COLLECTIVE CREATIVITY BETWEEN HUMANS AND MACHINES: EXPLORING IMPROVISATIONAL DESIGN-FABRICATION WORKFLOWS ENABLED BY ROBOTICS AND ARTIFICIAL INTELLIGENCE

Isla Xi Han

a dissertation
presented to the faculty
of princeton university
in candidacy for the degree
of Doctor of Philosophy

recommended for acceptance
by The School of Architecture

Co-Advisers: Stefana Parascho, Naomi Leonard, Forrest Meggers

May 2025

Abstract

Over the past few decades, robotic technology has been adopted in the architectural field mainly to automate the fabrication process and materialize complex parametric designs. While this approach ensures precision in form and assembly, it often lacks adaptability, accessibility, and resilience to change once construction begins on-site. In response, this research draws from human-robot interaction (HRI) and artificial intelligence (AI) to explore new frameworks where heterogeneous teams of humans and robots collaboratively design and fabricate without relying on pre-defined blueprints.

By integrating robotic precision and strength with human craft and sensitivity, this approach enables more evolving structures while lowering technological barriers to broader participation. Bidirectional communication between humans and robots fosters creativity, expanding design possibilities beyond automation. Additionally, it enhances sustainability by accelerating design-to-fabrication cycles and increasing tolerance for material dimensions.

This dissertation begins by establishing the theoretical framework for Collective Human-Robot Construction (CHRC) through a review paper centered on two intersecting research axes: autonomy-collaboration and design-fabrication. From this foundation, a series of physical prototypes—developed at increasing scales and across diverse material systems—serve to test and refine an improvisational design-fabrication workflow. These experiments span from sculptural to pavilion-scale structures, employing strategies ranging from the stacking of simple geometric units to the interlocking of organic bamboo rods and the assembly of wooden and steel tensegrity structures.

The dissertation also investigates different modes of HRI within fabrication and environment-shaping processes, some enhanced by AI to promote more intuitive and accessible human-robot engagement. Experiments were conducted to equip robots with vision and voice capabilities, enabling them to perceive the built environment and communicate with humans through natural language. With these enhanced HRI tools, humans and robots can co-create their surroundings in real time.

Grounded in HRI, AI, and materials science, this research explores strategies for making robotic workflows more responsive to human input. It envisions a future where design and construction are collaborative, inclusive, and dynamically responsive, redefining machines as co-creators rather than mere executors.

Acknowledgments

The completion of this dissertation has been made possible through the unwavering support, encouragement, and guidance of many individuals. First and foremost, I want to thank my co-advisors: Professor Stefana Parascho, who transformed my academic journey by introducing me to the fascinating world of robotic fabrication, and for inviting me to EPFL over the summers for invaluable research experiences; Professor Naomi Leonard, for opening doors to remarkable interdisciplinary collaborations spanning from engineering to art, and for providing me with a "home" at the Engineering Quad; and Professor Forrest Meggers, for always being there to support my academic and entrepreneurial pursuits, and for making the joint degree in Architecture and Materials Science a reality!

I am extremely grateful to my colleagues and friends at Leonard Lab, Princeton University and Lab for Creative Computation (CRCL), EPFL, who made my PhD journey both fun and unforgettable: Kathryn Wantlin, Giovanna Amorim, María Santos, Sarah Witzman, Anastasia Bizyaeva, Marcela Ordorica Arango, Charlotte Cathcart, Justice Mason, Ian Xul Belaustegui, Justin Lidard, Yenan "Daniel" Shen, Juncal Arbelaiz, Daniel Levy, Himani Sinhmar, Caroline Hana, Emily Yang, Udari Madhushani, Mari Kawakatsu, Jingwen Wang, Maxence Grangeot, Eric Duong, Eleni Skevaki, Alexandra Pittiglio, Marirena Kladeftira, Marie-Pierre Zufferey, Gabriel Vallat, and Isabelle Cogotti. I also hope to acknowledge my friend group in Computer Science: Jiaqi Su, Yunyun Wang, Yuting Yang, Xi Chen, and Zhongqiao Gao. From solving jigsaw puzzles to spontaneous weekend bungee jumping; from hiking the mountains of Veytaux, Switzerland to late-night beach walks in Vancouver, Canada; from pet photo sharing to tea ceremonies; and from troubleshooting robots under pressure to enjoying delicious lab snacks— each moment has been filled with laughter, support, and adventure!

I would especially like to thank the lab technicians and managers at Princeton Embodied Computation Lab (ECL), Princeton SEAS Robotics Lab, EPFL Structural Engineering Platform (GIS), Princeton University Library Makerspace, and Princeton Materials Institute Imaging and Analysis Center (IAC) — Bill Tansley, Grey Wartinger, Baffour Osei, Gregory Spirlet, Armin Krkic, François Perrin, Frédérique Dubugnon, Gilles Guignet, Gérald Rouge, Ariel Ackerly, and John J. Schreiber — for their incredible project supports and for ensuring my safety while working with the machines in the lab.

I am deeply grateful for the multidisciplinary research opportunities I had the privilege to engage in during my time at Princeton. In particular, I am especially thankful to Professor Glaucio Paulino (Civil and Environmental Engineering/CEE) for introducing me to the captivating world of origami engineering and material structural optimization — and for generously serving as my dissertation reader; to Professor Nan Yao (Princeton Materials Institute) for opening my eyes to the nano-scale world and teaching me how to observe materials down to the atomic level; to Professor Susan Marshall (Dance), Professor Dan Trueman (Music), Professor Jane Cox (Theater) for the amazing collaborations on *Rhythm Bots*, and to Mark DeChiazza and Tyler Kline for their support; to Professor Anirudha Majumdar (Mechanical and Aerospace Engineering/MAE) and Professor Jaime Fernández Fisac (Electrical and Computer Engineering) for introducing me to robotic control and safety; to Professor Joe Scanlan (Visual Arts) for enthusiastically supporting my exploration of AI-enabled human-machine interaction in art-making; to Professor Radhika Nagpal (MAE and Computer Science/COS) and Daniel J. Cohen (MAE) for their inspiring lectures on swarm control and robotics; to all the professors I had the honor of teaching alongside as an assistant in instruction: Professor Derek Lidow (Entrepreneurship/ENT), Professor Andrés Monroy-Hernández (COS), Professor Ken Anderson (ENT), Professor Alexander Glaser (MAE), Professor Ryo Morimoto (Anthropology), Professor Penelope Georges (Council on Science and Technology), Professor Sigrid Adriaenssens (CEE), Professor Liam Elliot (Music), Professor Benedikt Lehnert (ENT), Professor Stephanie Landers (ENT), and my co-advisors Professor Stefana Parascho and Professor Naomi Leonard; and to Professor Maria Garlock (CEE), with whom I had the privilege of working on exhibition design. Within the School of Architecture (SoA), thank you to Professor Daniela Mitterberger for research inspiration; to Professor Arash Adel for kindly serving as my final public oral (FPO) examiner; and to Professor Axel Kilian, who first triggered my interest in construction robotics during my Master's Studio in 2017 and led an incredible trip to Switzerland and Germany where I saw construction robots in action for the first time. Thank you to SoA program manager, Daniel Claro, for his hard work and dedication in supporting the logistics that made both my FPO and dissertation possible. Additionally, thank you to all my amazing students across disciplines — your passion, curiosity, and engagement made every class a joy!

Beyond the funding, laboratory space, and equipment provided by my co-advisors, Professor Stefana Paraschо and Professor Naomi Leonard, the following funding sources also supported the research in this dissertation: Princeton University First-Year Fellowship, CreativeX, SoA PhD Conference Travel Fund, Dean's Fund for Scholarly Travel, and CAADRIA Young Award travel fund. I am also grateful to Professor Ryo Morimoto and Professor Alexander Glaser for sponsoring my SPOT robotic dog SDK and operation training at Boston Dynamics headquarters in Massachusetts. For career development and entrepreneurship supports, I would love to thank the training programs from GradFUTURES, Princeton Research Computing, and Synergiiize Innovator Program; as well as funding supports from U.S. National Science Foundation (NSF) Innovation Corps Hubs Program - Northeast Cohort, Keller Center Annual Innovation Forum Pitch Competition Award, Keller Center Student Project Funding, Keller Center eLab Summer Accelerator, Prospect Student Venture Grant, Princeton E-Club Pitch Competition Grant, Microsoft for Startups Founders Hub, GradFUTURES Social Impact Fellowship, and Princeton University Administrative Fellowship. Thanks to my co-founders, Sophie Mengzhu Jiang, Genyuan Hu, and Priscilla Qizhen Zhang at MoVA Realities LLC for the great adventures together! I hope to especially thank Manda Ryan, Stephanie Landers, Derek Lidow, Elaine Caron, Nena Golubovic, and Beth Ellen Jarvie from Keller Center; Evangeline "Eva" Kubu, James M. Van Wyck, Sonali Majumdar, and Amanda Peacock from GradFUTURES; Tony Williams and Laurie J. Viglione-Tzodikov from the Office of Technology Licensing; Anne-Marie Maman from Office of Innovation for their incredible support in technology transfer and professional development throughout my time at Princeton!

I hope to acknowledge my friends at Princeton University Rock Ensemble, Princeton University Curling Club, Princeton University Climbing Team, TOTEM Escalade at Ecublens, Gecco cohort, CHAOS Lab, Princeton University Figure Skating Club, Princeton Art Council Flamenco Dancing Class for the unforgettable performances, tournaments, and parties we shared!

A heartfelt thank you to my dearest parents, Xin and Hongkui; my loving husband, Eli; my adventure cat, Turbo "Bobo"; my "sister" by heart, Judy; and my parents-, sister-, and pug-in-law, Carrie, Frank, Lilah, and Gary — for always being there for me through the highs and lows!

To the ones who gave me roots and wings, Xin Zeng and Hongkui Han

— with endless love and gratitude.

Contents

Chapter I Introduction

1.1 Problem Statement

The role of the architect has shifted significantly over time. From craft to professionalism[1] to specialization, architectural workflows have become increasingly compartmentalized[2]. The linear workflow from design to fabrication depending on pre-calculation and standardization[2] introduces inefficiencies in time, labor, and material usage. For example, the communication overhead among designers, structural engineers, software developers, and fabricators slows down prototyping and complicates adjustments to the final design. As a result, there is a growing need for interconnected platforms (e.g., Building Information Modeling[3,4]) and collaborative approaches that integrate design, engineering, and construction, making the process more responsive and adaptive.

Industry 4.0 aligns with this shift by redefining production paradigms through customization, intelligence, and connectivity. Unlike the automation-driven advancements of Industry 3.0 in the 1970s, which emphasized mechanization for efficiency, Industry 4.0 prioritizes interconnectivity between physical systems, human operators, and digital intelligence[5]. Advanced robotics is a core pillar of this transformation, identified by the World Economic Forum as one of four key megatrends shaping Industry 4.0[6,7]. Central to advanced robotics is the concept of autonomy, where machines exhibit self-regulation, real-time communication, and seamless interaction with human operators[8]. Beyond advancements in functionality and efficiency, robots in Industry 4.0 must also evolve in terms of flexibility and adaptivity, responding to human input and environmental variations through sensor networks and artificial intelligence[7,9].

Research in construction robotics has experienced significant growth over the past two decades[10]. First, industrial robotic arms proved their capacity to streamline construction processes by automating tasks (e.g., bricklaying[11,12,13], timber prefabrication[14]), leading to greater efficiency. Second, robotic precision enables the accurate delivery of planes and angles, facilitating the efficient fabrication of complex parametric forms and textures (e.g., customized welding[15], stone carving[16]). Third, robotics has inspired designers to explore novel approaches to material assembly and fabrication, expanding the possibilities of architectural construction (e.g., robotic 3D printing[17,18,19], vaulting[20]).

Transitioning from research labs and prefabrication factories to construction sites for robotics integration, however, remains limited by two key challenges: (1) accessibility—most designers and community members without a technical background struggle to engage with robotic technology due to the highly specialized knowledge required, and (2) versatility—current workflows lack the adaptability needed to work across different materials and site conditions[21]. Unlike controlled manufacturing environments, architectural applications require robots to operate in unstructured, dynamic sites where factors such as varied assembly methods, evolving construction phases, multidisciplinary human teams, and local regulations introduce complexities. Furthermore, the prevailing linear workflow from design to fabrication limits the role of robotics to construction, overlooking their potential as collaborative design partners alongside humans. The absence of intuitive and engaging human-robot interaction (HRI) in construction robotics, coupled with a lack of research on robotic agency in design, further restricts their integration. These barriers prevent robotic fabrication from becoming an intuitive, responsive, and inclusive part of the architectural design-fabrication processes.

This dissertation promotes interactive and adaptive means of HRI in design-fabrication settings, fostering collective creativity and craft between humans and robots. By developing methodologies for human-in-the-loop design-to-fabrication workflows, this research aims to lower the technical barriers to robotic integration while enhancing adaptivity in material and site-specific applications.

1.2 Purpose and Objectives

The purpose of this dissertation is to develop a framework for Collective Human-Robot Construction (CHRC) that enables improvisational, human-in-the-loop robotic fabrication in architectural contexts. This research challenges conventional linear workflows that rely on pre-planned blueprints, proposing instead an adaptive process where human and robotic agents collaboratively generate novel material assemblies and formal expressions. Case studies in this dissertation explore a range of structural systems, from stacking to interwoven sticks to tensegrity, demonstrating increasing complexity to validate the workflow's versatility. For small-scale prototypes, UR5 robotic arms were employed, while larger sculptural or pavilion-scale structures utilized various ABB robots, including stationary and track motion platforms. Additionally, a custom-built swarm robotic system was integrated into one case study to create an immersive HRI environment. By emphasizing shared decision-making and improvisational construction, this approach fosters co-creativity and co-intelligence between humans and robots, enhancing their collaborative roles in the creative processes in architecture.

Conceptually, the research situates at the intersection of HRI and collective robotic construction (CRC)—a growing field defined in Section 2 as CHRC. The key objectives of this research are:

1. To establish a conceptual framework for CHRC (Section 2).

2. To integrate and evaluate HRI methods—including 2D and 3D visual (Sections 6, 7, 8), audio (Sections 8, 9), natural language (Section 9), and stigmergic (Section 8) communications—to enable novel human-in-the-loop robotic fabrication processes in architecture.

