beads, sand, and walnut shells, for example, vary in size from $\sim 400\mu m$, to $\sim 850\mu m$, to $\sim 1000\mu m$. In addition, they differ dramatically in surface texture, with glass beads being much smoother than sand and walnut shells being much rougher. Finally, they differ in weight, visual appearance, and ability to absorb liquid.

For all four test prints, an identical toolpath was used to create a hexagonal lattice structure of 12 cells. This object measures 15 cm x 15 cm x 15 cm. The toolpath was adjusted to print the object along a continuous spatial polyline, starting at the lower portions of the build tank and moving the nozzle up through the granule volume. The geometry of the lattice structure and its orientation in the tank avoids any vertical lines or alignment between the nozzle and the toolpath, and instead consists mainly of diagonal movements of the dispensing system.

The subsequent NGP printing process uses exactly the same technical settings for all four objects. After curing, the parts were carefully removed from the build tank and compared with each other. As expected, the print made from the fine glass beads **(Fig. 6.10 (a)** is the most accurate, while the coarser sand and walnut shells resulted in rougher print quality **(Fig. 6.10 (b))**. This is likely due to the smaller particle size of the glass beads, which absorb the binder better, and to their smoother surface, which creates less friction as the nozzle moves through the volume. It is also noteworthy that the print made from walnut shells is visibly thicker than the glass bead print. This is probably the result of the larger particle size of the material. This difference could also be related to the fact that the coarser geometry of the particles creates larger air pockets between them that fill with more binder, which in turn can bond with more particles. In comparison, the result of the sand print falls between the other two. However, the sand print is remarkable during the printing process itself, as the print is accompanied by a noticeable scratching noise, probably caused by the friction between the stainless-steel nozzle and the granular sand particles. Finally, the dual-material print also turned out to be surprisingly successful, showing high accuracy compared to the digital toolpath. Regardless of the different materials, the liquid binder was able to adhere the glass beads and the walnut shells well to each other, resulting in a quite strong hybrid part with different mechanical properties. Even the reuse of the mixed material left in the build tank did not prove much of a problem. Since the particle sizes of the two materials used differed greatly, they are easily separated from each other by using a coarser strainer that only allows one material to pass through.

Technological Comparison

In this study, the same geometry from the previous experiment is used to compare several 3D printing technologies: Selective Laser Sintering (SLS), Stereolithography (SLA), Fused Deposition Modeling (FDM), and Non-Planar Granular 3D Printing (NGP). The objective of this study is to evaluate NGP's performance in comparison to a few of the established technologies and identify it's key advantages **(Fig. 6.11)**. In this analysis, only computer simulations were conducted, without being printed, using commonly used slicing software.

The first technology to be examined is SLS, because it shares a similar powder-based material approach with NGP. In this simulation, the Formlabs Fuse 1+ 3D printer is used, along with the proprietary Formlabs software, Preform. The SLS technology uses the unsintered powder surrounding the 3D printed object as an inherent scaffold, therefore, not requiring any additional 3D printed supports. Despite the high resolution the technology is capable of achieving, the layer-based approach is a key factor in extending the overall printing duration.

The second and third technologies to be examined are SLA and FDM, both of which require 3D printed support structures to achieve the tested geometry. This factor leads to significant material wastage, as depicted in **Fig. 6.11 (b)** and **Fig. 6.11 (c)**. The platforms selected for this study are the Formlabs Form 3L SLA printer, and the Raise 3D N2 FDM

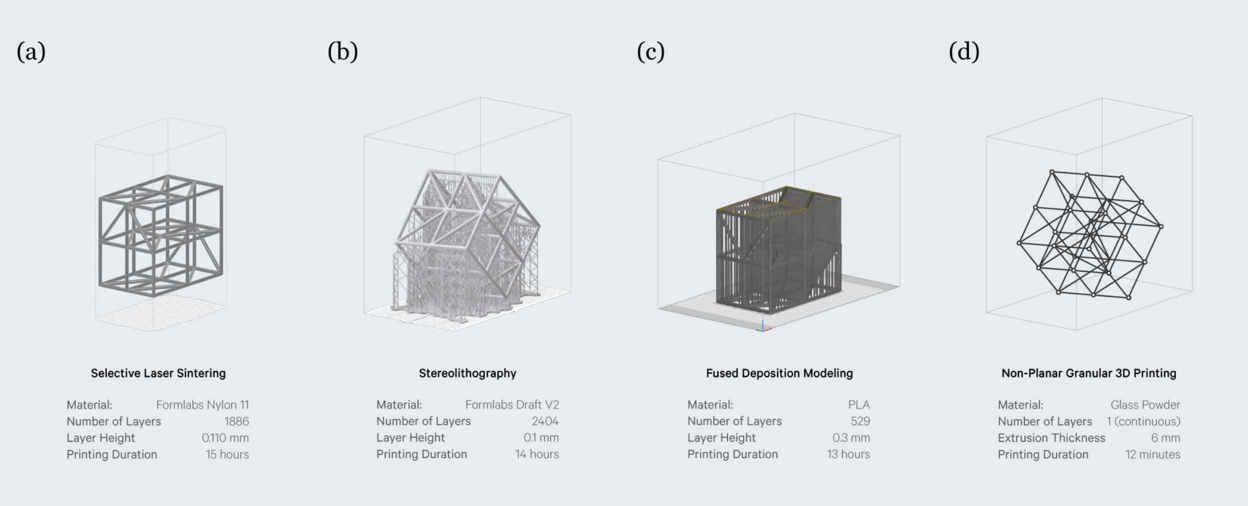


Figure 6.11: Comparison of several 3D printing technologies applied to the same 3D model, highlighting differences in material usage and printing durations.

printer, chosen for their relatively high speeds and compatibility with commonly used slicing software. Even though both 3D printers employ a layer-based approach, the layer heights can be adjusted to marginally reduce the printing duration. However, it is important to note that the SLA workflow requires additional post-processing. This includes cleaning and UV curing the 3D printed parts, further extending the overall production time.

Finally, the NGP process is examined and compared with the other technologies. As illustrated in **Fig. 6.11 (d)**, an obvious distinguishing factor is that the NGP process does not require a 3D model in standard mesh format. Instead, it uses a user-defined toolpath that significantly reduces both the size of the G-CODE file and the preparation complexity. Perhaps one of the most important advantages of the NGP process is that it is not layer-based, significantly cutting down the printing time to approximately 1.5% of the duration required by other methods. However, it is important to note that the drying time of the liquid binder used in the NGP process varies, and can therefore, significantly increase the overall printing duration.

6.8 Implementations

To conclude this study, a fourth experiment is conducted to determine whether the NGP process can be used for the development of products. This experiment is performed taking into account the findings and best practices from the previous experiments that influenced decisions related to toolpath design, printing speed, and material selection. The main challenge here is that the object to be printed is larger than a single container and taller than

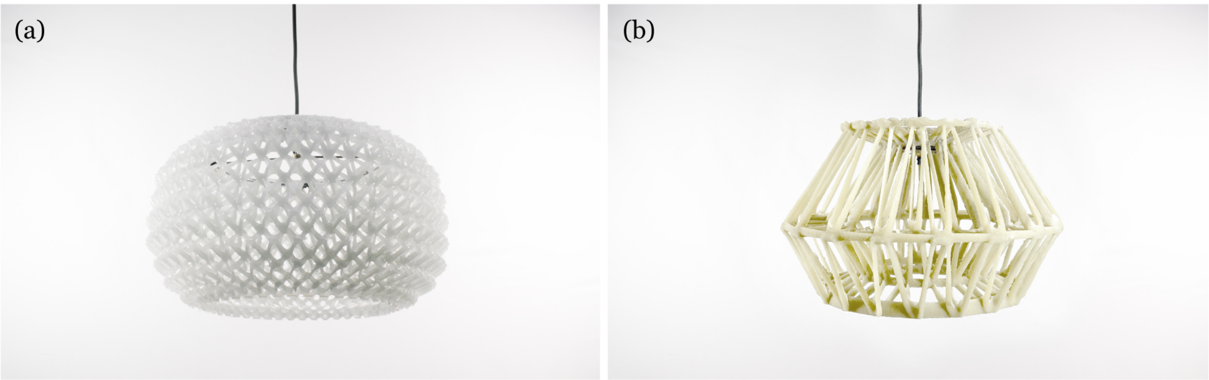


Figure 6.12: Demonstration of the NGP process in the context of a product development in which lattice objects with unsupported geometric features are produced. (a) printed in 4 hours and (b) printed in less than 45 minutes [68].

the printing nozzle. In the previous tests, the size of the tank and the amount of material it contained depended on the length of the dispensing nozzle. Therefore, the depth of the granular volume in the tank must be approximately less than or equal to the length of the nozzle. This contingency also limited the size of the printed test objects in the previous experiments. To overcome this limitation, a modular build tank is developed that allows multiple containers to be stacked and sequentially filled with granular material during the printing process, increasing the effective print volume.

In this experiment, two test objects were printed, as shown in **Fig. 6.12**. Both designs are composed of geometric lattices that would typically require additional supports. The two objects exceeded the print volume of a single container and took advantage of the modularity of the build tank design. Furthermore, the larger size of the test objects required quantities of liquid binder greater than a single cartridge could provide. This challenge was approached in two different ways. The first object design had an outer diameter of 50 cm and 35 cm height, shown in **Fig. 6.12 (a)**, and was divided into four toolpaths, each requiring approximately the amount of binder in a 20 oz. cartridge. This printing process therefore necessitated the replacement of cartridges after the completion of each of the four toolpaths. While this was in principle possible without any problems, it meant that the team had to be prepared with the pre-mixed liquid resin in order to quickly exchange the cartridges manually.

The second object had an outer diameter of 50 cm and a height of 40 cm and due to its size was divided into three toolpaths, as shown in **Fig. 6.12 (b)**. In comparison, the printing process for the second object was much smoother. This was mainly due to the more complex dispensing system used. Here, the two-part resin was stored in two tanks and fed in a 3:1 ratio via a variable speed pump to a mixing nozzle at the end-effector. This setup makes it possible to inject larger amounts of resin into the granular material and to fine-tune the mixing ratios and curing times to the specific needs. The setup also made the printing process much faster, as no manual steps were required. The same glass beads were used as granules in both tests. Another reason why the second print is significantly faster is the use of an epoxy resin with a lower viscosity, which was absorbed more quickly by the glass beads and therefore resulted in more significant thickness variations depending on the motion speed of the robot. To account for this material behavior, the three toolpaths of this test object were programmed with variable speeds for different sections of the printed geometry. This ensured that the base and central attachment point of the geometry were printed with thicker extrusions, making these areas stronger.

These tests establish that the NGP process can be successfully integrated into the fabrication of products and enables the printing of shapes larger than the nozzle and the original build tank. Although both objects are quite similar in their external dimensions, the first test took about five times as long as the second. This was primarily due to the fact that the cartridges had to be refilled manually and the liquid binder had to be mixed in a cumbersome way. The second test was much faster and took only about 45 minutes to complete. While the size of this print also required stacking more sections of the modular containers and filling them with granules, this step only took about two minutes. The decisive time saving observed in the second test came from the use of the complex dispensing system. The ability to store the 2-part binder in separate containers and mix it by means of precise pumps automated the process and made the printing sequence much cleaner and less prone to human error.

6.9 Conclusion

This study contributes to the field of large-scale 3D printing by introducing a novel additive manufacturing process called Non-Planar Granular 3D Printing (NGP). The aim of developing this technology is to address some of the key challenges in 3D printing and bring forward new opportunities related to printing speed, material diversity, and scalability. The experiments presented in this paper explored some of the key capabilities and limitations of the new NGP process. This was demonstrated using a series of benchmark tests that had challenging geometric features which would be difficult to produce using conventional 3D printing techniques.

The research also uncovers several critical limitations of the NGP technology through comprehensive experimentation and analysis. Some of these challenges have been mitigated through hardware and process developments and findings. Notably, the air-sleeve nozzle design contributes to allowing the NGP technology to accommodate a more diverse material palette, aligning with the primary objective of this research, which is to expand the number of materials that can be used as granular elements in the process. Additional advancements encompass a novel pumping system and a modular build-volume, both of which enhance the process scalability. This integrative approach highlights the impact of physical experimentation on shaping the technological framework of the NGP process.

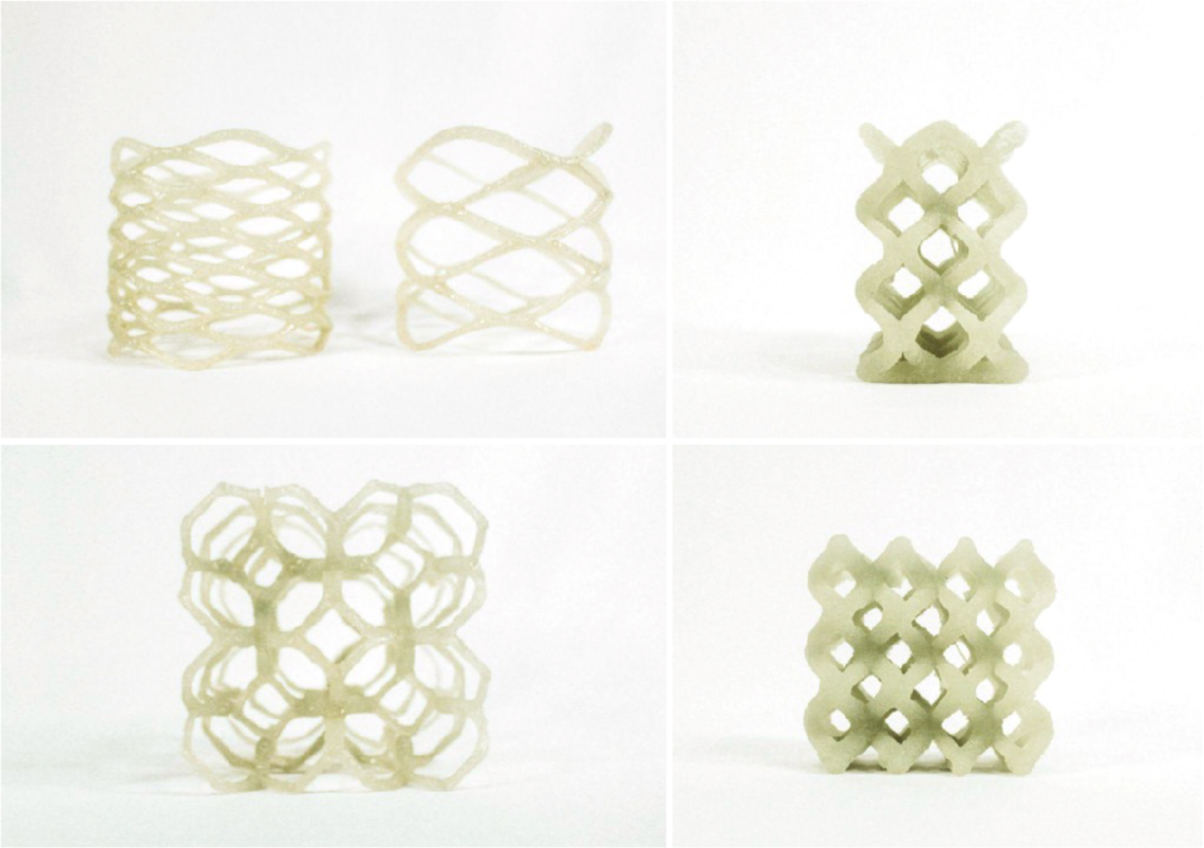


Figure 6.13: Since non-planar granular 3D printing (NGP) does not require additional support structures to print overhangs and bridging elements, prototypes with different shapes and challenging geometric features can be produced much faster [68].

In conclusion, there are several possible avenues for future work that build on the findings presented. First, further research and experimentation can be conducted to refine the process of developing multi-material objects, which seems to be one of the most unique features of the NGP process. For example, by developing a system to selectively fill the tanks, granules could be placed exactly where a particular material is desired. This could result in opportunities to fabricate structures with mechanical and functional material gradients. In addition, future research could investigate the integration of mechanical components into the NGP process. For example, hardware embedded in the build volume can be enclosed by the 3D printed material and serve as reinforcing elements or as mechanical fasteners and connectors. The results of this study form a solid basis from which to investigate new possibilities and should be understood as an invitation to further develop this promising technology.

Chapter 7

Support-Free 3D Printing

7.1 Overview

A fundamental challenge that calls for innovative construction solutions is the scarcity of construction source material [296]. Over the past eleven decades, the global use of natural resources for the construction and transport infrastructure increased exponentially [149]. Sand and gravel represent a substantial portion of this material, making them the most extracted materials globally . Ever since , global material use has been growing on average by 2.7% annually [298].

The emergence of digital fabrication technologies offers promising avenues for addressing some of the current construction challenges. However, to realize the potential in fostering sustainable structures, these technologies must be integrated with material-efficient construction methods and sustainable material systems [322]. Addressing some of the highlighted challenges, this research investigates the potential of computational design and robotic additive manufacturing as tools for exploring avenues for more sustainable construction practices.

At the intersection of the ancient techniques of vault and brick construction with modern additive manufacturing, this chapter introduces a series of studies that aim to maximize the capabilities of additive construction. Focusing on exploring the untapped potential of non-planar 3D printing, inspired by traditional craftsmanship and ancient construction processes, the research investigates the feasibility of using 3D printed clay and adobe to construct a series of compressive structures, that can be achieved without relying on formwork and falsework. Progressing from smaller explorations, the research sets out to construct a so-called Nubian vault at an architectural scale using 3D printed adobe.

A primary objective of this research is to bridge the gap between traditional building techniques and robotic manufacturing processes, demonstrating how ancient architectural principles can not only be adapted and maintained, but also drive innovation for contemporary construction practices on a material, structural, and construction sequence level. The research conducts a close analysis of ancient construction techniques, adapting their fundamental principles into 3D printed toolpaths. It draws parallels between traditional structural elements such as loose bricks and the extruded materials used in construction 3D printing, highlighting how the structural behaviors and construction strategies can be transferred from one method to the other.

Through multi-scale physical prototyping, the experiments presented in this research focus on replicating the distinctive structural qualities of ancient vaults and domes – particularly their self-supporting double-curved geometry – into non-planar large-scale 3D printing, clarifying some of the challenges associated with toolpath design, material mixtures, and drying times. The research highlights an iterative development process, where various geometric configurations are tested on a smaller-scale before progressing to the construction of an architecture-scale prototype. The initial small-scale tests, made of 3D printed clay, allow for the exploration of different vault and dome configurations and parameter optimization to ensure structural stability. These primary trials provided valuable insight that guided the construction of a full-scale Nubian vault.

Addressing the challenge of material scarcity and sustainable construction, the constructed full-scale prototype utilizes locally sourced materials as a viable alternative to commonly used 3D printed concrete, thereby exemplifying the implementation of sustainable construction. Moreover, the final experiment also demonstrates the use of a self-sufficient, mobile industrial robotic 3D printing and pumping platforms. Through this integrated approach, the research emphasizes the importance of resource efficiency and fabrication sustainability. This workflow points towards a future where the scarcity and obstacles associated with traditional resources can potentially be mitigated through innovative and environmentally conscious construction practices.

7.2 Introduction

Interest in 3D printing has grown substantially, particularly from automated construction companies and research institutions seeking efficient and cost-effective solutions for housing and construction [128] [174] [55][309]. This growth can be traced by mapping the prevalence of publications in this area of research, which has been increasing over the past decade. Tay et al. (2017) identified the latest research trends in large-scale additive manufacturing, where questions of material development are most frequent [290]. Led by challenges concerning material properties and behavior, this area of research is continuously evolving to address some of the technological limitations of large-scale additive manufacturing.

The most recent developments in large-scale 3D printing have utilized viscous and cementitious materials that have proven suitable for their property tunability and handling during the production process. However, these loose compounds are sensitive to gravity and environmental factors, and are not able to sustain high tensile forces while in their wet state. These considerations limit the design of 3D printed structures to simple, vertical extrusions that are sliced into horizontal layers, parallel to the ground plane [236] [33]. While additive technologies are hailed for their promise to expand the variety of possible architectural forms, the properties of viscous materials have eliminated those that require formwork or external support integration. This limitation is particularly noticeable in recent 3D printed buildings which, for the most part, include only printed interior and exterior walls; examples of 3D printed roofs remain limited. Most roofs of 3D printed buildings are made of flat timber or metal structures, limiting possible design opportunities, and requiring off-site fabrication and deployment.

Printing the roof

3D printing roof structures has been largely unexplored. Perhaps the first 3D printed roof was fabricated by the Italian company D-Shape in 2010 for the Milan Triennial [65]. The fabrication of this roof was achieved using large-scale binder deposition with magnesium oxide through a binder-jet 3D printing process. Implementation of such a process creates a support structure using the material that is unsolidified in order to reinforce the gable roof during the printing. AICT, a 3D printing construction company based in California, also fabricated a series of barrel-vaulted roofs by printing semicircular extrusions as concrete prefabricated elements that could then be lifted and rotated to create an enclosure [11]. Another example of overhead structures, in this case a ceiling, was fabricated by the Block Research Group at ETH. In this example, a 3D printed formwork whose geometry had been structurally optimized was used to create prefabricated concrete floor tiles (and subsequently a patterned ceiling) in which thin vaults were stiffened by diaphragms to create a structurally optimized horizontal overhead surface [35]. In each case, the construction of the roof using additive manufacturing is accomplished through the use of formwork and prefabricated elements that are moved into place on the construction site.

Supporting Structures

The quest to construct wide-span roofs can be traced back to ancient architecture. In early Egypt, for example, barrel vaults were constructed from adobe using various masonry techniques to build storerooms within temples [77]. Ancient Roman architecture continued to advance techniques for wide-span structures using masonry and concrete casting, with the Pantheon being perhaps one of the most notable examples [60].

Analyzing vernacular architecture as a historic precedent unveils the diverse materials, structural configurations, and construction methods that distinguish different regions of the world. In roof construction, vernacular dwellings historically utilized materials such as timber, turf, stone, and adobe. Regions lacking abundant timber resources took advantage of creative methods to construct structures that harnessed compression such as vaulted roofs, arches, and domes. In most cases, the construction of these roof structures required the use of timber as a structural formwork material, or soil, which could be removed after the structure was completed. *Corbelling*, a method of vault construction used by many civilizations, had not yet developed curving arches; it involves the successive placement of masonry elements in layered, cantilevered arrangements to form spans. This can be seen in Mayan temples or in the Cardenha buildings in Vale de Poldros, Portugal **(Fig. 7.1)**, where dry

Figure 7.1: Cardenha buildings in Vale de Poldros featuring corbelled masonry roofs [71].

stone masonry was used in the construction of the roof [181]. Mediterranean tile vaulting is another notable method that gained prominence in medieval Spain and was introduced to the United States by Guastavino [69] [213]. This method makes use of thin ceramic tiles in structural vaulting in which minimal formwork (centring) is required during construction. Regions constrained by timber scarcity, such as the Saharan desert, explored alternative methods to roof construction that did not require any use of formwork. The ancient Nubian technique entailed inclining layers of brick in the shape of a parabola towards a rear wall to efficiently transfer forces from the temporary structure with minimal tension and bending [66].