3. To enhance the agency of construction robots by incorporating techniques such as local and global design preferences, including formal analysis, color filtering, and collision avoidance (Sections 6, 7, 8), and AI-enabled natural language interpretation (Section 9).

4. To lower the barrier to robotic fabrication by developing an improvisational design framework in which humans (without requiring robotics expertise) and robots collaboratively make design decisions for the same structure or environment (Sections 6, 7, 8, 10).

5. To demonstrate the adaptability and transferability of this improvisational framework across diverse material systems and robotic models (Sections 6, 7, 8, 10).

At the material assembly level, enhancing robotic adaptability reduces waste by eliminating the need to cut building elements into standardized shapes (Sections 7, 8). Collaborative efforts further eliminate the material cost for temporary support structures by allowing one robot to serve as temporary support while another places new elements, forming spanning structures (Sections 7, 8). Additionally, integrating human-robot collaboration enables the design and fabrication of complex, irregular structures—such as asymmetric tensegrity systems—that would otherwise be extremely difficult to conceive or assemble (Section 8).

On a broader scale, this dissertation redefines the role of robots in architecture, expanding their function beyond fabrication to space-making and community formation. Robots serve not only as mediators in collaborative design-fabrication with humans (Sections 7, 8, 9) but also as integral elements of the built environment, actively shaping spatial experiences through inter-agent interactions and swarm behaviors (Section 10).

More generally, in the context of rapid technological advancements and the transformative impact of Industry 4.0, this dissertation underscores the necessity of developing new design-fabrication methods to keep architecture relevant to its time. The ultimate aspiration for this research is to merge human creativity with robotic precision, transforming material assembly processes to produce more innovative, engaging, and expressive spatial outcomes.

1.3 The Structure of the Dissertation

Beyond the Introduction and Conclusion, Chapter II provides a collection of reviews to establish the study's background. Section 2 defines the research gap between CRC and HRI, introducing a new research domain called Collective Human-Robot Construction. Sections 3 and 4 present more focused mini-reviews as sources of inspiration: Section 3 examines space-aware construction through stigmergic robotics, while Section 4 explores time-series-based material actuation.

Chapter III presents three case studies that use improvisation as a framework for structuring building sequences in which humans and robotic arms collaboratively design and fabricate structures at various scales and with different materials. Section 6 explores collective creativity between humans and a UR5 robotic arm. In this setup, humans develop creative solutions to solve prompts generated by the robot based on visual inputs, leading to a shared design goal. Section 7 expands this improvisational design-fabrication framework to a larger architectural scale, using organic bamboo sticks as building elements. Periodic 3D scanning captures and abstracts the evolving structure, providing input to two ABB robotic arms on track, which then generate and position guidance sticks for human builders based on the updated geometry. Section 8 further accelerates the robot's response time by integrating visual servoing to control robotic movements. Tensegrity structures serve as the fundamental structural logic, and several functions are developed to enable robotic arms to make localized decisions, adapt to existing structures, and assist human builders in real time.

Chapter IV delves into the concept of ambiguity in human-robot interaction and collaboration. In Section 9, artificial intelligence—specifically a large language model—is employed to enable verbal natural language communication between humans and robots for movement execution. The robot is granted a degree of agency to interpret and respond to ambiguities in human instructions, allowing for more flexible and intuitive interaction. Section 10 describes the development of Rhythm Bots, a swarm robot installation and its corresponding digital twin in virtual reality (VR). This project explores collective behaviors between humans and robots using the nonlinear opinion dynamics (NOD) model[22] through multi-modal sensory experiences, examining how embodied interaction and real-time feedback shape collaborative dynamics.

Chapter V emphasizes the aspect of craftpersonship in human-robot collaboration, particularly in constructing intricate tensegrity forms. It explores tensegrity as both a craft and a design tool, providing computational models (Section 11) and structural and material optimization tools (Section 12) to enhance human builders' understanding of tensegrity systems. These resources enable more effective collaboration with robotic agents in the projects discussed in earlier chapters. Readers are encouraged to refer to this chapter when engaging with tensegrity-related fabrication processes in previous chapters.

Chapter II Background

Chapter Overview

Chapter II introduces the research domain of Collective Human-Robot Construction (CHRC), which sits at the intersection of Collective Robotic Construction and Human-Robot Interaction. To situate CHRC within the broader research landscape, Section 2 presents a review paper that categorizes related work along two research axes: *Fabrication-Design* and *Autonomy-Collaboration*. Through this framework, Section 2 identifies critical challenges and opportunities that are further examined in subsequent chapters in this dissertation. The key impacts of CHRC research can be summarized as follows:

- New formal expressions
- New ways of designing and fabricating
- Expanding the scale of robotic applications in the construction sector
- Increasing efficiency in communication, computation, task allocation, and material usage.

Sections 3 and 4 present more domain-specific mini-reviews that inspire the methods explored in later chapters. Section 3 investigates how spatial cues can organize collective robotic construction while incorporating human influences within the same built structure. Drawing from nature and swarm robotics, the exploration of stigmergic logic—where humans and robots communicate through the built environment—forms the basis for the improvisational workflows discussed in the following chapter. This stigmergic building logic is also implemented and tested in Experiment I of Section 7.

Section 4 shifts focus to the materials science aspect of soft robotic actuation, examining Ionic Polymer-Metal Composites (IPMCs) and their capacity to morph over time under the influence of an electric field. The capability of IPMCs to change shape dynamically introduces an essential design consideration—how the movements and dynamics of materials influence the spatial experience and interaction between humans and robots. This perspective is integrated into the design processes explored in subsequent chapters, where robot movement itself is a key element in shaping the built environment.

Section 5 further contextualizes the research scope through a case study on the Light Vault, addressing the challenges and strategies involved in developing a transferable robotic construction workflow. This discussion highlights the negotiation between task-specific and generalizable robotic functions, underscoring the need for adaptable solutions — an issue that will be further explored in the upcoming chapters.

Chapter II includes adaptations from the following papers:

Han IX, Meggers F, Parascho S. Bridging the collectives: A review of collective human–robot construction. *International Journal of Architectural Computing.* 2021; 19(4): 512-531. doi:10.1177/14780771211025153

Han IX. Sematectonic Stigmergy in Construction Robotics: A Review. MAE567-CBE568 Final Paper, Princeton University, Instructor: Prof. Daniel Cohen. November, 2021.

Han IX. A Concise Review of Ionic Polymer-Metal Composite (IPMC) for Soft Robotics Actuation. MSE501 Final Paper, Princeton University, Instructor: Prof. Marcella Lusardi. December, 2023.

Han IX, Bruun EPG, Marsh S, Tavano M, Adriaenssens S, and Parascho S. From Concept to Construction-A Transferable Design and Robotic Fabrication Method for a Building-Scale Vault. In *Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture: Distributed Proximities, ACADIA*. 2020.

2

Bridging the Collectives: A Review of Collective Human–Robot Construction

This section of the dissertation has been adapted from the following publication:

Han IX, Meggers F, Parascho S. Bridging the collectives: A review of collective human–robot construction. *International Journal of Architectural Computing.* 2021; 19(4): 512-531.
doi:10.1177/14780771211025153

Overview

This section explores the intersection of multi-agent, autonomous, and intelligent robotic systems with architectural design and fabrication. Recent advancements in these technologies have unlocked novel possibilities for collaborative construction processes. A key challenge lies in enabling humans and robots to work collectively, maximizing the potential of robotic systems in the building sector.

The section emphasizes the importance of making technical knowledge from fields such as robotics, materials science, and human-robot interaction accessible to designers. By doing so, it becomes possible to refine and expand current construction methods to address architectural challenges effectively.

To bridge this gap, the section introduces and defines a new research domain: **Collective Human-Robot Construction (CHRC)**. Situated at the confluence of Collective Robotic Construction (CRC) and Human-Robot Interaction (HRI), CHRC aims to integrate human creativity with robotic precision in architectural design and fabrication. The section reviews foundational work in CRC and HRI, synthesizing insights to propose a framework for CHRC, which envisions collaborative construction as a transformative approach to shaping the future of architecture.

2.1 Introduction

Developments in robotic fabrication have inspired new methods of architectural construction [23]. While most existing fabrication processes rely on a predefined sequence of movements executed by one or multiple machines, recent developments in the field have focused increasingly on more dynamic and flexible methods of multi-robotic fabrication and the advantages it brings to design and construction [24].

Processes involving multiple machines may be aimed at increasing a machine's reach, speed, and efficiency. In addition to these goals, several projects investigate how multiple machines may support each other or take on individual tasks that lead to new construction processes and outcomes[25,26,27,28]. As a result, machine interaction and control in multi-robotic processes have developed into a central area of contemporary research in robotic fabrication.

Even though crucial to the success of robotic fabrication processes, the role of humans in these processes has often not been the primary concern. Humans were viewed as users or designers pre-defining robotic tasks. However, even in the simplest robotic processes, humans are directly involved. They often perform as more than just the executors of tasks by monitoring the robotic process, making necessary adjustments, and improving the construction procedures on the fly. We can view robotic construction processes from two perspectives: 1) full automation aimed at replacing humans, and 2) synergistic processes between humans and machines that expand available design and construction possibilities. While automation might lead to faster and more efficient construction processes, taking advantage of human agents in the fabrication process is a much more valuable and sustainable goal. Instead of reducing human workers' presence on construction sites, it is worthwhile to explore how humans can be supported by machines and vice versa. Therefore, the interaction between humans and robots, along with the control of multiple machines, becomes a crucial research area for the further development of robotic construction.

Human-machine interaction, as well as machine-machine collaboration, are not new research areas. Although they have only recently found their way into architecture and design, they are building upon a substantial body of knowledge from other disciplines such as robotics, mechanical engineering, and computer science. With its unique placement between technical and artistic disciplines, architectural research has the potential to link multiple such disciplines through new approaches and applications. Therefore, it is essential for architects and designers to have access to the knowledge outside our field, in this case specifically that of robotics. By making existing methods and developments accessible to designers, we can identify new areas of research at the intersections of robotics-related disciplines and architecture, which would not be accessible by addressing each topic individually.

We have identified the fields of Collective Robotic Construction (CRC) and Human-Robot Interaction (HRI) as central to our investigation since they cover researches from both robotic and human perspectives in the construction process. CRC focuses on multi-robotic systems collectively modifying a shared environment[29,24] while HRI is dedicated to defining and crafting the relationship between humans and robotic systems[30,31,32,33]. Our review aims to bridge these two areas and identify a new research domain in Collective Human-Robot Construction (CHRC).

This subsection is structured as follows. Firstly, we give a critical survey of existing works in CRC and HRI. Then, we set up two principal research axes (ranging from *autonomy* to *collaboration*, from *design* to *fabrication*) to situate and connect major topics in CRC and HRI. Finally, we locate research gaps between CRC and HRI and highlight near-future opportunities in the newly defined field, CHRC. As a result, this subsection is intended to be a review paper that goes beyond the depiction of existing research but critically highlights research gaps and resulting new opportunities.

2.2 Preliminaries

Collective Robotic Construction (CRC) concerns "embodied, autonomous, multirobot systems that modify a shared environment according to high-level user-specified goals", as defined by Petersen et al. in 2019[24]. This is an emerging field that integrates research on *multi-agent systems*, which explores the distributed operation of autonomous agents in a network, into *construction robotics*, which focuses on automating the construction process through the use of robots[34]. According to Petersen et al., CRC can be a critical tool to enhance the scalability and adaptability of robotic fabrication in the architectural field by integrating design, construction, mechanism, and control.[24]. However, CRC examples, such as termite-inspired robot construction[35], tensile web construction[36], and micro-robot truss construction[37], are mainly conducted in controlled lab environments at the moment, with humans often acting as operators for robots. Thus, there is research space to further explore alternative ways in which humans can interact with such swarm robotic systems to create new fabrication processes or make existing robotic construction methods more transferable to dynamic construction sites.

Human-Robot Interaction (HRI) focuses on "understanding, designing, and evaluating robotic systems for use by or with humans," as stated in Goodrich's survey in 2008[31]. The literature on HRI has expanded rapidly over the past 15 years[38]. It consists of broad and diverse topics, which can be loosely organized into five major categories: navigation, perception, management, manipulation, and social[32]. The rich literature in HRI covers frameworks and methods for creating collaborative, interactive, and efficient working relationships between humans and machines.

As both CRC and HRI are young research domains that have become exponentially active within the past two decades, we expect to find previously un-discovered bridges between the two literature spaces. Besides, because humans and construction processes are inseparable in the building industry (both in terms of design and execution), exploring the topic between CRC and HRI can help better leverage robotic technologies in the overall building sector.

In the following subsections, we blend the notion of collectiveness into HRI and human factors into CRC. Collective agents open up new ways of collaborating and decision-making in design procedures (e.g., less centralized control, stigmergic mechanisms, or feedback-based processes) and material manipulation. Meanwhile, better integration of human operators into the robotic construction process accelerates technology transfer of robotics into real-world practice, expands fabrication methods by combining both parties' strengths, and ties digital fabrication back to human scale and values. In addition, some shared inspirations drawn from biology and game theory for CRC and HRI are also discussed in this section. The intentional cross-referencing interweaves literature reviews between the two domains and aims to reveal potential gaps and opportunities.

2.2.1 Collectiveness

The term collectiveness implies a networked system linking individual agents into a whole. A collective or multi-agent system contains more than one agent to form a higher-level entity through interactions among the agents. Ferber defined the terms "agent" and "multi-agent system" as follows in 1999:

"An agent can be a physical or virtual entity that can act, perceive its environment (in a partial way) and communicate with others, is autonomous and has skills to achieve its goals and tendencies. It is in a multi-agent system (MAS) that contains an environment, objects and agents (the agents being the only ones to act), relations between all the entities, a set of operations that can be performed by the entities and the changes of the universe in time and due to these actions[39]".