7.3 Analyzing Historic Techniques

Throughout the ages, humankind has demonstrated substantial uses of arches, vaults, and domes that have appeared in diverse forms according to the local context in which they were initiated [157][176]. Differences in materials and construction techniques were driven by a complex matrix of factors such as environment, material abundance, and other socio-cultural patterns [176]. Throughout all eras, the construction of vaults, arches , and domes has provided exemplary structural systems and areas of shelter. Although these long-spanning, unsupported forms are effective, they are expensive because of the requirement for temporary falsework and construction labor. Regions of the world with limited access to timber, however, made structures whose stability mainly relies on compression to resist gravity loads, eliminating the need for falsework [85][96].

3D printing unsupported structures in large-scales requires the use of formwork and falsework, which complicates the construction process and defies the overarching vision of 3D printing, which aims to reduce construction cost and waste. The additive nature of masonry construction used in the above-mentioned structures offers the opportunity for comparison with 3-D printing; we may learn from the ancients and adapt their methods in the printing of large-scale structures. To better illustrate the potential of adapting brick laying logic into

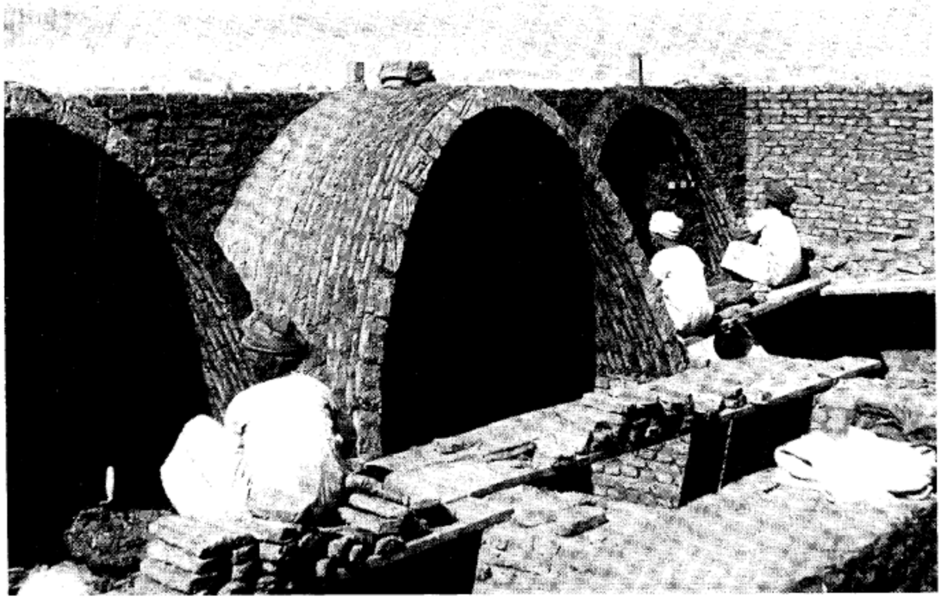


Figure 7.2: Ancient Nubian vault construction, wherein the inclined faces of the layers forming the vault provide support for the subsequent layers [96].

3D printing applications, it is useful to first look at historic precedents and highlight the different strategic approaches in various world regions. A key quality that is common in all case studies is their use of elements with low tensile strength, which demands strategies that maximize compression.

Some of the oldest vernacular construction methods used adobe and rammed earth to construct compressive structures. Countless examples of earthen structures which were built over a thousand years ago have survived into the 21st century, including the Great Wall of China, in which some sections that are made of earth [219]. Evidence has also shown signs of earth construction built by Phoenicians in the Mediterranean basin around 814 B.C [219]. Another notable example is the city of Shibam in Yemen, which contains earthen high-rise buildings that were built over a hundred years ago [13]. A more relevant example of a funicular structure that uses mudbrick as the main construction element is Taq Kasra, which remains the largest brick vaulted structure in Persian history. Because of the material used and method of construction, the funicular shape of the vault results in compression behavior [85].

Ancient Persian architecture is known for its rich geometric layouts and engineering knowledge, which has been influenced by cultural and religious changes in the region. Around 2000 B.C marks the beginning of arched roofs, which are made using brick and mudbrick [124]. Notable architectural elements in ancient Persian architecture are dome structures such as bulb domes. Additionally, important features to highlight are the corner conditions, such as *squinches* and *pendentives*, which act as transitional architectural elements between square plans and domes with round bases. Squinches gradually morph the geometry of a square into an octagon, and then into a hexadecagon with sixteen sides, which approximates the shape of the circular dome base[85]. Pendatives, on the other hand, are triangular segments of a spherical surface, which fill the upper corners of a room to form a circular top for a dome to be placed [222].

Roman vaults are another notable example which makes use of the technique of centering, which is a type of formwork that is used to create arched and vault structures. Since the arch is not able to support its own weight until the keystone is inserted, this method requires formwork for temporary structural stability. Roman vaults are capable of covering wide spans, making them effective solutions for roof structures. Although the construction of Roman vaults requires the use of formwork, they have the advantage of surface continuity, which may be an adaptive solution to 3D printing applications that require continuous material deposition.

In comparison to Roman vaults, *Gothic vaults* are structures that use less formwork, allowing for complex, yet creative structural solutions. Gothic vaults rely on the use of ribs as formwork, while masonry filled the gaps between the crossing ribs. The formwork is only temporarily used, and is removed once the mortar is dry [85]. *Fan vaults* are also introduced with the gothic influence in England. Fan vaults are composed of concave sections with ribs spreading out like fans [295]. An example structure can be found in the interior of the Gloucester Cathedral in England.

Another common method of creating enclosed spaces is *corbelling.* As a rule of thumb, maintaining corbelled angles that are larger than 65° can obtain stable layers due to the minimization of the overall cantilevered amounts and helps shift the center of mass of the structure towards the base [206]. Corbelling is also used in drystone applications where structures are built without the use of mortar and are completely dependent on compressive forces [122].

In areas with low availability of timber or other formwork material, alternative methods had to be developed for the construction of room structures and enclosures. The Nubian vault, a method of formwork-less vaulting, was invented in ancient Nubia and rediscovered by Hassan Fathy. The structure utilizes a back wall against which layers of brick rest. The brick layers are then sequentially optimized to maximize compression, creating a catenary shape, as shown in **Fig. 7.2** [85][66][36]. An example of Nubian vaults can be found at the New Gourna Village in Egypt [117] [273].

Masonry and 3D printing

Similarities between masonry construction and 3D printing are most evident in the behavior of the unit (brick or extruded layer), and the layering sequence of both systems. The comparison between masonry walls and 3D printed layers has been discussed since early proposals for large-scale 3D printing. Pegna (1997) referred to the 3D printing process as "a new approach to masonry" [223]. Carneau et al. (2020) also subdivides 3D printed struc-

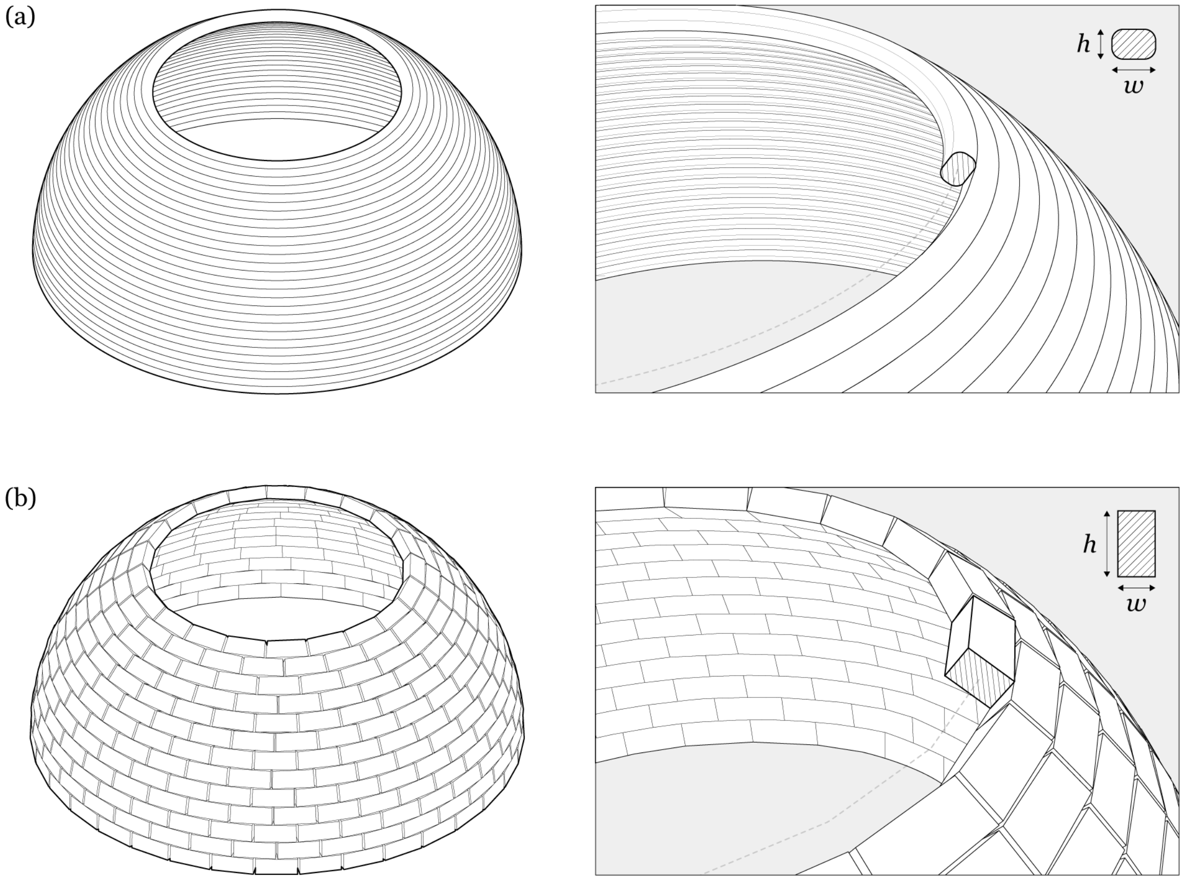


Figure 7.3: Comparison of a 3D printed dome and a masonry dome. (a) the 3D printed dome features inclined layers, specified by extrusion dimensions. (b) the masonry dome is constructed from bricks that are defined by specific dimensions, featuring a similar orientation and alignment to a target surface as the 3D-printed dome.

tures and masonry walls into three categories: the component, the layer, and the complete structure [49].

Masonry walls are composed of discrete elements (bricks) with specified dimensions, and are typically connected together using mortar. Mortar is required for the stability of bricks during construction until it sets. Similarly, 3D printed extrusions can also be defined by the dimensions of the width and height of the deposited material. Like bricks and mortar, extruded materials are dependent on the adhesion between layers until the materials have cured and taken form as shown in **Fig. 7.3**.

Masonry structures are composed of horizontal layers made by stacking numerous components. These layers follow a certain direction that defines the straight or curved form of the masonry wall **(Fig. 7.3 (b))**. 3D printed structures are also composed of layers that commonly represent cross-sections of the 3D printed geometry **(Fig. 7.3 (a))**. This process is often composed of a number of steps determined by the resolution of the 3D printed object.

Both masonry walls and 3D printed objects made of viscous materials encounter a phase of instability during construction. In the third category of classification proposed by Carneau et al. (2020), both masonry walls and 3D printed objects are well suited for compression, while they are both weaker in tension [49]. Based on the above-mentioned levels of classification, some of the challenges in large-scale 3D printing related to formwork integration, material instability, and form restriction can potentially follow footsteps of ancient masonry builders by translating the logic and construction sequence of masonry, to viscous material extrusions.

7.4 Motivation

Many of the current 3D printing projects focus on the construction of vertical walls, avoiding the printing of horizontal, long spanning structures such as roofs. Most of these projects rely on the extrusion of viscous materials such as concrete, which is extruded in a liquid state and requires a hardening period. This material characteristic presents a challenge when constructing unsupported geometry, since each printed layer relies for stability on the support of the preceding layer, which may not have yet hardened.

The historic pursuit of constructing roof structures dates back to ancient times, as different regions of the world utilized a rich variety of materials, structural designs, and construction techniques. Some of these methods included harnessing compression to construct vaulted roofs, arches, and domes made of loose bricks that were strategically stacked in patterns.

In the context of construction 3D printing, there is an opportunity to draw inspiration from these age-old techniques and incorporate them into the design of 3D printing toolpaths. By adapting some of these ancient approaches, extruded wet materials could potentially take advantage of ancient principles to overcome current drawbacks in construction 3D printing.

Masonry structures are composed of individual units in the form of stones or bricks that are often laid in a systematic manner and/or bonded together to form architectural elements that not only vary in textures, colors, and appearance, but also in structural performance. Many different repetition criteria and laying patterns have been developed throughout the history of masonry construction. Sumerians, for example, laid bricks in plano-convex herringbone pattern arrangements that provided double interlocking in dual directions, preventing vertical compression and possible horizontal shear **(Fig. 7.4)** [243][75]. Following a herringbone pattern ensures interlocking in both directions, which prevents undesired continuity in the joints. In this condition, bricks are bonded together on at least on two sides, maximizing their contact to one another, preventing falling during construction and guaranteeing the structure's stability upon completion. 3D printing adopts a similar approach, where

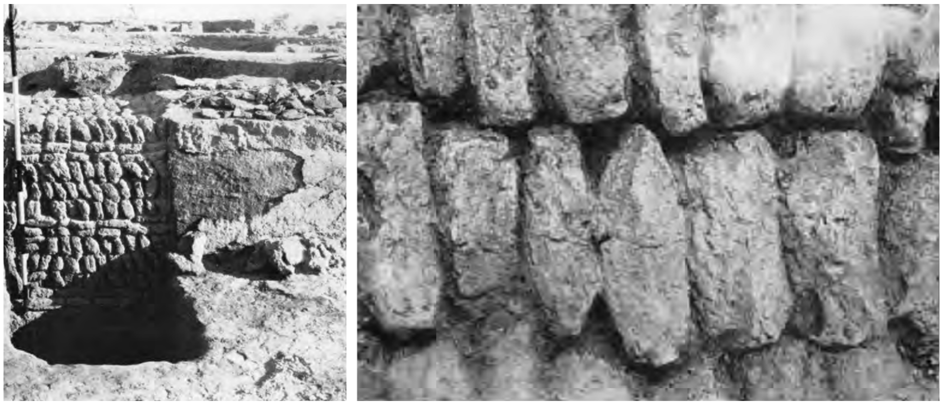


Figure 7.4: Interlocking plano-convex brick arrangements at Khafaje, Iraq [130].

layer-by-layer deposition causes the risk of cold joint formation between layers, making the weakest link in the structure [144]. This is mostly common when 3D printing viscous and cementitious materials such as concrete

A key quality of masonry construction is stress behavior, where individual units do not sustain tensile strength, and therefore are required to work in complete compression. Masonry units in vaults, domes, and arches are oriented in such a way that the thrust line causes minimal stress at the joints between masonry units. If the thrust line is perpendicular to the joints between masonry units, the result is a compression-only structure. When theoretically comparing masonry units to 3D printed layers, particularly in the construction of arched geometry, 3D printed layers are preferably oriented to be as near as possible to the perpendicular vectors to the thrust line.

A challenge in 3D printing using viscous and cementitious materials is ensuring the stability of the printed object as more layers are being loaded. Carneau et al. (2020) identifies the potential failure modes in mortar 3D printing: a global instability of the object, a plastic collapse, and an elastic buckling of the structure [49]. Reiter et al. (2018) also illustrates the link between the yield stress of the material and the time since the material has been extruded, highlighting the possibility of failure during the printing process [249]. This research is driven by the challenges associated with viscous material instability and the promising similarities between ancient masonry construction and construction 3D printing. The aim of this research is to investigate and validate how the ancient principles of masonry in constructing compressive forms can be adapted into 3D printing strategies.

7.5 Proposed Fabrication Method

The concept of support-free 3D printing refers to the adaptation of logic and construction sequence strategies in historical construction of compressive forms to methods of toolpath generation, targeted towards 3D printing viscous and cementitious materials. Bridging the past and the present, ancient masonry construction shares intriguing similarities to the more recent large-scale 3D printing process, particularly in aspects such as material behavior, repetitive layering, and the instability of the discrete unit. Masonry structures are built from brick units, which are connected sequentially using mud or mortar, taking their final stable form when the material dries or sets. Similarly, the structural integrity of 3D printed layers of extruded material is dependent on layer adherence and the drying of the material throughout the construction process. Both masonry work and large-scale 3D printing rely fundamentally on stacking layers of identical components in a repetitive manner. Drawing a parallel with traditional masonry construction techniques, most approaches to construction 3D printing use planar layers. When constructing curved forms, this approach can be compared to corbelled masonry, where the geometric contouring of arched shapes like vaults and domes leads to a distinct stair-stepping appearance, resulting in non-uniform layer displacements.

The experiments discussed in this study take advantage of non-planar 3D printing, ensuring that the printed layers correspond with the line of thrust, culminating in structures that are entirely in compression. This approach is comparable to that of domes or arches constructed using brick joints, which are aligned at right angles to the line of thrust. Several studies have demonstrated the potential application of masonry vault construction techniques to additive manufacturing, using either computer simulations or by fabricating small-scale prototypes [199]. This research further explores this concept, initially by presenting geometric configurations that are suitable for the suggested freeform 3D printing method. Subsequently, the studies evaluate these designs, beginning with small-scale experiments and culminating in the construction of a full-scale Nubian vault that is printed in-situ.

7.6 Research Objectives

In response to the challenges addressed in the previous sections, this study seeks to test and validate a method of formwork-free 3D printing. A primary objective is to gain a better understanding of the proposed method and its application through the critical testing and evaluation of adapting traditional brick-laying patterns into robotic 3D printing toolpaths for support-free 3D printing.

A core challenge driving this research is the high costs associated with formwork and falsework construction needed when constructing horizontal structures such as roofs or shells. Furthermore, due the use of formwork only temporarily, construction generates significant material waste, making the construction of certain geometric configurations inefficient [266]. While some formwork solutions are reusable, reducing material cost, they remain labor intensive and require long construction times.

This research aims to address these challenges by suggesting an alternative approach and testing its viability, benefits, and constraints. The objectives of the proposed method are three: first, to reduce material waste in construction; second, to reduce the amount and cost of required labor in large-scale construction while also lowering energy consumption; and third, to significantly reduce construction time when building roof structures. Furthermore, this study is also fueled by question regarding scalability, self-sufficiency, and the efficient use of historically proven, sustainable, low-impact materials.

The research addresses these challenges on a multitude of levels, with specific goals outlined for each. At the geometric level, a main objective is to investigate various architectural typologies such as vaults and domes through a comparative analysis of their construction strategies and their translation into 3D printable toolpaths. The aim is to test these typologies on a lab scale and potentially combine successful configurations in order to arrive at new ones.

On the material level, the focus is to first conduct experiments using 3D printed clay as a base material that is comparable to wet, extruded concrete or adobe. This exploration helps understand the behavior of viscous materials during the construction process, informing the optimization of the toolpath and overall workflow. The ultimate goal is to then use adobe as a material in a large-scale experiment. While challenging, adobe's slower curing time compared to concrete emphasizes the importance of geometry and process workflow over the reliance on material properties.

On the process level, the research compares 3-axis and 6-axis 3D printing platforms through physical testing. This comparison helps identify the benefits of multi-axis extrusion and non-planar 3D printing in this context, as compared to layer-based techniques.

The final objective of this research involves large-scale experimentation. Throughout the process, insight from lab-scale studies informs a full-scale experiment, integrating knowledge on the material, geometric, and process levels. The final full-scale experiment serves as a technology demonstrator of the proposed method. It also allows for the evaluation of the proposed method at a real-world construction site under environmental elements.

7.7 Experiments

Experiment 1: Adapting Masonry Principles to 3D Printing

Setup

To better understand the viability of 3D printing unsupported forms using a viscous, structured fluid, it is essential to first gain insight through small-scale prototypes that test various aspects of the design and fabrication process. In these preliminary experiments, clay served as the primary 3D printed material. The clay was filled into plastic tubes mounted to an end-effector of a robotic arm, where a motorized piston within the tube facilitates the clay extrusion through a nozzle during the printing process. Drawing inspiration from traditional brick construction, some of the geometric forms printed during these tests were not sliced into planar layers. Instead, non-planar toolpaths were sometimes utilized, operating in multiple axes and nozzle orientations simultaneously. The prototypes are used to examine various geometric forms such as vaults, arches, apses, and domes. The objective is to understand how these forms can be realized through strategic toolpath planning, without the requirement of a supporting auxiliary structure. Concurrently, some tests explore toolpath strategies, aiming to gain an understanding of how the weight of the extruded material affects the unsupported geometry, especially when scaled up to a larger prototype.

At the platform level, the experiments demonstrate the capabilities of both 3-axis and 6-axis robotic configurations, highlighting benefits such as even material deposition, made possible by conforming to the curvature of the printed geometry. Additionally, testing various platforms allows for a better understanding of the forms that are achievable even when utilizing some of today's commonly used 3-axis gantry-style robotic platforms.

Geometry

Examining the historic precedents outlined in the previous section helps identify various geometric forms that can potentially be 3D printed following principles of masonry construction. This section demonstrates a series of experiments where these forms are 3D printed using clay. The forms discussed in this section are based on five basic typologies: domes, apses, vaults, squinches, and pendentives. It is important to note that the forms discussed in this section only present a preliminary selection of funicular structures, and not all possible configurations. This series of tests further investigates various combinations of these preliminary forms demonstrating the potential to arrive at novel architectural possibilities.

Dome

A simple way to 3D print a domes is through corbelling. However, in the absence of formwork, a pointed dome is more favorable than a hemispherical dome **(Fig. 7.5 (c))**. That is because the angles of unsupported cantilevering sections in a pointed dome are smaller, enhancing structural stability. In addition to the conventional corbelling of layers, **(Fig. 7.5 (c))** illustrates an added inclination to the extrusion nozzle. This adjustment ensures that the printed layers are perpendicular to one another, effectively eliminating local bending moments and contributing to the overall stability of the printed dome.

Fig. 7.5 (a) and **Fig. 7.5 (b)** also demonstrate a squinch dome, which is composed of a square plan in which the four corners meet a point above the center of the plan. In this study, a squinch dome is printed using two different methods. **Fig. 7.5 (b)** demonstrates the possibility of 3D printing the dome through the *corbelling* of planar layers. This approach is challenged by the accumulation of the printed material's weight in the upper parts of the dome. Another challenge is the slow drying time of the wet clay, and its inability in a wet state to support the weight of printed layers. To address this challenge, during this test, the printing speed was increased in the upper layers in order to reduce the weight of the higher parts of the structure. By increasing the movement speed, less material is used in the upper layers, thus reducing the wall thickness and the overall weight. It is worth noting that this approach does not require any nozzle inclinations, and therefore can be printed using a 3-axis printing platform.