One major advantage of a collective system is that it can form large-scale complex entities without requiring each agent to perform complicated computations or actions. When it comes to physical power, a group of swarm robots can manipulate material elements that are much larger in scale than any individual robot can individually manage. Examples of such can be seen in emergent structures[40] and distributed timber constructions[?]. Computational-wise, collective intelligence can achieve significant complexity without requiring heavy information processing from each agent. Wisdom of the crowd is generated through a diverse and decentralized collective that supports individual independence and provides appropriate aggregation mechanisms[41]. Another implication of collectiveness particularly in architectural design is group creativity, which involves multiple agents coming up with new ideas and creations, often in an improvisational manner. Group creativity, or improvisational creativity, differs from the traditional product or compositional creativity due to its non-linear workflow and equal emphasis on process and final result[42,43,44]. Existing examples demonstrating the possibility of heterogeneous human-robot teams improvising together can be seen in music and theatrical performances (e.g., multi-robot-human jazz jam session[45,46] and theater improvisation[47]). However, more experimental projects in human-robot improvisational construction are needed to assess the potential of robotics technology's influence on group creativity in architectural design and fabrication.

Research interests in collective or multi-agent systems emerged way earlier than the prevalence of robotics, dating back to the 18th century[48,49,50]. Thus, many notions in the collective systems are not robot-specific (e.g., the Object Management Group[51], Foundation for Intelligent Physical Agents[52], Knowledge-able Agent-oriented System[53], and General Magic's Models[?]). However, researchers should still be aware of this area of research and actively transfer general principles into heterogeneous human-robot teams in design-fabrication contexts.

The construction industry consists of highly collective human social structures, including but not limited to roles such as architects, engineers, construction workers, electricians, landscape designers, and interior designers. Because relationships amongst these professions can be influenced by technological, social, and economic factors, introducing a new tool such as the robot can often induce relationship changes within construction-related occupations. For example, the recent prevalence of Building Information Modeling (BIM [54]) has improved the workflow across design, engineering, construction, and maintenance. Similarly, the notions such as Robot-Oriented-Design [52,55] were introduced to adjust the value chain "corresponding with information flows between enterprise, product, machinery, robots, costumers and all complementary sub-processes. [56]" This helps the industry to better address social, environmental, and financial dimensions.

2.2.2 Human Factors

Robotics and automation were initially invented to assist humans in completing tasks; hence, the human factor is an important subject to consider in order to create corresponding robotic systems and human-machine relationships.

The human factor, in relation to robots, can be interpreted in many ways. for example, humans can be trained (e.g., operators) or untrained (e.g., consumers and passersby), supportive or disruptive, individual or collective. Regardless of the specific types, humans generally make mistakes, perform less consistently, and are biased [57]. Thus, researchers can always draw references from psychology and sociology in building a fundamental understanding of human behaviors before designing a befitting robotic system. For the purpose of this review, we limit the role of humans to trained users involved in a construction project, such as designers, engineers, and construction workers.

HRI covers topics regarding how humans interact with robots. The three major components of HRI are defined as: Robot, Human, and System [32]. In 2004, Yanco updated a list of taxonomy for HRI [58]. Key aspects concerning human factors include:

1. *Ratio of People to Robots*: the ratio of people to robots directly affecting HRI in a system [58].
2. *Level of Shared Interaction Among Teams*: the collaborative versus independent controls between human and robot agents [58].

3. *Interaction Roles*: for example, the five roles that humans can take in an interaction with robots, as defined by Scholtz: supervisor, operator, teammate, mechanic/programmer, and bystander[59].

4. *Type of Human-Robot Physical Proximity*: the level of physical proximity between humans and robots. Huttenrauch and Eklundh proposed five modes: avoiding, passing, following, approaching, and touching[60]. In addition, the emerging subdomain under HRI named physical Human-Robot Interaction (pHRI) focuses on the physical side of the brain-body duality in robotic systems with the presence of the human.

5. *Decision Support for Operators*: the interface between human and robot – specifically how information is conveyed to form decisions, e.g., how sensors are integrated.

With the cyborg as a metaphor, human abilities have also been enhanced and extended by computational and robotic tools. People can now sense and visualize information that was previously out of human's inherent capability with the aid of external instruments, such as smart devices (e.g., smart phone[61] and smartwatch[62]), skin-based interface[63,64], and wearable (e.g., head-mounted displays[65,66], backpack and portable hand-held devices[67]). In addition, hybrid or mixed reality starts to merge physical and digital environments into one, allowing humans to have more meaningful interactions and controls over computational and robotic tools[61].

2.2.3 Inspirations: Biology and Game Theory

Bioinspirations

Multi-agent robotics often draws inspiration from nature, such as self-assembly (e.g., crystals of bacterial flagella[68], multi-cellular organism development[69,70], and species of ants, bees, and wasps[71]). The collective behaviors in groups emerge from local interactions, with the overall pattern tuned by positive and negative feedback loops. The recent implementation of opinion vectors also allows for a smooth switch between consensus and dissensus among uniformed swarm groups[72], enabling more nuanced control over multi-robotic systems.

Through a control matrix, swarm algorithms allow multi-agent robots to be responsive and flexible, which are desirable qualities in forming safe and robust interactions between robots and humans. Goodrich et al. explored the leader (attract) and predator (repel) styles of human influences through a bio-inspired robot team.[73]. According to Goodrich, ”leaders are more effective in influencing coherent flocks, but predators can be used to divide the flock into sub-flocks, yielding higher performance on some problems[74].” Their research combines HRI with Bio-inspired Robot Teams (BIRT) into HuBIRT (human interaction with bio-inspired robot teams), providing a new way of considering humans' relationship with swarm robots. Furthermore, the biological concepts have inspired new roles in robotic teams such as mediators[75] to facilitate a more integrative control system that can fulfill a wider range of spatio-temporal tasks[76]. Besides the branch of bio-inspired robotic models focusing on mediator's roles, another branch discusses the different algorithms for swarm communication models (e.g., metric, topological, and visual) and emphasizes the importance of the deliberate selection of such models to enhance the task performance of a swarm system[77].

The bio-inspirations for swarm robotics introduce structures and hierarchies into the management and coordination systems. Instead of the traditional controller-agent[78] or peer relationship[79] with robots, the biological examples mentioned above suggest roles in-between. As mediators, humans can coordinate a large group of swarm robots with a more flexible and fine-tuned control. However, most researches in this area remain in the theoretical or simulated stage, with few examples in real-life robotic applications. It is a great opportunity and challenge to bring these bio-inspired multi-robotic models into design and fabrication applications.

Economics and Game Theory

Economics, especially game theory, has also inspired control methods for collective robotic systems with concepts of negotiation and decision making. Studies inspired by game theories, in general, focus on the cooperation of selfish rational agents[29] in achieving utility-maximizing scenarios with respect to other agents' decisions. In multi-robotic task allocation, one can construct a price-based task market, and each robot is programmed to act selfishly and buy[80] or auction[81,82] tasks for maximum profit[83].

Game theory is broadly applicable to various robotic problem types[84] and can yield efficient and responsive computational frameworks[85]. In 1993, LaValle and Hutchinson brought game theory into multi-robotic scenarios by conceptually applying game theory to topics such as "multiple robot coordination, high-level strategy planning, and information gathering"[84]. In 2008, Meng demonstrated a dynamic-programming function, where a nonzero-sum game is formed so that optimal overall robotic performance can be accomplished[85]. This game-theory-based framework is designed to be efficient and robust in a dynamic environment with real-time responsiveness.

Game theory has influenced not only multi-agent robotics but also human-robot interaction. In 2008, Lee and Hwang proposed a game-theoretic approach to communicative interaction and cooperative decision making[86]. In 2016, Hadfield-Menell et al. proposed cooperative inverse reinforcement learning (CIRL) that effectively achieves value alignment in a partial-information human-robot game[87]. Game theory can also be used to better understand HRI. For example, in 2016, Wu and Paeng used the game theory approach to show that "a human may grow to trust a robot teammate more than a human teammate"[88,89]. Besides, studies in heterogeneous teams also draw inspirations from game theory. In 2010, Tarasenko applied Lefebvre's Reflexive Game Theory (RGT)[90] to model mixed groups of humans and robots, where both parties are represented with a unified hierarchy and methods of solution are considered simultaneously with practical applications[91].

Both the biological and economic concepts provide new inspirations for integrating humans into a heterogeneous robotic team with a less centralized and more flexible control system. This flexibility in coordination can help humans better predict the robots' next moves, split tasks with robots in a more organic manner, and influence task executions on the fly. However, researches in the theses areas are currently conducted mainly in simulated or lab environments. It remains a challenge to transfer these methods into real-world applications, especially in the construction industry, efficiently and robustly.[92].

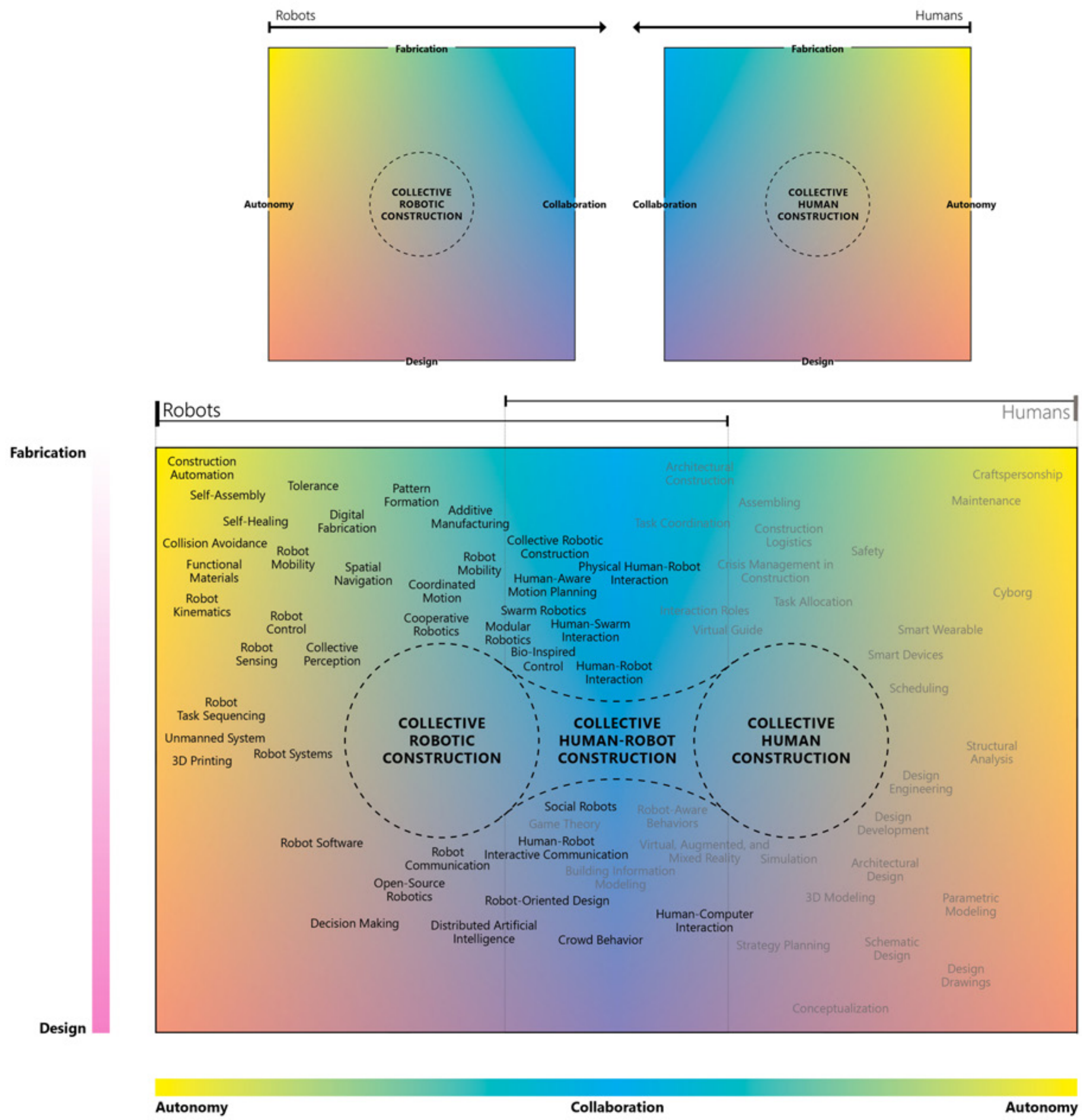


Figure 2.1: Bridging the Collectives: Collective Human-Robot Construction

2.2.4 Research Problems across CRC and HRI

Goodrich and Schultz defined HRI problems to be "to understand and shape the interactions between one or more humans and one or more robots" that can be broken down into the following constituent parts[31]:

1. Level and behavior of autonomy,
2. Nature of information exchange,
3. Structure of the team,
4. Adaptation, learning, and training of people and the robot, and
5. Shape of the task.

Meanwhile, as defined by Petersen et al., CRC consists of four major areas: Robotic Systems, Assembly Algorithms, Building Design, and Functional Material. Overall, the research scope of CRC and HRI is not just limited to technical challenges such as robotic systems and material manipulation methods but extends to areas of social dynamics and team management, such as in swarm behavior, task assignment, human-robot collaboration, and more. Although both CRC and HRI are already interdisciplinary fields, a meaningful bridge can be made between the two by carefully laying out related research problems onto research axes relevant to the robotic and architectural scope.

2.3 Research Axes

In this paper, we propose two research axes (*autonomy-collaboration* and *design-fabrication*, see Figure 2.1) to situate the ranges of topics encountered in CRC and HRI, as well as industry-specific topics regarding human collectives in the building sector. The *autonomy-collaboration* axis covers technical aspects in robotics such as sensing, controlling, and communicating. The *design-fabrication* axis helps situate multi-agent robotic researches into the field of architecture. Together, these two axes aim to map out research domains and gaps in collective human-robot construction. In Figure 2.1, a gradient diagram qualitatively illustrates how sub-branches of CRC, HRI, and architectural design fabrication topics mentioned in the reference list of this review paper fit into the research scope spanning across *autonomy-collaboration* and *design-fabrication* axes. The main diagram in Figure 2.1 is formed by merging two human and robotic collective construction diagrams into one. As a result, the horizontal *Autonomy-Collaboration-Autonomy* axis in the key diagram is mirrored around *Collaboration* with the left and right ends illustrating each of the robotic and human collectives.

2.3.1 Autonomy-Collaboration

Autonomy

Autonomy is a research topic that is critical to both CRC and HRI. Beer et al. have provided a loose definition for autonomy in humans or machines as "the extent to which a system can carry out its own processes and operations without external control[93]." They also provided a more specific definition of robotic autonomy to be "the extent to which a robot can **sense** the environment, **plan** based on that environment, and **act** upon that environment, with the intent of reaching some **goal** (either given to or created by the robot) without external **control**[93]."

There are two major groups of opinions on autonomy's implications in the HRI context. Huang et al. suggests that higher autonomy yields less interaction between humans and robots[94,95,96,97]. Their research on *unmanned system (UMS)* aims to maximize system performance with minimal human intervention. Goodrich and Olsen echo the point by associating the idea of *neglect* with autonomy. They argue that the length of a time period in which a person can *neglect* the robot is directly associated with how effective the robot performs its tasks independently[98,99]. Therefore, less interaction is required if the robot has a higher level of autonomy[58].

A contrasting perspective suggests that increasing the level of autonomy requires more complex types of collaboration among agents[100,31,101,33]. In other words, there's a positive correlation between autonomy and collaboration. With higher levels of autonomy in robots, a more balanced partnership can be established, where humans and robots work together toward a common goal with proper communication and complementing skill sets [30,101]. For example, Fong suggested a model where robots can ask a human for advice and take advantage of human perception and cognition especially when facing arbitrary situations [30,102].

While robotic systems can range from fully autonomous to teleoperated, *adjustable autonomy* has introduced the notion of switching between a range of autonomy modes or levels [103]. *Adjustable autonomy* opens up a design space which allows for fine-tuning the level of HRI to achieve desired performances. For example, *adjustable autonomy* allows for strategic direction of human attention, which can be helpful when human focus is required in design decisions on-site or emergency response in hazardous conditions.

Different modes of autonomy have been proposed by existing robotic control frameworks. For example, Bruemmer et al. from the Idaho National Engineering and Environmental Laboratory (INEEL) proposed a robot control architecture that consists of four primary autonomy modes: *teleoperation* (human has full and continuous control of the robot at a low level), *safe mode* (human directs the robot's movement; robot takes initiatives to protect itself), *shared control*(The robot takes the initiative to choose its own paths for local objectives), and *full autonomous* (robot performs global planning and only requires high-level tasking input from humans) [104]. Bruemmer and Walton also created a dynamic umbrella of adjustable autonomy control that can "support a spectrum of team interactions as individual capabilities change and needs arise [105]."

Collaboration

Collaboration requires agents to have a certain level of autonomy but focuses on the coordination between multiple agents. Wang identifies five team-performance measures: trust, compliance, transparency, mission success, and correct decisions, with trust being a foundation in human-robot teams [106,107]. Researchers have shown that a better understanding of a robot's decision-making mechanisms can help enhance trust for human operators [108]. In Hoffman's latest fluency metric scale, he provided a list of subjective items to consider when evaluating Human-Robot Collaboration [109,110]. By analyzing through aspects like trust in the robot, human-robot fluency, positive teammate traits, and more, human-robot collaboration is studied through a more subjective and experience-based perspective.

Collaborations among humans are increasingly influenced by advancements in machines. Human-Computer Interaction (HCI) provides new interfaces for directed, collaborative, and passive crowd-sourcing in the context of collective intelligence [111]. Besides, the prevalence of cloud computing has inspired the concept of Human-Robot Cloud. HRC enables distributed computation, storage, sending, and actuator networks [112]. Meanwhile, researches related to physical collaboration among collectives are also essential. The study of Physical Human-Robot Interaction (pHRI) concerns HRI in close physical proximity. It explores human-friendly robot design (e.g., lightweight machines with flexible force control [113]) and human-aware motion planning (e.g., with velocity constraints [114], sampling-based costmap planners [115], and dynamical systems [116]). Aside from challenges regarding HRI in close proximity, another research lens focuses on embodying interactions in space. As stated by Eng et al., an interactive space consists of "data from human activity, human opinions, and the activity of the space" [117]. In these settings, changes in human groups influence the distributed manipulators to form an interactive environment that exhibits collective agency across human and machine. Examples of interactive spaces include the Flexing Room [118] and Ada [117].

How humans and robots communicate with each other is important for collaboration. In 2015, Mavridis gave a thorough review on the topic of verbal and non-verbal human–robot interactive communication [119]. Mavridis used a list of ten desiderata to guide his review:

1. Breaking the "simple commands only" [120] barrier.
2. Multiple speech acts [121].
3. Mixed initiative dialogue (e.g., the Karlsruhe Humanoid [122] and the Biron and Barthoc systems at Bielefeld [123]).
4. Situated language and the symbol grounding problem (e.g., ELIZA [124], the Loebner Prize [125], and the POETICON project [126]).
5. Affective interaction (e.g., the Kismet robot [127] and the ATR Robovie robot [128]).

6. Motor correlates and Non-Verbal Communication (e.g., eye gaze cues [129,130] and gestures [131]).
7. Purposeful speech and planning (which concerns navigation through uncertainties).
8. Multi-level learning (e.g., Machine Learning [132] and crowd-sourcing in HR [133]).
9. Utilization of online resources and services (e.g., the Roboearth project [134] and its Rapyuta cloud engine [135]).
10. Miscellaneous abilities (that can deal with multiple conversational partners [136] with multilingual capabilities [137]).

Mavridis' review suggests a trend toward more fluid communication, encompassing numerous formats and the dynamic integration among them. In robotic fabrication, enhanced communication among humans, robots, built structures, and the larger environment enables feedback loops that help to balance the fabrication and design concerns [138]. Not only can we develop new ways of strengthening connectivity across the builder, tool, and environment, but we can also rethink built space as a medium, where the building becomes a living organism that can shift and adjust based on the inhabitants' inputs. For example, in robotic research, Nagpal has promoted the idea of communicating through built structures via collective agents [35]. In architectural theory, Kilian proposed the flexing room where the human-machine interface is represented by the space itself [118].

2.3.2 Design-Fabrication

The *design-fabrication* axis aims to tie the research domain to the building sector. The *design* end of this axis is related to the virtual aspects, including topics in decision-making, information representation and exchange, communication, and more. Meanwhile, *fabrication* concerns the physical processes, including but not limited to material manipulation, localization, navigation, tolerances, collision avoidance, robotic kinematics, and human-robot physical interactions.

Topics in *design* draw references from fields such as Human-Computer Interaction [139] and how CAD and BIM influenced the building industry, but with additional consideration in collective robotics as the driving factor. Bock first proposed the term *Robot Oriented Design (ROD)* in 1988 [52] and published a same-titled book in 2015 [55]. According to Bock, ROD is concerned with "the co-adaptation of construction products and automated or robotic technology, so that the use of such technology becomes applicable, simpler, more robust, or more productive or efficient." An example such as ROD lies in the middle of the *design-fabrication* axis. Besides, emerging research starts to explore how design tasks can be split and distributed to robotic collectives, where individual robots make decisions based on inputs from the other robots and the environment. For example, Yablonina's co-design strategy with larger groups of smaller robots showcases a codependent development of the process, object, and machine [140].

2.4 Discussion

2.4.1 Collective Human-Robot Construction

After reviewing CRC and HRI, we identify a potential research domain situated in-between the two and define it as follows:

Collective Human-Robot Construction (CHRC) concerns multi-agent construction involving both human and robotic collectives. It is an emerging interdisciplinary field that combines collective fabrication, human-robot interaction, and heterogeneous teams. Research focused on CHRC spans from autonomy to collaboration, indicating novel ways of designing and fabricating.

2.4.2 Motivations for Defining CHRC Research Space

CHRC is a unique field compared to its neighboring ones. It differs

1. from CRC with a focus on human factors,
2. from HRI due to the emphasis on collectiveness, and
3. from human-robot teams through its application in construction.

The purpose of this review is to draw attention to the specific overlapping research topics concerning collectiveness, human-robot teams, and construction, and provide the terminology of CHRC to refer to this particular area.

CHRC is critical in joining forces and intelligence of robotic and human collectives to achieve greater impact in the field of construction (ranging from team dynamics [141] to economic profits [142]). The distributed timber construction with collective robots acting as joints [143] is one recent example among others (e.g., tensile web construction [36] and micro-robot truss construction [37]) that shows the potential of CRC in creating complex spatial structures. Both the emergence of dynamic autonomous control and diverse collaboration models have opened up possibilities for new ways of designing. For example, Yablonina's mobile robotic fabrication system for filament structures takes a step further from ROD to imply a co-design scenario between human and distributed robotic agents[?] . From a broader industrial point of view, distributed collective systems have the advantage of responsiveness and robustness [72,144,145]. Combining human sensitivity and creativity with robotic strength and accuracy can help solve existing problems concerning tolerance and scalability [146] to accelerate the transferring of novel fabrication methods from lab to real world construction sites. Therefore, in the long run, CHRC has the potential to help expand the adoption of robotic technology especially for on-site construction challenges [147,148].

In a nutshell, CHRC is a promising field for exploring:

1. New formal expressions
2. New ways of designing and fabricating
3. Expanding the scale of robotic applications inthe construction sector
4. Increasing efficiency in communication, computation, task allocation, and material usage.

2.4.3 Future Challenges and Opportunities in CHRC

The emerging CHRC field is filled with challenges and opportunities. Moving forward, we need to not only tackle technical problems (e.g., multi-agent decision making, control, communication, and learning) but also design integrative systems to efficiently bring the two collectives together (humans and robots) in pursuing design and construction tasks in real-world practice. While there is rich literature in conceptualizing collective systems and human factors, further work is needed to synthesize the two themes into construction applications.

Figure 2.1 provides a visual indication of potential research gaps to fill in CHRC. The clustering of robot-related topics toward the fabrication end of the axis indicates a potential utilization of robots in assisting design processes. The blue column at the center gathers topics directly related to human and robot collaboration. Thus, there is rich potential in bridging and blending such topics. For example, *social robots* can be paired with *robot-aware behaviors* to create design fabrication scenarios where robots and humans are both orienting their decisions and behaviors based on the other's characteristics. Another example is to connect *Bio-Inspired Control* and *Interaction Roles* in swarm robotic teams (fig. 2.1). The topic has already been slightly touched upon in Goodrich's HuBIRT research[73], although it was not oriented toward architectural fabrication. Similarly, due to the mirrored layout along the *Autonomy-Collaboration-Autonomy* axis in Figure 2.1, one can also fold the diagram vertically in half and find potential research bridges across the "robots" and "humans" areas on symmetric locations in the diagram. Such examples include the symmetry between robot's *self-healing* and human-operated architectural *maintenance*, between robots' *collective perception* and human's extended connectivity through *smart devices*, or between *robot sensing* and *smart wearable*. It is also worth mentioning that the research topics that are qualitatively located on Figure 2.1 are dynamically shifting with on-going development of the subjects. Therefore, there can be motivations to actively push one topic toward a certain research direction. For example, *3D Printing* is currently located toward the robot's *Autonomy* end of the axis. However, this doesn't mean that *3D Printing* would not benefit from more feedback and input from sensors and human operators.

To accelerate the bridging across the disciplines, iterative prototypes of collective construction systems can be developed to further expand humans' roles in existing CRC systems or collective behaviors in HRI. For example, Petersen et al. identified the human element in CRC by stating that "Future research will also reveal where humans are best placed with respect to CRC, e.g., to define goal specifications, to provide online corrections when robots commit rare, but inevitable errors, or to support and maintain robots."[24] Besides, from the perspective of HRI, more complex, nuanced, and flexible interaction among heterogeneous multi-robot-human teams shall be further developed. Based on this review paper and its corresponding diagram (fig. 2.1), researchers may further advance CHRC through:

1. Bringing heterogeneous team inspirations (e.g., from the inter-species relationship in nature and game theories) into collective construction systems involving diverse human roles and robotic types;

2. Iteratively transferring collective construction systems from a simulated or controlled lab environment into real-world construction settings and building environment[146]. This requires more consideration of problems such as latency, tolerance, control, and management.

3. Creating proof-of-concept projects to set cornerstones in adapting techniques and methods from the neighboring field (e.g., HRI, CRC) into the discipline of architecture and design;

4. Leveraging fluid and dynamic control and communication models[105,112,116] to distribute design decisions (e.g., co-design strategy[?]) and form complex structural and material systems[149,35];

5. Developing management strategies to prepare for a safe, efficient, and flexible application of CHRC on site;

6. Investigating topics of group creativity and social dynamics in heterogeneous human-robot teams. For example, one can imagine scenarios where humans improvise with robots in addition to pre-composed assembly procedures to achieve site-specific structures. Alternatively, one can also utilize human-robot group creativity for emergency management at the construction site;

7. Rethinking the roles of design and construction professionals, specifically in how to best allocate humans' capabilities and attention, given the potentials and constraints of robotic intelligence and kinematics (e.g., ROD[52,55]); and

8. Exploring new forms and functionalities of space, providing dual dimensions in physical structure and embodied control. For example, smart devices and wearable can be designed to empower the human body with higher sensibility and capability when collaborating with robots. Thus, more fabrication strategies using mixed or hybrid reality can be developed to provide additional platforms for humans, computers, and robots to create and construct collectively.

2.5 Conclusions

Both robotic systems and human groups in the construction sector observe a trend toward decentralization and collaboration. This review's purpose is to identify gaps between Collective Robotic Construction (CRC) and Human-Robot Interaction (HRI) literature to define a new research domain in Collective Human-Robot Construction (CHRC). Both CRC and HRI are young but active research domains, and there are on-going discussions on how humans can interact with collective robotic systems. However, there is a less-touched research space in reviewing human collectives (e.g., institutions, professions, corporations) in relation to multi-agent robotics, as well as one targeted toward the construction industry connecting collective robotic tools with the existing operational and informational structure, such as BIM. This paper reveals promising research areas in bridging the collectives (humans and robots, see fig. 2.1). Developing CHRC is essential for leveraging robotic technology within the existing building industry to create scalable impacts. By combining humans and robots' collective intelligence and capabilities, we can increase efficiencies (in communication, material processing, and fabrication) and create formal and organizational structures that are far more complex than either party can create alone. Thus, the emphasis on human elements in robotic construction reveals potential for a safe and pleasant collaboration model where human creativity and sensitivity can be best manifested. By bringing these two seemingly disparate research areas together into the field of construction, we can open up previously unknown possibilities for architecture and design.