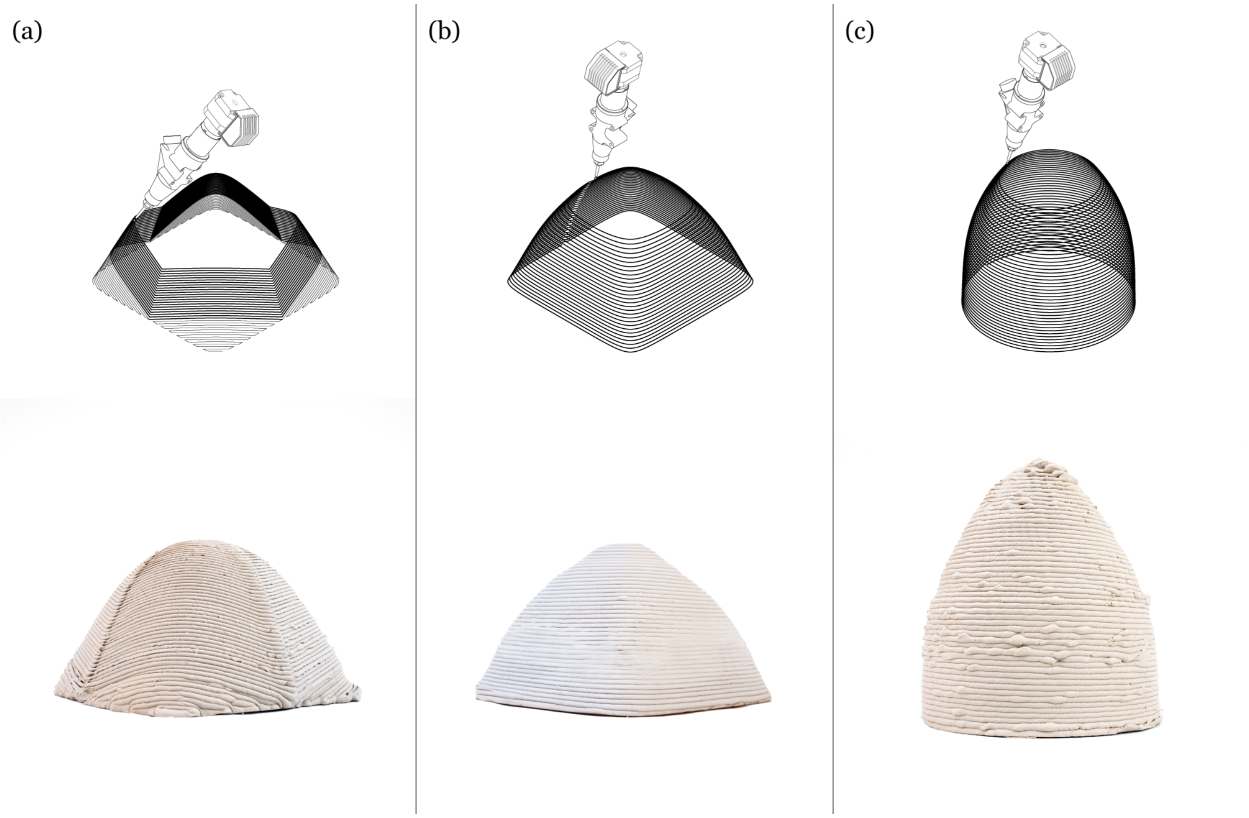


Figure 7.5: (a) 3D-printed squinch dome featuring four squinches at each corner of a square base, merging into continuous layers that progressively close the dome. (b) 3D printed dome constructed using corbelled layers that are adapted to a square-base plan. (c) 3D printed pointed dome constructed using corbelled layers.

A second method of achieving a squinch dome is demonstrated in **Fig. 7.5 (a).** Here, the four squinches of the dome were made of layers that lean towards the outside corners of the square plan. In this process, each squinch is printed separately, being made of enough layers to reach the middle of each edge of the square plan. Once the layers of the corners met, the printed layers that follow were merged into continuous non-planar layers. During this printing process, the nozzle orientation is continuously changing, always leaning towards the center of the dome, perpendicular to the printed layers.

Apse

An apse is characterized by a semicircular vertical wall that is covered with a hemispherical vault, or semi-dome, and can effectively be 3D printed without the need for formwork or falsework. Illustrated in **Fig. 7.6 (b)**, each layer of the 3D printed apse leans at a 30-

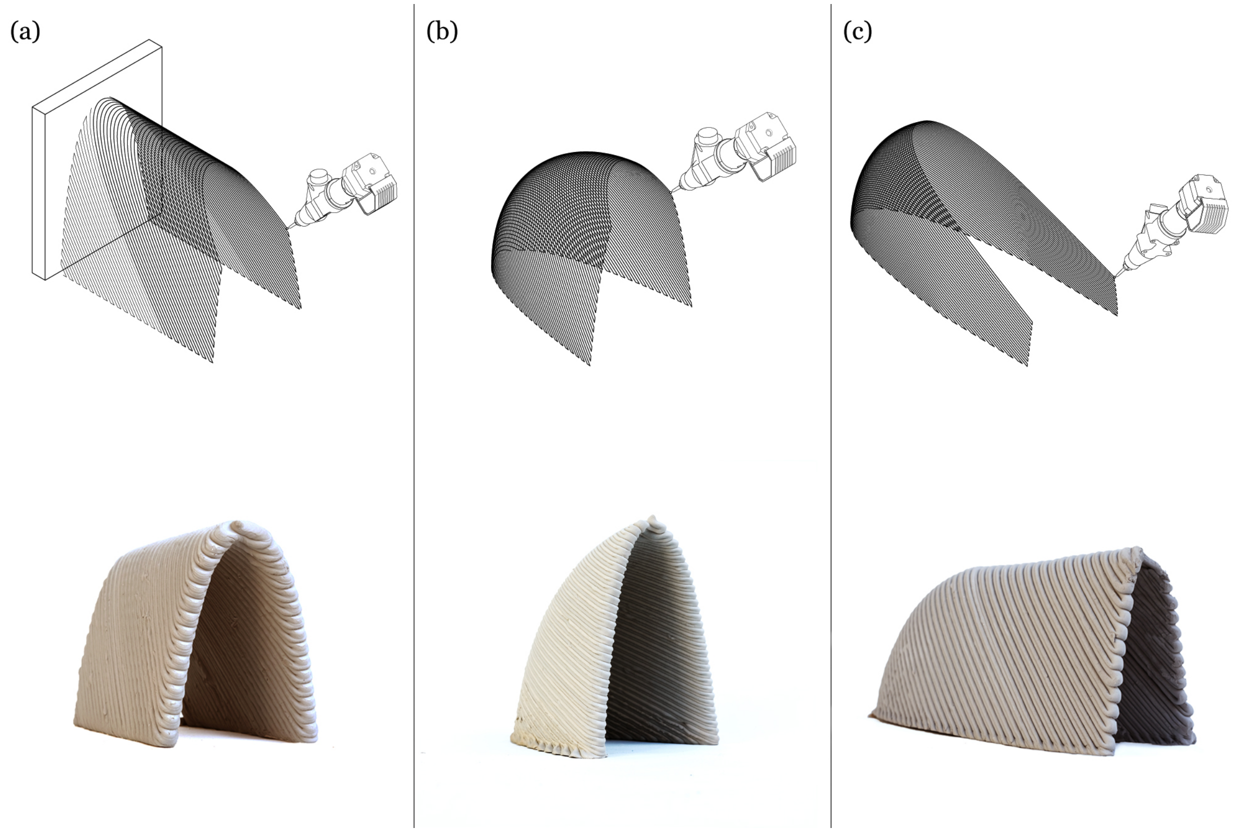


Figure 7.6: (a) 3D-printed Nubian vault with angled layers that lean towards a back wall. (b) 3D-printed apse composed of layers leaning at a 45° angle. (c) 3D-printed hybrid structure combining a Nubian vault and an apse.

degree angle. The construction process involves the initial printing of successive arcs that gradually increase in size to form the semicircular base of the apse. Subsequent layers are then added vertically while maintaining the same 30-degree inclination. The printed layers then gradually decrease in scale, culminating in the construction of the hemispherical roof of the apse.

Vault

A *Nubian vault*, essentially an arched ceiling or roof that is extended into space making a tunnel-like structure, can be 3D printed utilizing leaning layers as shown in **Fig. 7.6 (a)**. In the construction of the Nubian vault demonstrated in this experiment, the geometry was sliced into planar layers that are angled against a back wall. In this experiment, although the back wall could have been 3D printed, it was made of wood, and served the purpose of supporting the printed layers. During the printing process, the extrusion nozzle was oriented to

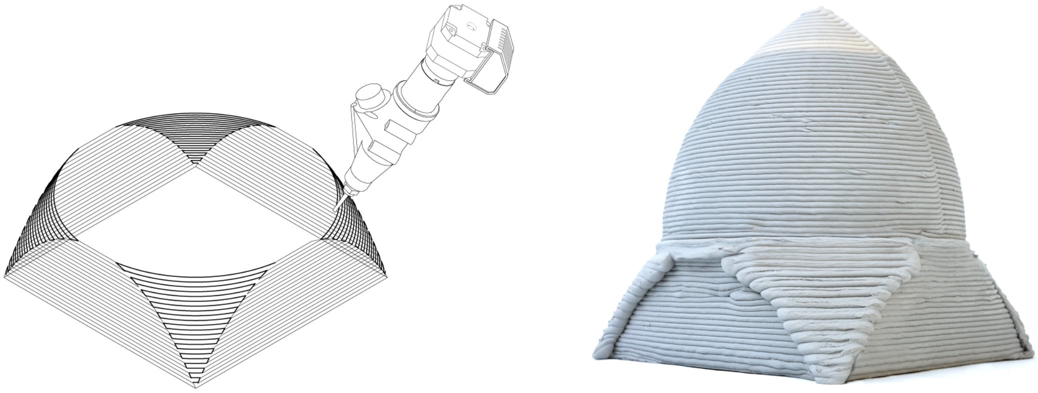


Figure 7.7: 3D-printed clay pendentives, designed to transition from a square to a round plan to support a pointed dome.

the perpendicular direction of the cross-sections, allowing for the vault construction without the need of additional formwork. The printing begins at the two lower corners of the vault, where it meets the back wall. Initially, smaller layers were printed, gradually increasing in size. These layers not only lean towards the back wall, but also toward the vault's center, enabling them to eventually meet the layers from the opposing side. As the printing progresses, the layers from both sides merged into continuous layers that cover the entire span of the cross-sections making up the Nubian vault. The printing then continues with layers being sequentially added, maintaining the leaning angle and advancing towards the front of the vault, ultimately forming a tunnel structure. **Fig. 7.6 (c)** also demonstrates another form of Nubian vault, where the back wall is substituted with an apse that is composed of the same arched vault profile. The construction of the apse begins from the ground plane, allowing it to effectively bear the weight of the vault's leaning layers. This approach results in a tunnel-like structure with a semicircular end profile.