3

Sematectonic Stigmergy in Construction Robotics: A Review

This section of the dissertation has been adapted from the following course paper:

Han IX. Sematectonic Stigmergy in Construction Robotics: A Review. MAE567-CBE568 Final Paper, Princeton University, Instructor: Prof. Daniel Cohen. November, 2021.

Overview

Stigmergy refers to the indirect communication between agents through their shared environment. Instead of having a blueprint of what the final structure should look like, the construction process is programmed into each agent in a sense that they know exactly how to react given a certain local spatial configuration. While marker-based stigmergy often uses chemical-based signals in space to alter agents' succeeding behaviors, sematectonic stigmergy, instead, has an ongoing physical construction (i.e., nests) as the medium for communication. Because stigmergy does not require each agent to know the global map, it has the benefit of not requiring high computational power or intelligence from individual agents. Therefore, even simple agents can collectively build a magnificent structure that is sophisticated and grand in scale with the stigmergic algorithm. Since Grassé coined the term "Stigmergy" in 1959 and Wilson on "Sematectonic Stigmergy" in the 1970s, advancements in mathematical models were made to describe stigmergic behaviors, which further inspired hardware materialization of such models in robotic teams for construction tasks in the 21st century. This paper reviews key concepts and models in sematectonic stigmergy and the robotic systems they inspired. At the end of this review, several challenges and opportunities are identified in this specific research field.

3.1 Introduction

Nest architecture is the physical manifestation of the swarm's building behaviors of social beings. The spatial layout and construction sequence of nests are closely related to the builders' abilities to sense, communicate, and construct. By studying the building behavior of insects such as termites and wasps, researchers have proposed numerous stigmergic algorithms to simulate existing nest constructions or inspire new structures.

The terminology "stigmergy" can be defined as the communication between agents via modifying shared environments. French zoologist Pierre-Paul Grassé first formulated this idea in 1959[150], where he stated in french "La coordination des tâches, la régulation des constructions ne déndentent pus directement des ouvriers, mais des constructions eux-mêmes. *L'ouvrier ne dirige pas son travail, il est guidé par lui.* C'est à cette stimulation d'un type particulier que nous donnons le nom de STIGMERGIE*"[150]. Instead of having the workers guiding the construction of a structure, the structure itself can inform the future construction behaviors of the workers.

There are two major categories for stigmergic communications: marker-based and sematectonic[151,152,153,154]. Marker-based stigmergy drops markers (i.e., chemical pheromones) to the environment to trigger subsequent behaviors. Behaviors assisted by marker-based stigmergy include food forging in ants and termites, which often inform swarm robotics topics in collective exploration[155], area coverage, and target searching[156]. In contrast, sematectonic stigmergy directly modifies the environment. This type of stigmergy often guides the nest construction for social insects such as wasps and bees, which inspires the design of multi-agent robotics for construction (i.e., Termite-Inspired Robot Construction Team[35]).

This review paper focuses on sematectonic stigmergy and the robotic systems inspired by it. The first section of the paper provides a historical context for stigmergic algorithms derived from social insects. The second part covers recent advancements in swarm robotic constructions using sematectonic stigmergy. Finally, the last section discusses research challenges and potential future directions in the field of stigmergic robotic construction based on the review.

3.2 Hypotheses and Algorithmic Models in Stigmergy

While building with swarm robotics using the stigmergic algorithm has only started to gain research interests over the decade, stigmergic construction with swarm teams can track its long history in nature from social insects such as wasps and termites. Once Grassé coined the term of *stigmergy* and Wilson

*English Translation: The coordination of tasks and the regulation of constructions does not depend directly on the workers, but on the construction itself. *The worker does not direct his work, but is guided by it.* It is to this particular type of simulation that we give the name STIGMERGY.

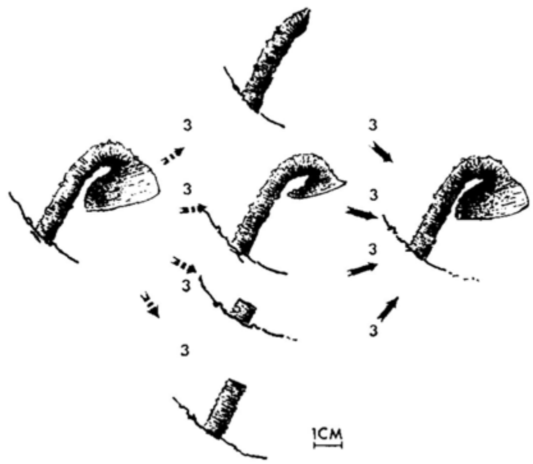


Figure 3.1: "Experiment 1 with *Paralastor* sp. showing the effects of breaking funnels back to earlier stages of construction. Broken arrows indicate experimental manipulations carried out by the author (Smith). Unbroken arrows indicate the subsequent responses by wasps. Numbers indicate the number of replicates of each experiment and the relative responses by the affected wasps." Illustration by Andrew P. Smith [157], ©1978 reprinted with permission from Elsevier.

specifically on *sematectonic stigmergy* [150,153], researchers started putting efforts into establishing numerous hypotheses and algorithmic models to describe such behaviors.

In 1978, Andrew P. Smith's experiments with *Paralastor* sp., a type of Australian Eumenid mud wasp, has successfully proved the robustness of stigmergic sequencing, which relies on local triggers instead of a pre-planned blueprint [157]. Before Smith's experiment, the dominant thoughts were that the social insects have an "inherited image" or blueprint of the final stage of the construction [158]. In contrast to this common belief, Smith's experiments with *Paralastor* sp. illustrated a scenario where local conditions stimulate the wasps' construction behaviors. Thus, the building procedure can be divided into several stages, where the completion of one stage triggers a new set of construction methods for the upcoming stage. In addition, as shown in Figure 3.1, Smith has showed that omitting or fast-forwarding construction steps would not disturb the wasps' construction flow. The wasps will take what's given and continue from there. Even though Smith did not mention the terminology of "stigmergy" in the report, his research provided evidence of the robustness and flexibility of stigmergy construction.

In addition to flexibility in sequencing, with makes collaboration among multiple agents easier, another desirable characteristic for stigmergic construction is its low computational requirement for the

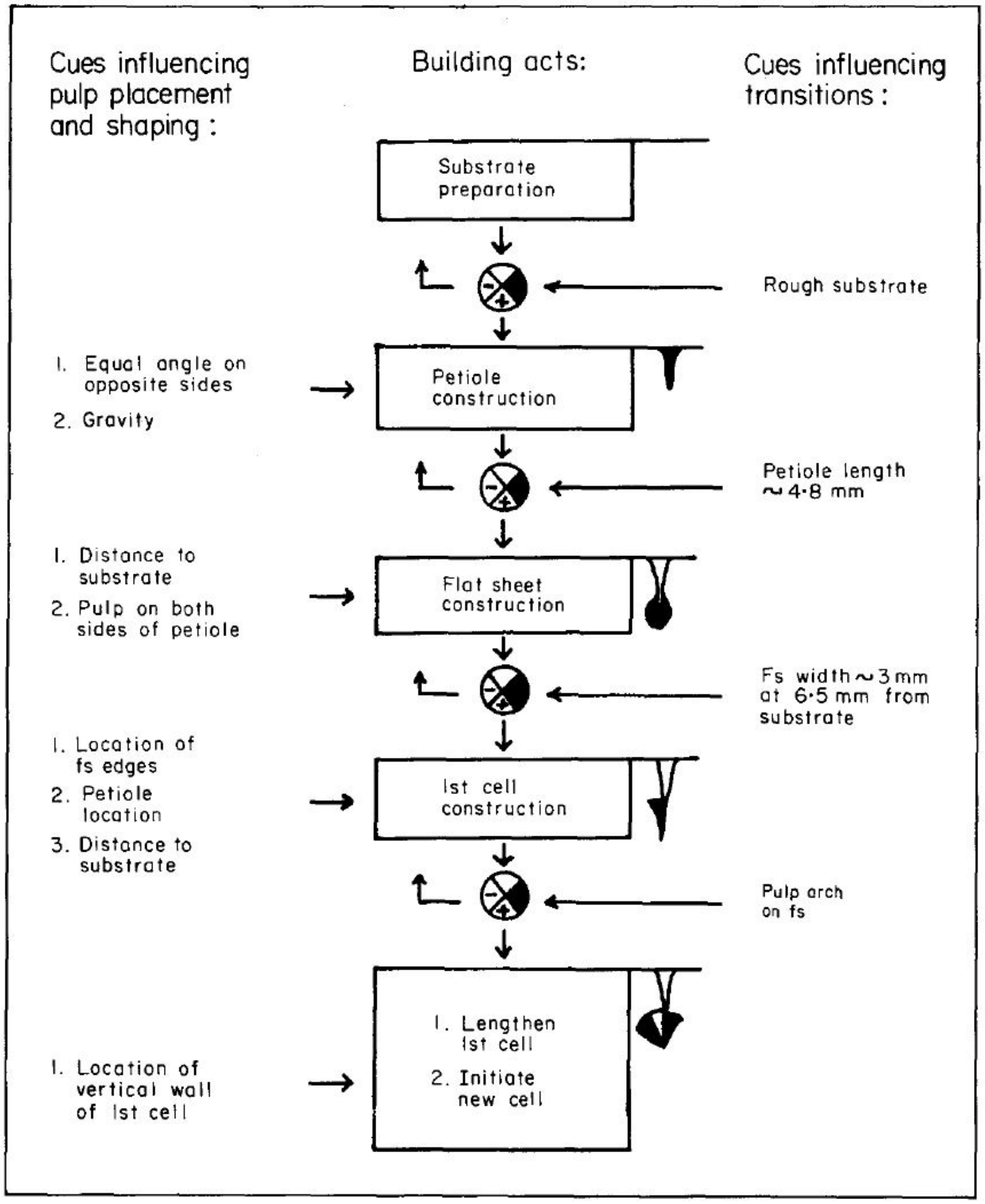
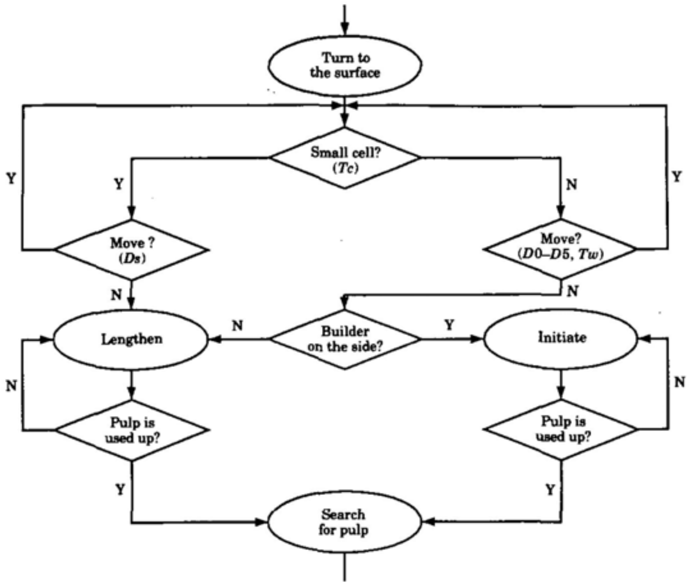


Figure 3.2: "Diagram of cues regulating construction during the initial linear series of nest construction steps in P.fuscatus. Building acts are shown in boxes. The step of construction is indicated in black in the accompanying illustration. Stimuli regulating transitions are given on one side and cues influencing how pulp is placed and shaped are listed on the other sides. +: transition cue condition met; -: transition cue condition not met; fs: flat sheet; ~: approximately." Illustration by H. A. Downing and R. L. Jeanne[159], ©1988 reprinted with permission from Elsevier.



Parameters used for the simulation of the building behaviour of the wasps

Parameter	Value	Interpretation
Wn	4	Number of wasps
Fp	0·25	Probability of finding pulp in the foraging area
Tc	5	Threshold for distinguishing between small and large cell
Tw	2	Threshold for distinguishing between the wall size
Ub	1	Unit used for one building subact
Lu	9	Load for one building act
Bc	4	Number of units used for the bottom of the cell
Am	0·50	Probability of ahead movement
ASm	0·20	Probability of ahead-side movements
Bm	0·02	Probability of backward movement
BSm	0·04	Probability of backward-side movements
Rs	0·05	Probability of returning to the surface from the side
D0	0	Probability of deposit pulp in the case of no high walls
D1	0	Probability of deposit pulp in the case of one high wall
D2	0·10	Probability of deposit pulp in the case of two high walls
D3	0·50	Probability of deposit pulp in the case of three high walls
D4	0·80	Probability of deposit pulp in the case of four high walls
D5	0·90	Probability of deposit pulp in the case of five high walls
Ds	0·95	Probability of deposit pulp in the case of small cells

Figure 3.3: "Decision for building and the building algorithms used by simulated wasp." Illustration by István Karsai and Zsolt Pénzes[160], ©1993 reprinted with permission from Elsevier.

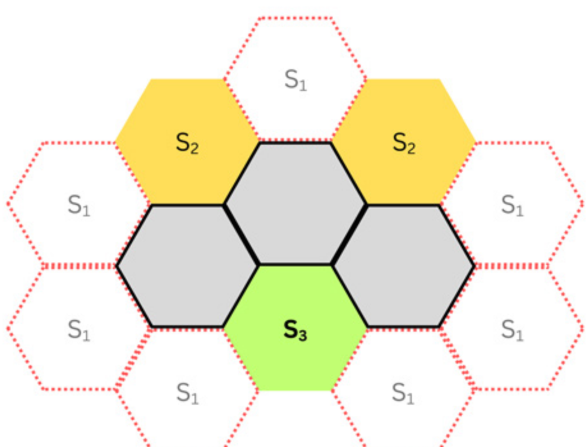


Figure 3.4: "Representation of the potential building sites that have one (S_1), two (S_2), or three (S_3) walls in common with the new cell added to the comb." Illustration by Isla Xi Han based on Guy Theraulaz and Eric Bonabeau's descriptions in 1999[161].

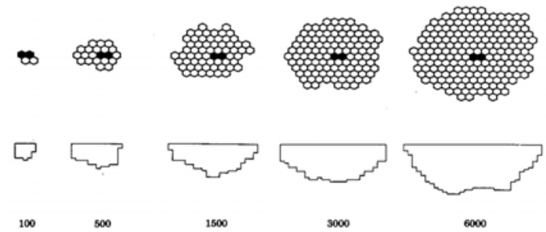


Figure 3.5: "Growth sequence of a simulated comb: views from beneath and side. The black cells mark the two first cells from which the building started." Illustration by István Karsai and Zsolt Pénzes in 1993 [160], ©1993 reprinted with permission from Elsevier.

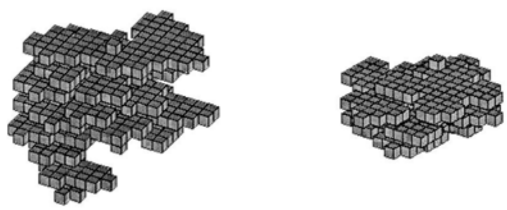


Figure 3.6: "Simulation of collective building with a 3D lattice swarm." Illustration by Guy Theraulaz and Eric Bonabeau in 1995 [164], ©1995 reprinted with permission from Elsevier.

individual agent. Even though the final structures built by swarms of agents are often large and complicated, the construction methods demanded from each individual are often simple. They can be covered by a combination of "if-then" and "true-false" decisions in most cases [159,160]. For example, István Karsai used a logic diagram to simulate the decision workflow for wasps, as shown in Figure 3.3. In Karsai's model, probabilities are assigned to different spatial configurations to simulate how likely a wasp will execute a specific behavior given the situation. A similar approach has also been conducted by Guy Theraulaz, Eric Bonabeau, and Deneubourg J.L., who also assigned different likely-hood of triggering subsequent behaviors based on local typology for wasps' cell construction [162,161]. For example, for a scenario shown in Figure 3.4, a wasp is about ten times more likely to fill in S_3 than S_2, leaving S_1 as the least likely option to start a new row before finishing existing ones [161,160,163]. Both the two groups of researchers have come up with viable methods that yield convincingly-looking biological architecture (see Figure 3.5 and 3.6). To incorporate the flexibility aspect of the stigmergic construction, where agents can come and leave without influencing the viability of construction, Theraulaz and Bonabeau integrated recurrent states into the chain of building states in their algorithm. This coordinated algorithm also satisfies the non-overlapping condition, "because all individuals cooperate in the current building state at any time. [164]"

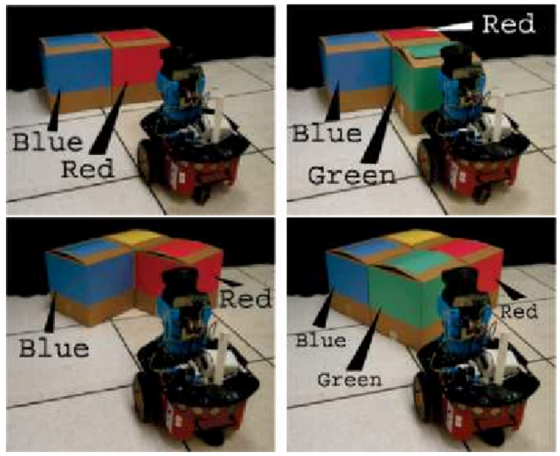


Figure 3.7: Distributed multi-robot system by Chris Jones and Maja J Matarić in 2004[165], ©2004 IEEE.

So far, the models we described comply with the strict form of stigmergy, which implies that structure alone is enough to guide the complete series of building behaviors. However, research by Downing and Jeanne in 1988 showed that more cues other than existing construction are needed to instruct the building process[159]. By observing the initial linear series of construction for *Polistes fuscatus* (a type of paper wasp), they identified a few extra cues the insects used in addition to existing built structures, such as gravity and the location and angles of other adjacent elements (Figure 3.2)[159]. Downing and Jeanne's research suggested that the stigmergic construction may not be as absolute as Grassé described. However, this doesn't prevent strict stigmergic algorithms from simulated biologically looking nest architecture[164], nor does it prevent researchers from developing stigmergy-inspired robotics, as additional cues can be easily integrated into robots through sensors and feedback loops.

3.3 Stigmergic Construction Robotics

Over the past decade, several construction robotic systems have been developed using stigmergic logic. An early example of such robotic systems was developed by Jones and Matarić in 2004[165]. They did not mention the term "stigmergy" in their report. However, they used "*distributed* multi-robot system (MRS)" to describe a very similar system, in which "each robot operated independently under local sensing and control, with coordinated group behavior arising out of local interactions between the robots and the task environment."[165] In this example, researchers assigned different colors to build-

Figure 3.8: TERMES[35]. Preprinted with permission.

ing blocks as local cues, which trigger a variety of actions from robots (Figure 3.7). Jones and Matarić's experiment can be viewed as an early example using stigmergic construction logic. However, the structures in their experiments are all planar, thus lacking spatial complexity.

One recent well-known example is the termite-inspired robot construction team designed by Werfel, Nagpal, et al.[35]. They started exploring the mathematical framework behind the robot teams since around 2005. They assigned rules for robots when facing different types of local conditions using "while" and "if-else" frames similar to those described by Downing and Karsai[159,160] What's more? Werfel and Nagpal also introduced algorithms for building blocks. These communicative blocks can provide richer instructions to robots interacting with them[166], which Werfel and Nagpal described using the term "extended stigmergy: augmenting the basic notion of stigmergy by increasing the capabilities of environmental elements"[145]. In 2014, the same research team developed the hardware for a robotic construction team to realized the stigmergic algorithms in 3D building processes[35] (Figure 3.8). However, even though Werfel and Nagpal introduced the term "extended stigmergy", their hardware example in 2014 only used passive tiles as building component[35] instead of communicative blocks as described in their previous mathematical framework[166].

On the topic of stigmergic building blocks, Sugawara and Doi realized a design for semi-active building blocks paired with simple robots in 2015. The researchers integrated IR LED on blocks to send stimuli to robots which are equipped with IR sensors[167,168]. However, the constructions are in 2D instead of 3D. In addition, their research almost entirely shifted the intelligence from robots into blocks; thus, the research focus is only tangentially related to stigmergic robotics.

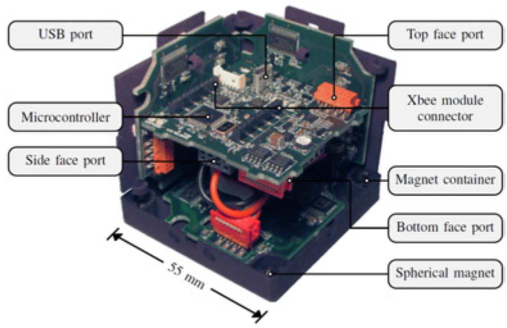


Figure 3.9: "Internal components of the stigmergic block." Designed by Michael Allwright, Navneet Bhalla, and Marco Dorigo in 2017[169], ©2017 IEEE.

Inspired by the early MRS example from Jones and Matarić[165], the extended stigmergy from Werfel and Nagpal[145], and intelligent blocks from Sugawara and Doi[168], Allwright, Bhalla, and Dorigo further advanced autonomous robot team with stigmergic blocks in 2017[169]. The researchers built an upgraded version of the stigmergic block inspired by Sugawara and Doi by having multiple colored LED and near field communication (NFC) at all sides of each block, as shown in Figure 3.9. Spherical magnets are placed at all corners to help align the blocks with one another. Each stigmergic block can compute, store data, and communicate with other blocks and robots. The researchers did three tasks in their "Structure and Marking as Stimuli for Autonomous Construction" paper using marking-based and structure-based stimuli first separately and then simultaneously to complete a partially-built construction[169]. As shown in Figure 3.10, the first green block functions as the seed block to initiate a sequence of construction behaviors towards a target shape. This seed block is similar to the first two starting cells in Karsai et al.'s simulation in 1992 (see the cells marked in black color in Figure 3.5). Even though the authors used different terminologies, for the purpose of consistency, we can interpret their "structure-based stimuli" to be parallel to "sematectonic stigmergy" and their "marking-based stimuli" to "marker-based stigmergy" as mentioned in the previous section of this review paper. Thus, Allwright, Bhalla, and Dorigo's research provided an example of robots mimicking both sematectonic and marker-based stigmergy simultaneously during construction.

In addition to combining different types of communications within stigmergy (sematectonic and marker-based)[169], stigmergy also can be paired with existing robotic control systems to improve their performances, especially in reducing tolerances at a local level[170]. For example, Ardiny et al. from École

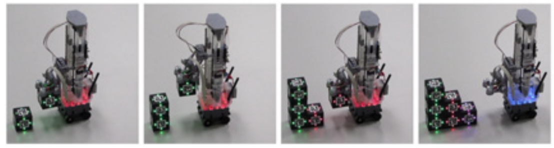


Figure 3.10: "Construction of a staircase by an autonomous robot, coordinated through the structure and markings of the partially-built structure.". Illustrated by Michael Allwright, Navneet Bhalla, and Marco Dorigo in 2017[169], ©2017 IEEE.

Polytechnique Fédérale de Lausanne (EPFL) combined stigmergy with simultaneous localization and mapping (SLAM). In their experiment, SLAM helped the robot to scan and locate itself in a previously unknown area, and stigmergy enabled the robot to construct a more coherent artifact based on local conditions[170]. By analyzing transnational error, rotational error, and overlap percentage of the resulting building blocks, the authors concluded that stigmergy could help robots place building components more reliably and coherently[170].

3.4 Future Challenges and Opportunities

Grassé's version of stigmergy is relatively strict, where the structure itself can inform the entire construction sequence. However, as indicated by Downing and Jeanne, the can be other secondary cues to accompany the stigmergic stimulus[159]. Allwright et al.'s robotic team has shown the viability of switching between or combining multiple cues[169]. Therefore, abundant research exists in mixing various forms of cues (e.g., from sensors, human interventions, other robots, and more) into the stigmergic construction to create hybrid communication and control systems.

Another research direction is to explore boundary conditions and limits in multi-robot stigmergic construction. For example, a recent paper in 2019 by Hunt et al. has identified "limitations to stigmergy in a spatially constrained, high-density environment,..., using repellent binary pheromone."[155] However, Hunt et al.'s research falls into the marker-based stigmergy category. Similar experiments can be done to test limits for sematectonic stigmergy.

The construction process is not continuous because agents need to fetch building components at some point in both natural and artificial settings. This discontinuity adds a layer of management and optimization into the construction problem. Research teams such as Sugawara et al. and Allwright et al. have developed the hardware (i.e., stigmergic blocks) for robots to differentiate between unused and used blocks[168,169]. However, managing the back-and-forth switch between block-foraging and block-building tasks is a whole other issue to optimize. Karsai and Wenzel have thought about related topics in 1998, indicating that social insects switch between different building patterns based on their colony size to optimize the switch between building, pulp foraging, and water foraging[171]. While there are modern attempts to this issue (e.g., the approach by Liyanage and Fernando[172]), more efforts are needed to push the robotic systems to achieve similar levels of efficiency as social insects.

Tolerance has been a constant issue when it comes to real-world constructions. Ardiny et al.'s paper has indicated that the stigmergic method can help build more coherent artifacts at a local level[170]. However, even though the tolerance issue is reduced in stigmergic construction, it still exists. Allwright et al. have inserted magnets at all corners of their building blocks to help alignments in the real world[169]. However, such a method may not be cost-effective or scalable. In the future, researchers may explore more economical ways (mechanical and computational) to tackle construction tolerances.

Most stigmergic constructions in nature are built by homogeneous teams (e.g., by the same type of wasp or termite). It would be interesting also to explore, simulate, and investigate stigmergy with heterogeneous teams. Although, in theory, human intervention would be easy to integrate into the construction process without disturbing the stigmergic agents[157], there still exists plenty of design space to discuss how humans can better engage in such building processes.

Yet another research direction exists in exploring complex 3D configurations. So far, most of the existing stigmergic robotic systems build in 2D or simple cubic 3D space. In nature, the social insects build more organic and expressive structures using simple stigmergic methods. Researchers can explore more sophisticated 3D techniques other than stacking cubic elements (e.g., using soft robotics and flexible construction material[173]).

Last but not least, researchers can brain storm more application cases for construction robotics with sematectonic stigmergy. From the perspective of typology, in addition to stacking, there can also be bridging[174], cantilevering, suspending, and more. In terms of size, one can also imagine stigmergic construction happening on a human-shelter scale or micro-scale to fulfill various practical functions.

4

A Concise Review of Ionic Polymer-Metal Composite (IPMC) for Soft Robotics Actuation

This section of the dissertation has been adapted from the following course paper:

Han IX. A Concise Review of Ionic Polymer-Metal Composite (IPMC) for Soft Robotics Actuation. MSE501 Final Paper, Princeton University, Instructor: Prof. Marcella Lusardi. December, 2023.

4.1 Introduction

The fields of soft robotics and artificial muscles are rapidly evolving, presenting a departure from traditional rigid-body robots. Soft actuation allows for complex and gentle movements, broadening the range of objects handled and environments navigated by robots. Ionic Polymer-Metal Composites (IPMCs), a sandwich-like material with an ionic polymer core and electrodes on either side, can induce bending motion under an electric field. Recognized for its lightweight nature, high flexibility, rapid response, and significant deformation capabilities, IPMCs have gained popularity in bio-robotics applications. This paper provides a compact review of IPMC material properties, encompassing actuation mechanisms, design parameters, and limitations. Additionally, it explores the prevalent use of IPMCs in soft robotic applications, aiming to offer insights into their current state in artificial muscles.