Pendentives

Earlier sections of this study that discussed ancient Persian architecture introduced squinches and pendentives, as strategies for reducing stress and transitioning from square to round forms. These forms can also be adapted into 3D printed layer strategies. **Fig. 7.7** illustrates the transitioning from a square plan to a pointed dome, achieved by first 3D printing arch-shaped walls that are made of successive planar layers. To transition from the wall ends to the base of the circular dome, the gaps between the squinches were filled with 3D printed pendentives, creating a smoother transition from a square to a circular profile. Finally, a

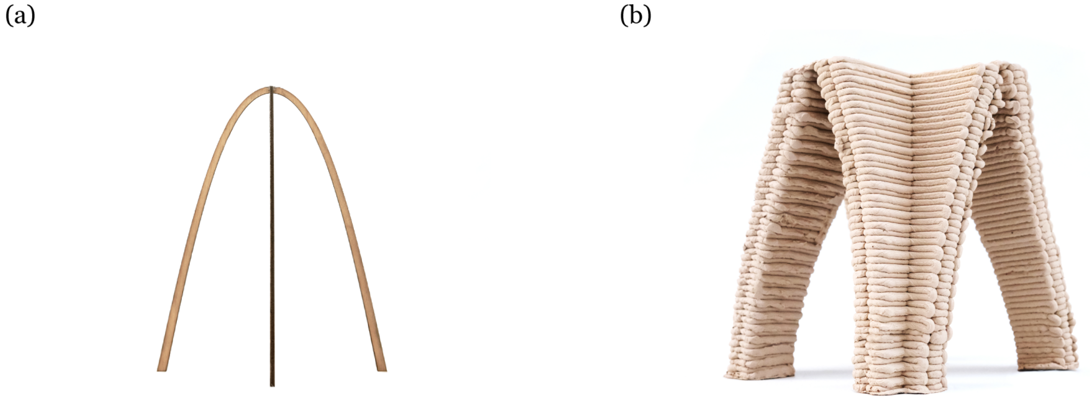


Figure 7.8: 3D-printed groin vault made of clay with minimal formwork (centering). The formwork was removed upon the completion of the printing process.

pointed dome was then 3D printed through corbelling at the center. This test demonstrates the coupling of multiple strategies to accommodate several geometric challenges. While the printing process of the arch-shaped walls, and the pointed dome can be done using a 3-axis printing platform, printing the corner pendentives requires the nozzle to be oriented away from every corner, to evenly fill the corner gaps.

Groin Vault

A challenging form to 3D print is the *groin vault*, which is composed of windows on four sides of a square-shaped plan. The difficulty in constructing the groin vault lies with the cantilevering form at the four corners of the structure. This form cannot be achieved with continuous extrusion, and therefore must be 3D printed in four separate parts. To achieve this, 3D printed layers were extruded following a corbelling pattern throughout the structure. To ensure the stability of the form, and to prevent the cantilevering areas from tipping over, minimal centering ribs were used in this experiment **(Fig. 7.8 (a))**, which are then removed upon the completion of the printed structure **(Fig. 7.8 (b))** . The groin vault demonstrated in this test was also designed to have a taller profile in order to reduce the overall formal curvature and increase the chance of printability due to the reduction in cantilevering steepness. An untested alternative to the centering approach could explore designing the base of each corner to be bulkier, serving as heavier counterweights, helping to balance the structure.

Figure 7.9: Intersecting Nubian vaults built using clay 3D printing.

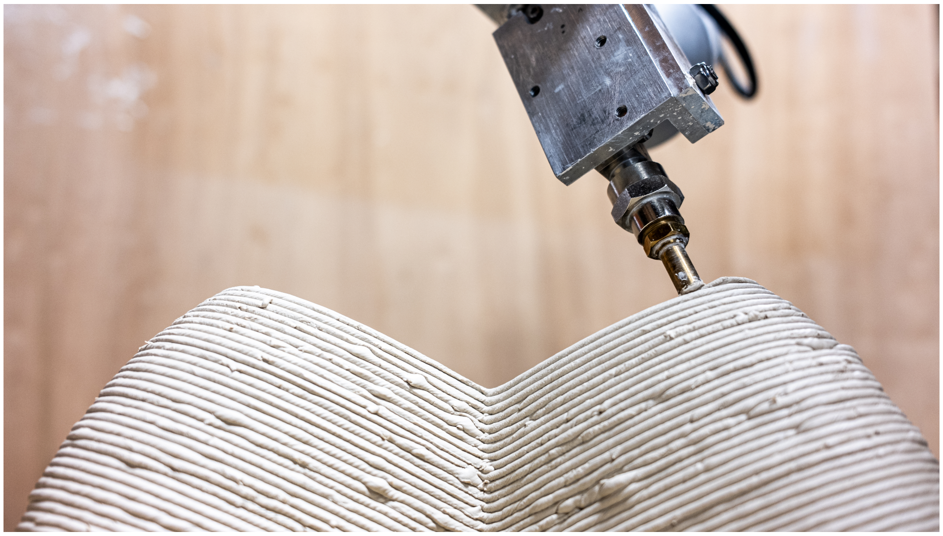


Figure 7.10: Multi-axis extrusion and conformal nozzle orientation that follows the tangent vector of the base surface.

Intersecting Vaults

While the translation from masonry to 3D printed toolpaths requires certain adaptations, these tests nevertheless provide a fundamental design grammar that serves as a resource for exploring novel geometric forms that may emerge from amalgamating these primary forms. The following test explored 3D printing intersecting Nubian vaults. **Fig. 7.9** demonstrates examples where two and four vaults intersect. The initial step in the printing process involved 3D printing the apses that form the rear profile of each vault. Subsequently, layers from each vault were separately printed, maintaining the apse profile and leaning angle, building up to the points of intersection where the layers of each vault converge. Following this step, the printed toolpaths eventually merge, similar to the technique used in printing a squinch dome. In this process, it is crucial that toolpath angles at each edge correspond to those of the respective vault they are part of **Fig. 7.10**. The orientation of the nozzle during the printing process is in constant change, ensuring that the extruded material is aligned perpendicularly to the layers from each vault and that they maintain their leaning angles. The layers were then continuously applied throughout the printing process, while their sizes diminish and finally converge as they approach the top of the printed vault.

Discussion

The series of experiments conducted in this section provided valuable insights into the material behavior, possible geometric configurations, and the viability of 3D printing long-spanning structures without relying on formwork. The knowledge gained provided the foundation for the subsequent phase: a large-scale prototype of a ground-supported Nubian vault. This particular design, tested on a smaller scale, shows considerable promise for scalability. The second experiment discussed in the following section not only addresses challenges related to scale, but also introduces complexities related to material preparation, drying time, material weight, and most importantly, subjecting the 3D printed structure to real-world testing and environmental exposure.

Experiment 2: In-situ 3D printed Nubian vault

This experiment took place in La Florida, Colorado, a location that has a rich tradition of using adobe in construction thanks to its natural abundance of alluvial soils possessing the ideal ratio of sand, clay, and silt for the production of earthen buildings. The readily available soil is typically excavated and mixed with water and straw, which is used as a binding agent, to create an adobe mixture that serves as the 3D printing material throughout the experiment. The adobe mixture is characterized by its ease of tunability through adjusting the dirt-to-water ratio. Printing tests revealed a direct correlation between the material's workability and structural integrity during the printing process. Mixtures with higher amounts of water have proven to flow more easily through the pumping system, while less water content resulted in a more structurally stable mixture, preferable for proper layer

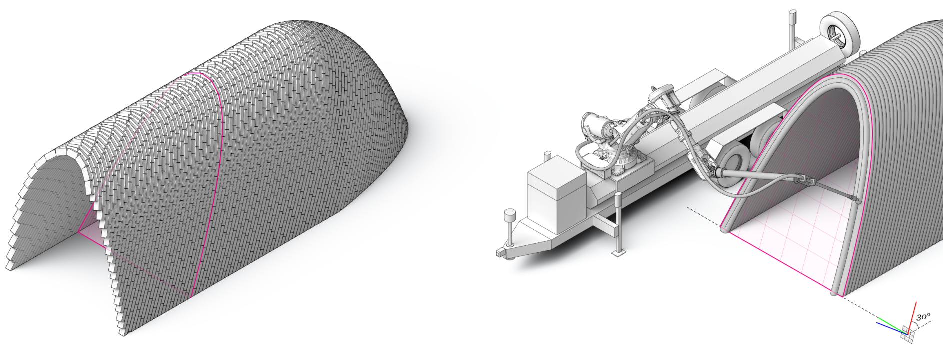


Figure 7.11: Illustration of masonry construction patterns translated into 3D-printed toolpath logic showing the slicing angle and nozzle orientation for the Nubian vault.

adhesion. Given these observations, developing an optimized mixing ratio that will facilitate a smooth printing process that ensures the stability of the printing object without clogging and interrupting the pumping system is paramount.

Setup

The configuration of this experiment consisted of a mobile, 7-axis industrial robotic arm mounted on a rail built upon a 6m long flatbed trailer. The robotic arm has a total reach of 3.2m and is placed on a 5m linear track. The entire configuration is designed with a wheeled, towable base, allowing it to be transported to the construction site for in-situ printing. The additional degrees of freedom of the industrial robotic arm offer precision in material deposition when printing non-planar layers. By allowing the nozzle to orient in a perpendicular direction to the printed toolpath, the platform guarantees consistent layer deposition and uniform extrusion throughout the printing process, as illustrated in **Fig. 7.11**. The setup includes an integrated gas-powered pump designed to channel the adobe mixture to the robot's end-effector. The process of preparing the adobe mixture consists of excavating soil near the printing site, which was then sifted to eliminate any aggregate sizes not able to be pumped by the printer. The sifted soil was then mixed with water and straw before being transferred to the hopper of the extrusion pump.

Geometry

A ground-supported Nubian vault was designed for this experiment measuring 5m in length, 2.5m wide, and 3m in height. The geometry consists of an apse and a vault, both made of a series of translated catenary arches. These arches originate from the ground level, and lean

Figure 7.12: 3D-printed adobe following a square-wave toolpath pattern.

at a 30º angle so as to first make an apse followed by an extruded Nubian vault **(Fig. 7.11)**. The toolpath takes the form of a square wave varying in amplitude in different regions of the toolpath **(Fig. 7.12)**. At the base, the square wave amplitude measures approximately 30cm, making a stable base. Towards the upper profile of the vault, the amplitude was reduced to approximately 20cm. This intentional reduction in the toolpath amplitude aims both to reduce the weight of the upper, unsupported regions of the vault, and to optimize stability while minimizing material usage.

Material

Most recent 3D printing projects use concrete as the extruded material. This preference stems from the well-understood properties offered by concrete and its widespread use in traditional construction. However, this study aims not only to demonstrate the use of a material with a lower environmental impact, but also to highlight the advantages associated with using adobe as a 3D printing material. It is important to note the challenges involved in using concrete in 3D printing when compared to using adobe. One critical factor is the limited time during which concrete remains workable after being mixed. As the material begins to set, time delays can jeopardize some of the components in the pumping system like the hose or the extrusion pump. The 3D printed vault demonstrated in this study was constructed entirely using natural, locally sourced mud **(Fig. 7.12)**. The absence of a chemical reaction to induce hardening in the extruded material simplifies considerations related to material workability durations or curing periods. Unlike concrete, adobe solidifies gradually by drying naturally, employing only wind and solar exposure.

Figure 7.13: 3D-printed Nubian vault during the construction phase.

3D Printing Process

In the execution of this experiment, the vaulted structure was segmented into multiple toolpath sections allowing every section to adequately dry before the continuation of the printing process. One of the key elements influencing the duration between the printed sections is the prevailing weather: sunny and breezy conditions expedite the drying process. To ensure controlled drying and stability, wood shoring was occasionally used during the construction. However, this was not needed to support the apex of the roof, but rather the leaning walls that extended at the base of the structure **(Fig. 7.13)**. A notable challenge in assessing when to safely add more printed layers is that while the external surface of the 3D printed adobe may appear to be perfectly dry, its interior core can remain damp. Proper drying is entirely contingent upon weather conditions, although during the experiment a large fan was used to assist in the drying of the structure. Because drying does not occur quickly inside the hose after printing has been completed for the day, the pump and hose can be left overnight without needing to be emptied and cleaned. A simple measure such as covering the pump to shield it from sunlight and wind is sufficient to prevent the material from drying. Thus, a seamless continuation of printing can resume immediately, as there is no need for equipment cleaning or platform recalibration between the printed sections.

Figure 7.14: Front view of the completed formwork-free, 3D-printed Nubian vault made of adobe.

Finishing and Preservation

To ensure the preservation of the 3D printed adobe structure and prevent the accumulation of water in the cavities formed by the printed texture, the 3D printed vault was coated with two layers of mud plaster composed of the same admixture as the adobe, as shown in **Fig. 7.15**. This coating yielded a smooth exterior finish, primarily purposed for preservation, while the interior of the vault kept its original surface texture, showcasing the visible 3D printed layers.

7.8 Conclusion

The chapter contributes to the C3DP field by exploring the use of 3D printing workflows to create compression-dominant structures such as domes and vaults, without using formwork.

Figure 7.15: The 3D-printed Nubian vault after plastering the outer surface with adobe.

The presented studies address a relatively untapped area of research with the C3DP field: the 3D printing of roofs. While some of the geometric forms discussed throughout the chapter have previously been examined by scholars, this work not only introduces further geometric explorations, but also rigorously tests them at various scales. In this chapter, the presented forms are first validated through small-scale experiments. Following that, some of these geometric forms are combined and adapted to develop new geometric configurations. Ultimately, the applicability of the proposed method is demonstrated in the construction of a full-scale 3D printed Nubian vault, made of locally-sourced adobe.

Despite significant advancements in additive construction technologies, the industry relies predominantly on concrete, a material with a harmful environmental footprint. The experiment presented here takes advantage of a material that has proven over millennia to be a dependable construction medium. Its abundance, smooth printability, and environmentally benign footprint make it particularly well suited to construction 3D printing. As previously noted, the robotic infrastructure utilized in this research emphasizes mobility and self-sufficiency, aiming to harness materials that are both abundant and indigenous to the construction site where the platform is deployed. The study proposes a framework that affirms the significance of drawing insight from ancient construction crafts. By combining traditional, time-honored techniques with contemporary construction technology, this project aims to arrive at new possibilities that can redefine the boundaries of large-scale 3D printing.

Chapter 8

Contributions and Future Outlook

8.1 Overview

This final chapter incorporates the theoretical, methodological, and technological contributions of this thesis. It underscores the implications of these contributions primarily in the context of architectural design, while also extending their relevance to the fields of design, science, engineering, and invention. Motivated by the desire to invite future contributions, this thesis promotes sustainable construction and enhanced fabrication processes by broadening technological capabilities. This research transcends current material and process restrictions, showcasing experiments that reveal viable workflows that are adaptable to a range of scales, materials, and additive manufacturing methods. This final chapter introduces the systematic approach for knowledge transfer that has motivated this thesis, encompassing developments on both, the hardware and software levels. These innovations have the potential to be implemented across various additive manufacturing processes, united by the commitment to sustainable design and construction efficiency.

This chapter aims not only to summarize the thesis chapters, but to also promote the transdisciplinary approach of this thesis, weaving together elements of design, modeling, analysis, and digital fabrication, while revisiting the core principles and experiments that facilitate the technological exchange throughout this research. To promote this approach, this chapter outlines the core ideas, principles, and findings that enabled this technology transfer. Additionally, the chapter aims to point out unresolved issues that could encourage future research and contributions. This overview serves as both, a conclusion and a source of inspiration that might initiate further research development and potential avenues for further inquiry.

The theoretical contributions discussed in the initial chapters of this thesis are grounded in a transdisciplinary approach, driven by curiosity and experimentation, linking diverse neighboring fields. This approach has led to discoveries and emerging opportunities, informed by insights from the fields of robotic fabrication, additive manufacturing, and formwork integration, motivated by the synergy of historic perspectives and the more recent technological advancements in each field.

The methodological contributions, mainly discussed in the third chapter, outline the systematic approach and technical means supporting this thesis through conceptualizing, and crafting novel workflows for non-planar 3D printing, challenging, and advancing current technological restrictions.

Finally, the technological contributions outlined in chapters four through seven, involve experimental approaches to additive manufacturing. While chapter four focuses on robotic control, and the ability to design unrestricted toolpaths, chapters five through seven propose additive manufacturing processes targeted towards waste mitigation, efficient construction, and the expansion of current additive manufacturing limits. These chapters also demonstrate the development of tools and workflows that facilitate these objectives on the software, hardware, and process levels.

8.2 Background

Following the introductory overview, the second chapter plays a pivotal role in this thesis, by establishing the foundational concepts and theoretical context in the fields of construction additive manufacturing, robotic fabrication, auxiliary structures, and the use of viscous materials in additive manufacturing. First, the chapter highlights the revolutionary impact of additive manufacturing technologies by enabling simpler production workflows of objects which previously required extensive process planning and assembly. The chapter introduces additive manufacturing concepts such as non-planar 3D printing, freeform 3D printing, and conformal 3D printing, and examines their untapped potential.

Furthermore, The chapter discusses some of the most common additive manufacturing techniques and their uses in various fields, while paying particular attention to their implementation in construction. A key observation made in this chapter is that the transition from small-scale to large-scale additive manufacturing applications is not straight-forward, and presents several challenges. Despite its effectiveness in efficiently producing geometric parts or cutting down production time, scaling up 3D printing processes to architectural dimensions introduces complexities such as material and process limitations and geometric restrictions.

The chapter then focuses on the use of viscous and cementitious materials in construction 3D printing, particularly emphasizing commonly-used extrusion and deposition methods. These materials, while stable after curing or hardening, pose challenges during the extrusion process when they are in their wet state. This drawback has led construction 3D printing projects to take a layer-based approach, where 3D printed structures are mainly composed of vertical wall extrusions.

This section of the chapter concludes by highlighting the necessity to address these limitations, suggesting that non-planar 3D printing approaches could offer solutions to some of these challenges, potentially opening avenues for unrestricted, efficient additive manufacturing workflows.

The second part of chapter 2 shifts the focus to the theoretical foundation of robotic fabrication, delving into its revolutionary impact in the architectural design field. This section first discusses the historical significance of industrial robotic arms, where they were mainly used for high-precision, and high-repeatability tasks for mass production. The chapter presents a novel perspective on industrial robotic arms, emphasizing their relevance to the narrative of the thesis. The chapter aims to draw a parallel between the traditional use of industrial robotic arms in mass production, and their emerging role in mass customization and creative applications. This shift views industrial robotic arms not as mass production machines, but as a catalyst for innovative fabrication, and design-driven research.

Subsequently, the chapter discusses the numerous efforts to automate construction throughout the 20th century. It highlights the focus of these approaches on the mass production of prefabricated building components. A contribution of this chapter is its comprehensive overview of the more current applications utilizing industrial robotic arms in architectural design. In this overview, the chapter highlights the advantages of using industrial robotic arms in additive processes. By leveraging their extended degrees of freedom, multi-axis 3D printing processes emerge as a promising avenue to expand the current technological boundaries and address some of the above-mentioned challenges.

The chapter also highlights two crucial components of industrial robotic arms: end-effectors, and control software, emphasizing their roles in enhancing the versatility of robotic platforms for various applications. Firstly, through the interchangeability of end-effectors, industrial robots are transformed from a milling machine, to a 3D scanner, to a 3D printer. This flexibility is particularly beneficial in research-driven design, where innovative concepts are frequently tested and developed. Furthermore, the chapter addresses control software and robotic programming workflows that are essential in toolpath design and planning. The section concludes by proposing that future research could potentially focus on advancements in both, end-effector and hardware design, and control workflow developments.

The final sections of the chapter reviews two crucial aspect of this thesis: the use of viscous and cementitious materials in additive manufacturing, and the integration of auxiliary structures. Focusing on the common use of viscous materials, particularly concrete, the chapter highlights the necessity of using formwork and falsework to shape viscous materials. Due to their fluid nature, viscous materials are sprayed, cast, or poured into formwork and left to solidify. A key theoretical contribution of this section is that it draws parallel between traditional formwork in construction and the use of support structures in additive manufacturing. In desktop 3D printing applications, temporary support structures or formwork are used when printing overhangs, voids, or other unsupported geometric features. These supports are typically composed of thin walls and are printed in low density volumes for easy post-print removal. A key insight from this section is the potential of adapting a similar approach to large-scale 3D printing, while considering alternative workflows to 3D printed supports. Potential avenues include stay-in-place or reusable supports that address the overarching challenge of waste mitigation and material efficiency.

The chapter synthesizes the three main topics: additive manufacturing, robotic fabrication, and formwork integration, suggesting a convergence that could potentially lead to novel additive manufacturing workflows. This approach aims to be scalable, efficient, and unrestricted, allowing for the creation of multi-dimensional complex forms across scales and material palettes. A contribution of this chapter is that it showcases the current state of each of the three fields, while pointing out opportunities that could emerge either by developing certain aspects of the field, or by merging the fields together to explore new possibilities.

8.3 Methodology

The third chapter provides a methodological foundation that supports this thesis. It introduces a transdisciplinary approach that serves as a guideline for the subsequent chapters. Moreover, this chapter serves as a road map for navigating the thesis, offering instructions for the utilization, workflow, and evaluation process for the experiments that follow this chapter.

First, the chapter identifies key themes and research challenges facing 3D printing using viscous materials, with a particular focus on material instability. Because this limitation impacts the design possibilities and geometric freedom, the chapter emphasizes the necessity for support integration, and the potential for suggesting alternative workflows. This research aims to address fundamental research questions concerning formwork integration via non-planar 3D printing across hardware, software, material, and process levels.

Furthermore, in response to the identified challenges and the methodological framework, the chapter introduces overarching themes that guide subsequent chapters. The chapter proposes three experiment categories centered on formwork integration, revolving around three support classification areas: support reduction, alternative support integration, and support elimination.

The chapter then outlines overarching objectives that serve as guiding principles throughout the thesis, aligning with each chapter's focus areas. These objectives revolve around looking into innovative strategies to enhance the capabilities of 3D printing using viscous materials in order to surpass current limitations; exploring the convergence of robotic fabrication, additive manufacturing, material design, and formwork integration for 3D printed structures; developing required software and hardware tools that are adaptable to various processes and materials; and finally assessing the efficacy of the proposed methods through physical prototyping spanning various materials and scales.

An important aspect of the research methodology highlighted in this chapter is the development of multi-scale prototypes that address these inquiries, serving as a medium for testing and evaluating the proposed processes. Initially, the research aims to validate concepts and assess their feasibility through small-scale experiments and samples. This stage allows for the filtration of ideas with less potential, simplifying the selection process of optimal tools, materials, and technologies for the proposed approach. Subsequently, insights that are gained from the initial experimentation stage inform the trajectory of the experiments to follow, guiding the evolution of the research.

Although well-intentioned, the proposed road map outlined in this chapter is subjective and represents one possible structuring method for this research. This approach remains open-ended, offering a particular framework for addressing research inquiries while allowing for future contributions.

8.4 Beyond Planarity: Designing With G-CODE

Chapter four of this thesis and the following three chapters deepen the technical contributions, particularly through the development of novel workflows and tools. This chapter in particular offers insight on advanced 3D printing controls and the ability to design non-conventional toolpaths for unrestricted 3D printing applications. Initially, the chapter outlines conventional 3D printing processes, which typically involve transitioning from 3D models, to slicing software, to G-CODE files. This workflow offers limited control over the 3D printing process. In response, this chapter introduces innovative approaches that bypass the need for conventional slicing software, aiming to enhance the customizability and level of control users have over 3D printers. The approaches presented in this chapter are important for the design of non-planar 3D printing toolpaths, a topic that is further explored in the later chapters. Chapter four also showcases practical applications of these software tools, highlighting their versatility across materials and scales.