4.2 Background and Motivation

4.2.1 Motivation Behind the Design of Soft Robots

Soft robots represent a significant leap toward emulating mechanisms that closely mimic the natural flexibility and adaptability found in living organisms, diverging notably from traditional rigid-body robots[175]. Soft robots offer enhanced safety in human-robot interactions (HRI) and excel in handling irregular objects and navigating challenging environments. Nevertheless, the development of soft robotics confronts numerous hurdles, including complex control systems, the necessity for innovative actuation methods, constraints in payload capacity, and the need for stretchable portable power sources[176]. Stella and Hughes[177] have summarized the key motivations behind the design of soft robots into three categories: 1) application solving; 2) advancing theoretical principles; and 3) improving understanding of biological systems.

Major application areas of soft robotics include nondisruptive exploration and monitoring of marine life[178], bio-medical intruments[179], object handling[180], and safe and innovative means of HRI[181].

4.2.2 Artificial Muscle

The development of soft robotics heavily relies on the advancement of artificial muscles. Artificial muscles can be defined as "a class of soft smart materials that respond to external stimuli and are capable of reversible deformation such as expansion, contraction, or rotation"[182]. In the context of soft robotics, the term "artificial muscles" can be used interchangeably with "actuators". Soft robotics and artificial muscles embodied the concept of "the material as the controller"[183], making the field of material science highly relevant and critical.

Types of Artificial Muscle

Artificial muscles can be categorized based on means of stimulus response, for example by electricity, magnetism, thermal energy (e.g., Shape Memory Alloy - SMA), pneumatic and hydraulic pressure, chemical stimulus (e.g., pH changes), light, and more.

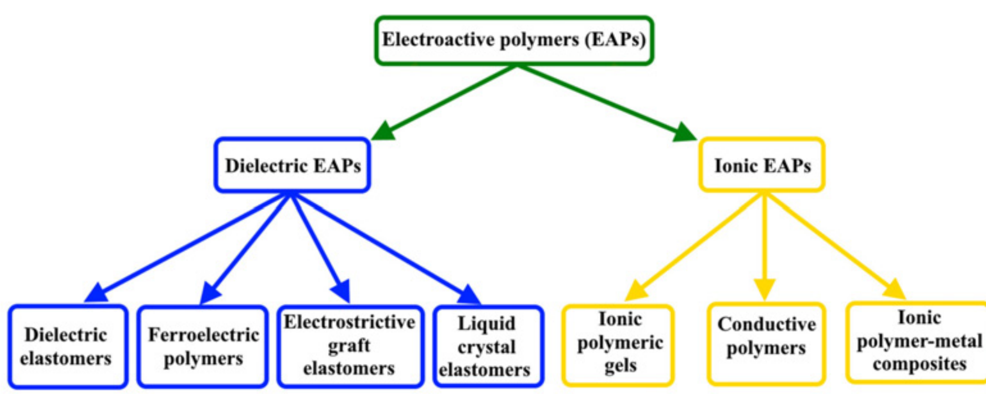


Figure 4.1: Electroactive polymers groups[184], redistributed under CC BY 4.0[185].

An essential material in the realm of electro-stimulated artificial muscles is the electroactive polymer (EAP), a polymer that undergoes changes in shape and/or size when subjected to applied voltage or electric field. This paper specifically delves into one of the subcategories within EAPs (see Fig. 4.1), which is the Ionic Polymer-Metal Composite (IPMC).

4.3 IPMC Material Overview

4.3.1 Structure

IPMC is characterized by a tri-layered structure. The composition comprises a thin electrolyte membrane (Fig. 4.2, Ionic polymer) flanked by noble metal electrode layers (Fig. 4.2, Electrode) on either side, resulting in a configuration resembling a sandwich[186]. This distinctive layering is integral to the functional properties exhibited by IPMCs.

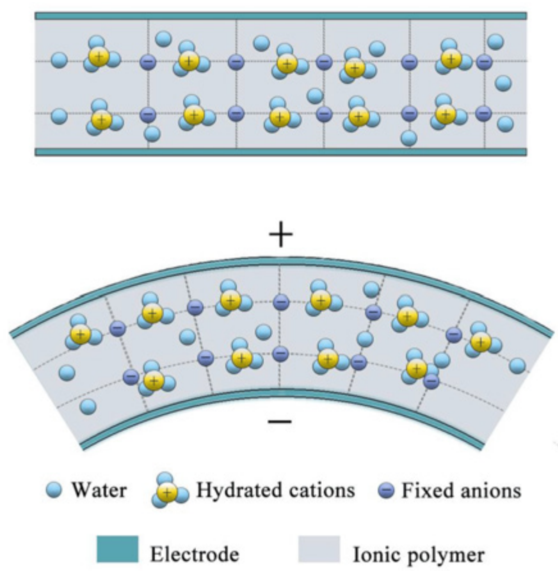


Figure 4.2: Ionic polymer-metal composite (IPMC) tri-layered structure[187], redistributed under CC BY 4.0[185].

The choice of materials for the base membrane of IPMCs is a critical aspect of their design. Notably, due to their analogous chemical structures and properties, materials such as Nafion, Flemion, and Aciplex are among the most widely utilized in this context[186]. These polymers share similar backbone and side chain, as well as the same sulfonate endbone group $-SO_3H$ (Fig. 4.3). These polymers serve as the foundation for the membrane, contributing to the overall performance and responsiveness of the IPMC.

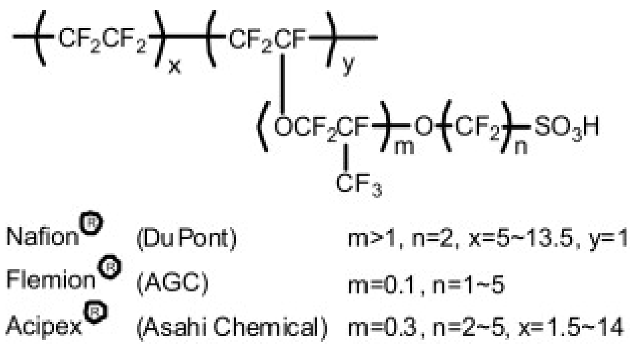


Figure 4.3: Common base membrane materials of IPMC: Nafion, Flemion, and Aciplex[188], redistributed under CC BY-NC-ND 3.0[189]

The selection of materials for the electrode layers also needs to be considered. Optimal choices, such as gold, platinum, and palladium, are known for yielding high-quality outcomes. However, in instances where cost considerations take precedence, more economical alternatives like copper may be employed[190], albeit with a corresponding compromise in performance levels.

4.3.2 Actuation

Upon the application of an electric field perpendicular to IPMC layers, the mobile cations within the polyelectrolyte migrate towards the oppositely charged electrode. This movement induces swelling at the negative side and shrinkage at the positive side, resulting in the overall bending of the IPMC actuator[191]. Together, there are five mechanisms to elucidate the bending deformation observed in IPMC under an electric field[192,193]:

- Swelling caused by the migration of hydrated cations;
- Imbalance in electrostatic forces resulting from cation migration;
- Dipole-dipole interactions induced by polarization of ion clusters;
- Electrochemical reactions occurring at surface electrodes;
- Electrostatic interactions between electrode particles and ionic polymers.

This bending motion of IPMCs under the presence of an electric field is vital for their utilization as actuators in soft robotic applications.

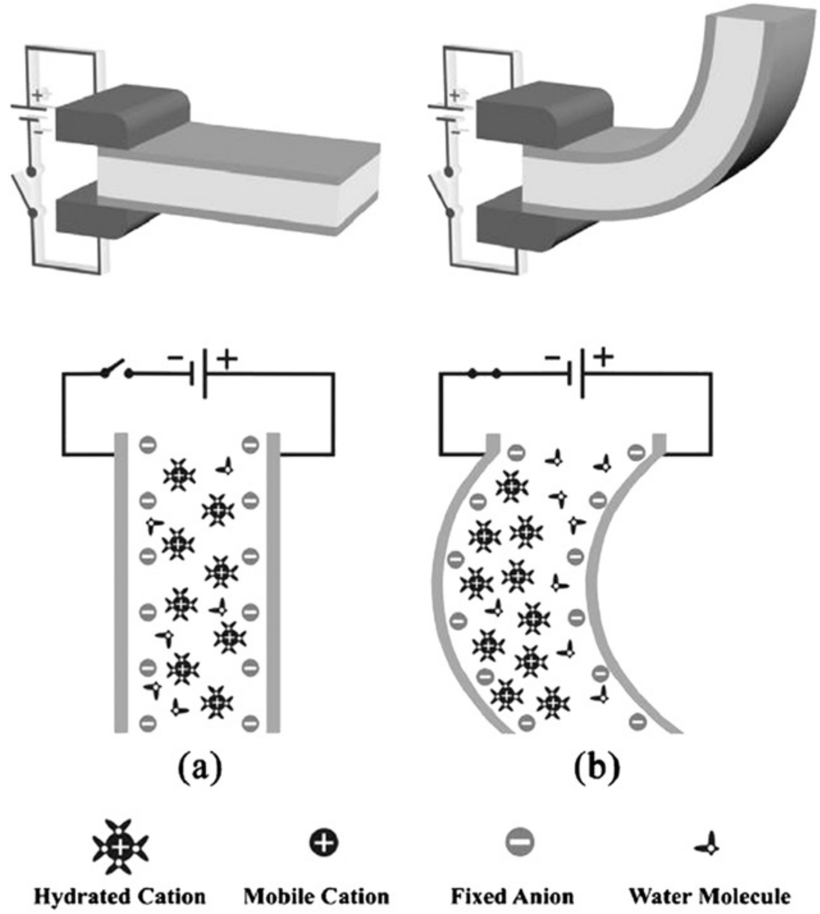


Figure 4.4: Working principle of an IPMC actuator. Left: before applying an electrical field. Right: after applying an electrical field[194,195], ©2014 reprinted with permission from Elsevier.

4.4 Structure-Property Relationship

Several key aspects would influence the performance IPMCs, including 1) the interface between the electrode and ionic polymer, 2) the type and thickness of the electrode, and 3) the type of liquid solvent. Correspondingly, the optimization of IPMCs can be achieved through improved material preparation processes, thoughtful material choice, and elaborated control methods.

4.4.1 Interfacial Surface Area

The effectiveness of IPMC actuation relies significantly on achieving a substantial interfacial surface area between the metal and polymer[186]. A robust interfacial contact not only enhances bonding strength but also contributes to superior overall performance. This aspect holds particular significance for IPMC, given its reliance on interfacial surface area to foster charge accumulation, a crucial element for the bending actuation process [196].

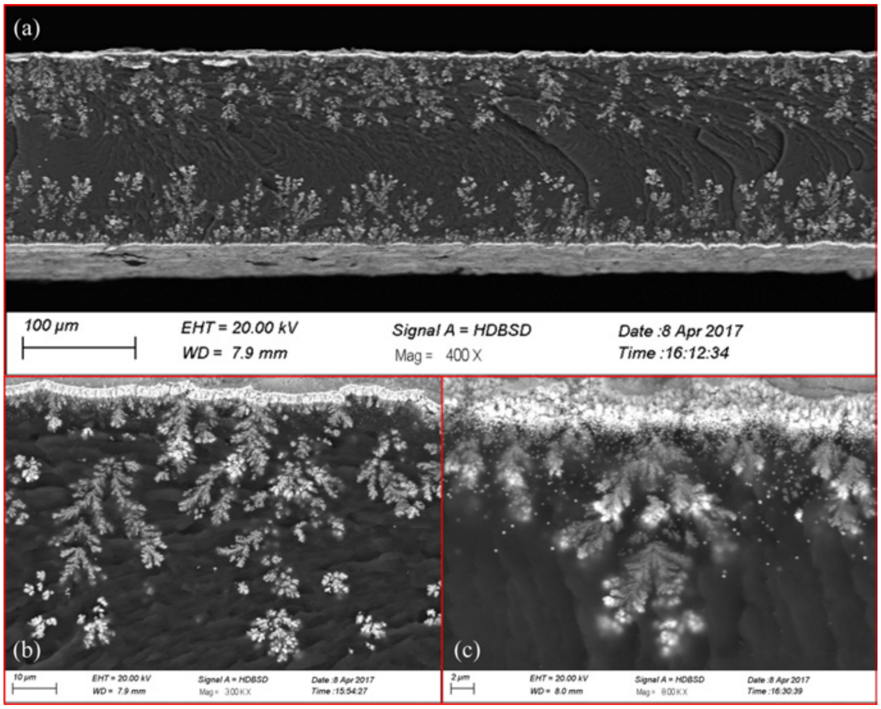


Figure 4.5: "(a) SEM image of Pd DIEs; the bottom images are the enlarged SEM images with magnification of (b) 3000× and (c) 8000×." by Wang et al. [196], ©2017 American Chemical Society, reprinted with permission.

Existing methods for augmenting interfacial surface area encompass impregnation-reduction (IR) [197], reductant permeation (RP), solution casting, and direct assembly process [198,196]. Latest researches have delved into the generation of dendritic interfacial electrodes (DIEs) characterized by a branching fractal shape (Fig. 4.5). The unique microstructure of DIEs not only substantially amplifies surface area but also minimizes metal consumption, thereby improving the performance of IPMCs [196]. Wang et al. [196] achieved the successful fabrication of dendritic metal electrodes, including palladium, platinum, silver, and copper embedded within an ionomer for IPMC. This was accomplished through the integration of an impregnation electroplating (IEP) stage with an impregnation-reduction (IR) step, all conducted under straightforward conditions [196].

4.4.2 Output Force Enhancement

The assessment of artificial muscle performance involves considering the output force as a crucial parameter, which can be evaluated through the generative blocking force. Yet, the thin electrolyte membrane within IPMCs, serving as the central layer, imposes limitations on the magnitude of force achievable during bending. For instance, a Nafion 117 membrane with a thickness of approximately 180 μm corresponds to an IPMC with an output force of less than 10 μN[186].

The low-voltage, low-output-force characteristic of IPMCs makes them well-suited for specific small-scale applications, such as biomedical devices, but it also limits their application for larger-scale mechanical systems and tasks that require higher force outputs. Addressing this challenge, researchers have explored three primary approaches, as outlined by Hao et al.[186]: 1) Adjusting the thickness of the electrode layers, 2) doping additives and tuning thickness for the electrolyte membrane layer, and 3) investigating alternative deformation mechanisms.