The first section of the chapter looks into the *Caterpillar* plugin, which is developed to integrate into the *Rhinoceros* and *Grasshopper* environments, offering components that are tailored for enhanced 3D printing control. The *Caterpillar* plugin components are adaptable to different 3D printing platforms, offering users advanced toolpath design, optimization, and visualization capabilities. The software tools enables users to create complex topologies that would have been difficult to realize using traditional slicing workflows. The examples presented in this chapter showcase the innovative potential of this 3D printing framework, highlighting the chapter's contribution to expanding the boundaries of 3D printing on the software tool level.

The second section of this chapter introduces *Potterware*, an intuitive design application aimed at users without advanced 3D modeling or computational design skills. *Potterware* allows users to create objects with intricate geometry and textures, catering especially to small-scale ceramic 3D printing applications. Unlike *Caterpillar*, which is geared towards broader applications, and users with prior CAD knowledge, *Potterware* is designed to appeal to a wider audience, including users without any previous 3D modeling or 3D printing experience. It's user-friendly interface, featuring parametric sliders, simplifies the design process, enabling the rapid creation of printable designs. *Potterware* allows users to push the limits of 3D printed clay, taking advantage of the unique properties of the material's plasticity, response to gravity, and machine parameters. Moreover, *Potterware* supports seamless integration with a wide selection of CAD tools and 3D printing machines. Users are able to export their designs as G-CODE files, or many other file formats, simplifying the transition from design to production.

A key contribution of this chapter is its focus on democratizing 3D printing software tools. By making these tools accessible and free, it opens up new possibilities for users, not suggesting a replacement of current design methods, but offering an alternative pathway in 3D printing practices. In doing so, the chapter lays the foundation for numerous avenues of future exploration, extending beyond the architecture field. It opens up opportunities for future designers to explore the application of the tools discussed in this chapter in various industries. A potential area of future research, for example, could be the enhancement of the toolset presented in this chapter. For instance, Caterpillar components, which are designed within the Grasshopper environment, offer potential for further development. A promising direction for development is the incorporation of real-time control in the 3D printing workflow. This would enable users to modify printing parameters mid-print, adapting to the dynamic behavior of the printed materials. These prospects highlight the chapter's contribution in setting the stage for potential advancements in 3D printing applications.

8.5 Conformal 3D Printing Using Bending-Active Formwork

The fifth chapter focuses on the first experimental category of support classification outlined in the methodology section of this thesis: support reduction. The first section of this chapter delves into the advantages of conformal 3D printing, a technique that is based on the direct deposition of materials onto a base formwork or substrate. The chapter examines the benefits, limitations, and challenges of current approaches to conformal 3D printing which use mesh formwork, mechanically-shaped granular substrates, or high textiles as a form of auxiliary structure. In general, the conformal 3D printing approach enhances printing speeds, mitigates material waste, and enables the production of new geometric forms that might be difficult to realize otherwise, particularly long spanning horizontal structures. Constructing long-spanning curved structures typically requires substantial amounts of support materials or formwork, making their construction inefficient and unsustainable.

Advancing the technical contributions of this thesis, this chapter presents an innovative conformal 3D printing approach using bending-active formwork. This method not only mitigates material waste, but also suggests using the formwork as a permanent form of reinforcement in the printed structure. To accurately conform to the substrate surface, the chapter proposes a workflow that utilizes a multi-axis robotic extrusion platform, allowing for precise material placement. This is achieved by the ability to adjust the extrusion nozzle orientation to align with the substrate surface's normal vectors. This strategy also aligns the toolpaths with the structure's primary force vectors.

The experiments section of the chapter demonstrate a series of design experiments to validate the proposed approach, leading to the fabrication of a large-scale prototype. Initial experiments use single strips as bending-active formwork to test process feasibility, while the final experiment demonstrates the construction of a gridshell roof structure.

A key area of research in this chapter is the development of computational tools for geometric toolpath planning and formwork registration. These tools are essential for accurate material placement onto physical objects. The first method tested in this process is 3D scanning. Using a handheld hybrid 3D scanner, a digital representation of the substrate surface is created to be used as a base of the printing toolpath. A second approach presented in this chapter uses vision-based position estimation. This technique uses a stereo camera to capture the position and orientation of a series of fiducial markers that populate the substrate surface.

Finally, the chapter presents a detailed demonstration of a large-scale experiment assessing the practicality of the suggested workflow. The chapter discusses crucial components of the experiment such as its setup, toolpath design, formwork registration, and finally the 3D printing process. The methodologies presented in this chapter significantly contribute to the central theme of this thesis, which revolve around the use of non-planar 3D printing, enhancing 3D printing workflows, reducing material waste, optimizing 3D printing toolpaths, and reducing printing durations.

In doing so, the chapter sets the stage for further research within this domain. While the experiments presented in this chapter demonstrate a specific gridshell design, further studies could explore various geometric configurations and gridshell patterns utilizing flat strips. Another starting point could focus on investigating alternative materials for the construction of the gridshell, further enhancing its tensile strength. This chapter, therefore, lays a foundation for future research in the construction 3D printing field.

8.6 Non-Planar Granular 3D Printing

Chapter six of this thesis broadens the technical scope of the research, addressing the second area of support classification: alternative support integration. Starting with an analysis of current 3D printing technologies that utilize granular materials, the chapter outlines some of their advantages and limitations. Granular, and powder-based 3D printing processes, although capable of printing complex geometries, are layer-based, slow, and are often restricted to a limited range of materials.

To address these challenges, the chapter introduces a novel additive manufacturing technique: Non-Planar Granular Printing (NGP). NGP is based on the selective deposition of a liquid binder into a volume of granular particles to create 3-dimensional objects. Like other commonly used 3D printing methods, NGP can accept standard CAD models as a starting point for toolpath generation. Additionally, the proposed method allows for non-planar 3D printing by freely moving the extrusion nozzle freely within the granular volume, facilitating rapid vertical extrusions such as lattice structures and other multi-dimensional forms.

A key contribution of the proposed method is its customizable nature, accepting a wide range of granular materials including recycled waste products. The method's versatility enhances material efficiency compared to other powder-based 3D printing methods which are often limited in material choices. Due to the nature of the process, the NGP method also presents significant improvements in printing duration.

Adding to the technical contributions, the chapter thoroughly examines the fundamental components of the NGP technology, presenting benchmark experiments to evaluate its capabilities. Some of the evaluated criteria include printing speed, extrusion thickness variations, multi-material printing, and process scalability. The chapter also compass the NGP method to similar technologies that utilize granular materials and multi-axis robotic extrusion. By doing so, the chapter provides a comprehensive overview of NGP's positioning in the broader context of 3D printing technologies.

Additionally, the chapter details developments of hardware tools that are tailored for the NGP process. These include a proprietary extrusion nozzle design that is capable of handling coarse, granular materials. Another hardware tool developed throughout the process is an advanced pumping system that is designed for large-scale applications using various binding agents, including multi-part binders.

Concluding with a summary of the key findings, the chapter points out potential directions for future research. By offering groundbreaking improvements, the NGP method marks a significant potential for broadening the scope of granular-based 3D printing processes. As the NGP method is novel, the chapter acknowledges that this research field holds potential for extensive testing to fully understand the technological capabilities of the NGP process. For example, future research could focus on testing the scalability of the process, beyond the scales demonstrated in the chapter's experiments. There is also potential for enhancements on the material level, such as exploring alternative binding agents, including biomaterials and other forms of natural binders. Another research direction could also investigate embedding hardware fixtures, or strategic packing of granular materials within the build volume. Such capabilities could significantly broaden the applications of the NGP process, enabling the fabrication of objects with embedded mechanical properties and functional gradients.

8.7 Support-Free 3D printing

The concluding chapter of this thesis addresses the third area of support classification: support elimination, contributing to the technical depth of this thesis on several fronts. The chapter begins by highlighting the challenge of 3D printing large-scale roof structures, in comparison to the predominant practice of 3D printing vertical walls and extrusions. The inherent difficulty of printing roofs lies in the inability to print steep overhangs and long spans due to the wet state of the extruded materials.

The chapter draws parallels between contemporary 3D printing practices and traditional masonry principles, finding common ground on the material, and construction process levels. A key aim of this chapter is to intertwine traditional building principles with robotic additive manufacturing, demonstrating how ancient architectural concepts can be applied to modern construction. This is demonstrated through a series of studies that utilize non-planar 3D printing that aim to expand the potential of additive construction by 3D printing unsupported horizontal roof structures.

Central to this chapter is a series of small-scale experiments that use clay as a 3D printing material, chosen for its viscous properties that can be compared to construction 3D printing materials on a larger scale. The experiments demonstrate the fabrication of small-scale roof structures such as domes, vaults, and apses through non-planar 3D printing and computational modeling.

The gained knowledge of this set of experiments is then transferred to a larger scale, moving towards constructing a full-scale Nubian vault using locally-sourced 3D printed adobe. The insights from the initial experiments inform this phase of experimentation, guiding the toolpath design, and the overall geometric form of the Nubian vault. This structure, combining a vault and an apse is 3D printed directly on the construction site, demonstrating the use of local materials as a sustainable alternative to the commonly used 3D printed concrete.

A main contribution of this chapter is that it points towards a future where resource and process limitations can be addressed through innovative, environmentally conscious practices. The project also showcases the use of a mobile industrial robotic printing and pumping platform. By doing so, the chapter emphasizes the significance of resource efficiency, fabrication sustainability, and the potential of gaining insight from ancient construction practices to potentially overcome current technological limitations.

In conclusion, this final chapter of the thesis stands out not only as a summary of the work presented, but also as a foundation and invitation for future research in architecture and other related disciplines. The methods and findings presented here possess broad applicability and could inspire other novel applications and innovative products. Within the architecture field, this research represents a modest beginning with the potential to sprout diverse research avenues. Future research could, for example, explore additional geometric configurations achievable through the tools and techniques discussed herein, or perhaps advance the foundational principles outlined. Moreover, collaborative efforts between designers, engineers, and scientists from neighboring disciplines could lead to innovative methods of reinforcing extruded materials, either by tuning the printed material or introducing reinforcement elements during the extrusion process. As this work concludes, the author is optimistic about the limitless creative possibilities for the next generation of researchers to build on this work. Profound gratitude is extended for the continuous support that has enriched this educational journey.

Credits

The projects demonstrated throughout this thesis have been accomplished through collaborative efforts. This section stands as a recognition, honoring the individuals whose contributions have been crucial in the realization of these projects. Their dedication and expertise have helped shape the trajectories and scope of the presented work.

Caterpillar (Chapter 4)

Project Team: Barrak Darweesh, Hao Zheng, Heewon Lee, Kyle Steinfeld

Potterware (Chapter 4)

Project Team: Ronald Rael, Barrak Darweesh, Virginia San Fratello, Constantina Tsiara, Sandy Curth

Conformal 3D Printing using Bending-Active Formwork (Chapter 5)

Project Team: Barrak Darweesh, Simon Schleicher, Yasaman Yavaribajestani, Michael Herrmann, Luai Kurdi

Non-Planar Granular 3D Printing (Chapter 6)

Project Team: Barrak Darweesh, Maria Paz Gutierrez, Simon Schleicher, Thalia Makhlouf, Noah Johnson

Support-Free 3D Printing: Clay Experiments (Chapter 7)

Project Team: Barrak Darweesh, Ronald Rael, Thalia Makhlouf

Support-Free 3D Printing: 3D Printed Adobe Nubian Vault (Chapter 7)

Project Team: Barrak Darweesh, Ronald Rael

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