Electrodes Thickness

The correlation between electrode thickness and the force generated by the IPMC actuator is non-linear, as demonstrated by Yılmaz et al. in their experiments with a gold electrode and a Nafion-based membrane[199]. Rather than a straightforward "thicker is better" relationship, their findings reveal an optimal thickness at around 45 nm that yields the most favorable electroactive characteristics for IPMC actuators.

Adjusting the Electrolyte Membrane

Similar to the electrode layer, the thickness of the electrolyte membranes can also be tuned to achieve more desired performance. He et al.[200] investigated the impact of varying Nafion membrane thicknesses on the blocking force of IPMC. Their observations revealed that as the thickness increases, both the elastic modulus of the Nafion membrane and the blocking force of IPMC increase; however, concurrently, the current and displacement decrease.

Besides adjusting the thickness of the polymer membrane, researchers have also achieved better output force of IPMC through doping additives to the electrolyte membrane [186]. For example, Ru et al. [201] enhanced the performance of an IPMC actuator by introducing water-soluble sulfonated multiwalled carbon nanotubes (sMWCNT) into the Nafion matrix. This innovation resulted in an IPMC actuator with increased bending deformation and output force, particularly when subjected to low driving voltages.

4.4.3 Back Relaxation

Upon the application of a DC voltage to an IPMC utilizing water as a solvent, a swift escalation in deformation is observed, followed by a gradual return, extending even beyond the initial position. This phenomenon, termed the relaxation effect of IPMC, introduces a pronounced instability that proves disadvantageous for the application of IPMC actuators in soft robotics. To address back relaxation, three types of solutions have been developed:

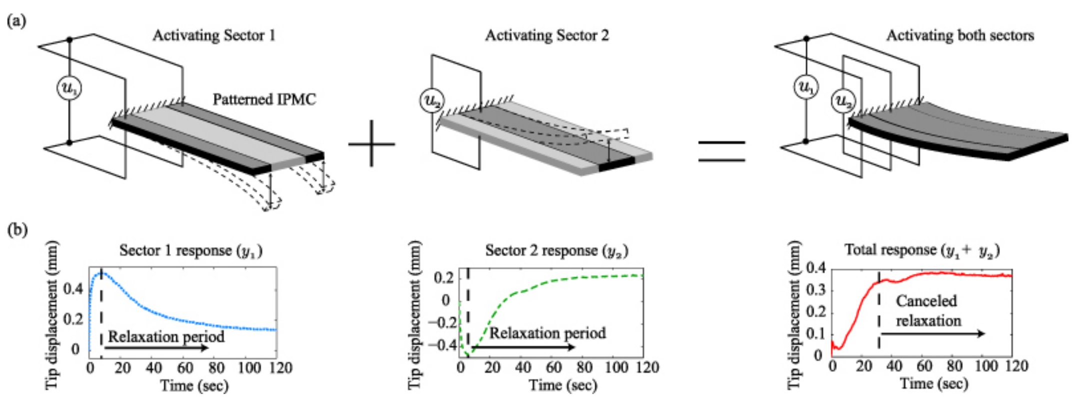


Figure 4.6: Concept for controlling patterned electrodes: (a) independently controlling each sector to produce a net canceling effect and (b) corresponding experimental step responses. [202], ©2012 IOP Publishing Ltd, permission conveyed through Copyright Clearance Center, Inc.

- Encapsulating IPMC at a fixed water content [203]. By preventing dehydration, which could adversely impact the morphological evolution of the surface electrode [204], this approach aims to maximize the deformation of IPMC while minimizing relaxation [203].

- Employing ionic liquid instead of water as a solvent [205]. Ionic liquids, fluid at or above room temperature, contain anions and cations of varying sizes [206]. Their inherent ionic conductivity facilitates movement within the Nafion membrane, while the stability of these liquids addresses issues like electrolysis and evaporation encountered with water as a solvent [182].

- Combining patterned electrodes with specialized control methods, as explained in Figure 4.6 [202].

4.5 Applications of IPMCs

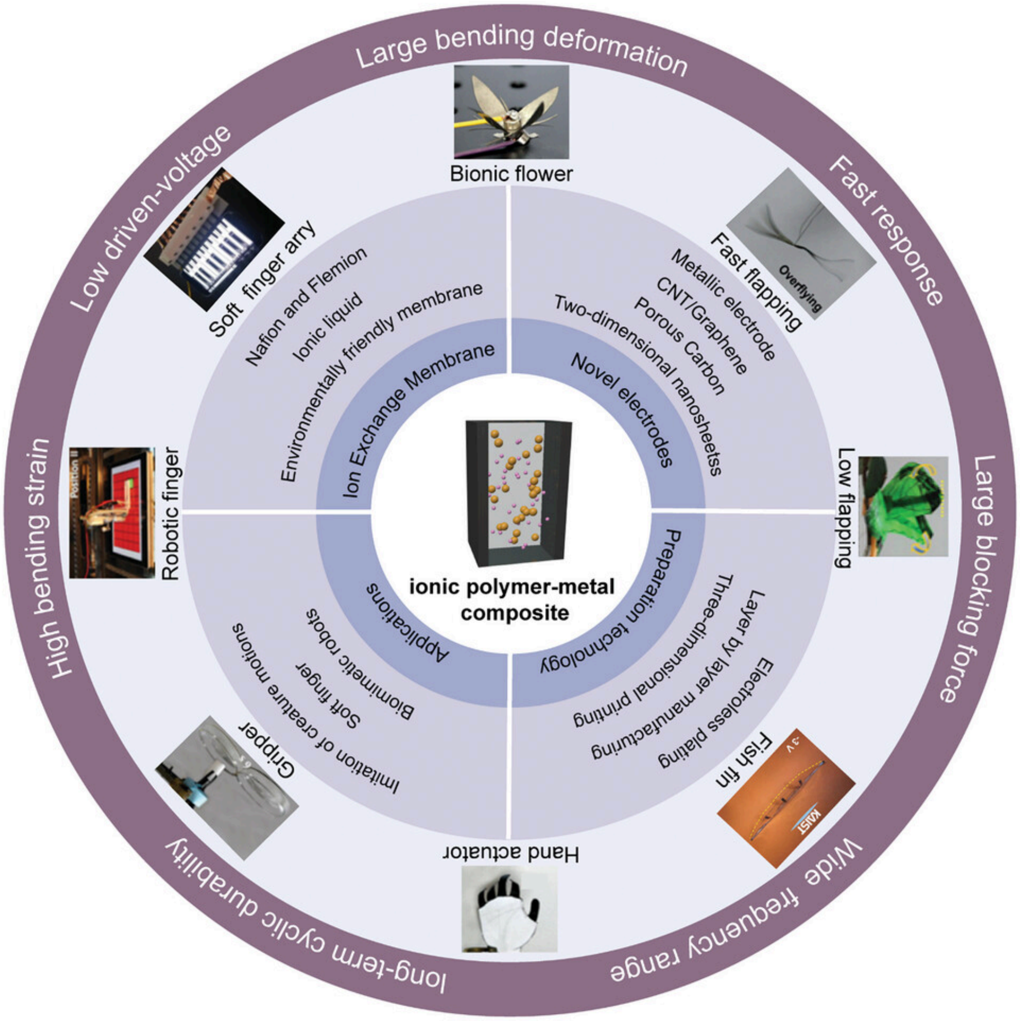


Figure 4.7: Schematic illustration of the compositions in IPMCs and their applications [182], redistributed under CC BY 4.0 [185].

Overall, IPMC is a great candidate for artificial muscle due to many of its desirable characteristics (Fig. 4.7), including: high energy density, large deformation, fast response, lightweight, high flexibility, as well as precise and fast low-voltage electrical control (0.5-10V) [182]. Zhang et al. [182] illustrated a wide variety of IPMCs applications in Figure 4.7, ranging from bio-robotics to wearables.

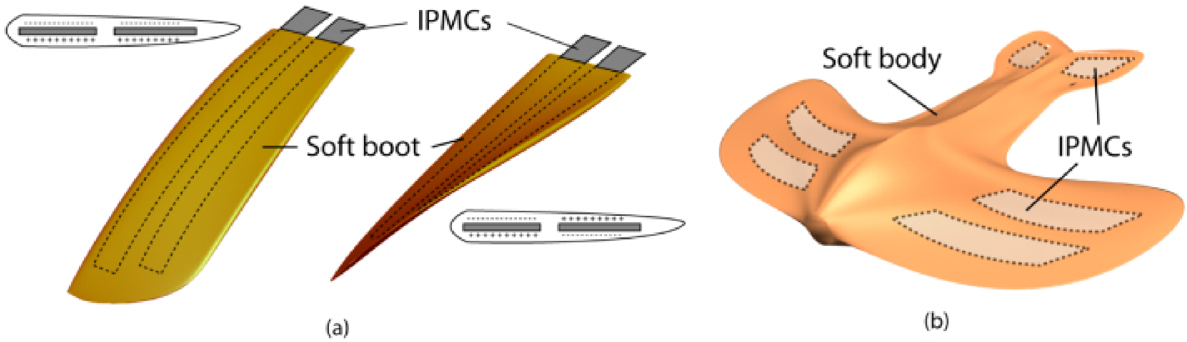


Figure 4.8: (a) IPMCs embedded into soft boot structure illustrating bending and twisting motion by selectively activating electrodes and (b) example soft bio-inspired robotic platform with embedded IPMC actuators for controlled deformation of control surfaces.[207], ©2013 IOP Publishing Ltd, permission conveyed through Copyright Clearance Center, Inc.

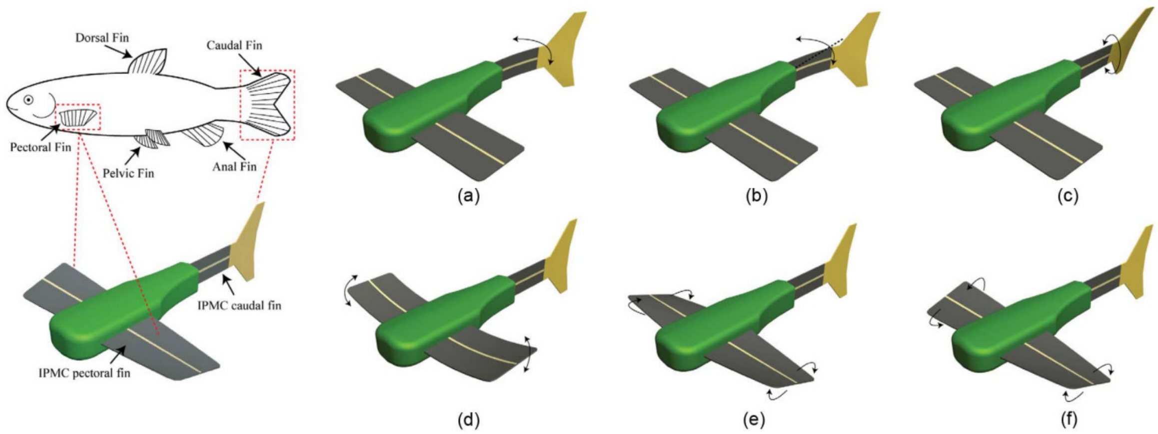


Figure 4.9: A typical fish and illustration of the robotic platform driven by IPMC fins and possible maneuvering capabilities. (a) Caudal fin bending "thrust generation"; (b) caudal fin bending (nonneutral axis) "yaw"; (c) caudal fin twisting "roll/banking"; (d) pectoral fin bending "translation/roll/banking"; (e) pectoral fin twisting "pitch-dive/surface"; and (f) pectoral fin twisting "roll."[208], ©2014 IEEE.

IPMCs excel in performing bending oscillations when subjected to a low-voltage alternating signal, with the oscillation being directly proportional to the frequency and amplitude of the input signal[209]. Consequently, IPMCs present a promising choice for actuating underwater robots, where they can serve as fins[209,207,208]. IPMCs can be used either by embedding them in other soft sleeves, such as casting with rubber RTV 500 Resin in Figure 4.8[207], or by applying them monolithically, as shown in Figure 4.9[208].

4.6 Limitation

While showing many desirable properties, IPMCs also face several limitations. Firstly, as a relatively new material, researchers are still exploring the optimized methods to prepare such materials in consistent quality, leading to a lack of standardized preparation processes [186]. Secondly, as elaborated in Section 4.3, the phenomenon of back relaxation presents a significant impediment to the stable and accurate performance of IPMCs. Thirdly, the susceptibility to solvent evaporation not only affects the immediate performance of IPMCs but also diminishes their lifespan. Last but not least, due to their thin-membrane central layer, IPMCs exhibit a low blocking force, rendering them suitable for low-voltage, small-scale applications but limiting their effectiveness in tasks requiring a more substantial payload. These limitations underscore the need for continued research and innovation to overcome these challenges and unlock the full potential of IPMCs in diverse applications.

5

From Concept to Construction: A Transferable Design and Robotic Fabrication Method for a Building-Scale Vault

This chapter includes adaptations from the following paper:

Han IX, Bruun EPG, Marsh S, Tavano M, Adriaenssens S, and Parascho S. From Concept to Construction-A Transferable Design and Robotic Fabrication Method for a Building-Scale Vault. In *Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture: Distributed Proximities, ACADIA*. 2020.

Chapter Overview

The LightVault project demonstrates a novel robotic construction method for masonry vaults, developed in a joint effort between Princeton University and the global architecture and engineering firm Skidmore, Owings & Merrill (SOM). Using two cooperating robotic arms, a full-scale vault (plan: 3.6 x 6.5m, height: 2.2m) made up of 338 glass bricks was built live at the "Anatomy of Structure: The Future of Art + Architecture" exhibition. A major component of the project was developing a fabrication method that could be easily adapted to different robotic setups since the research and prototyping, and final exhibition occurred at locations on different continents. This called for approaches that balanced the generic and the specific, allowing for quick and flexible construction staging and execution despite the variability associated with building in a new setup (i.e., varying robots, material, and scale).

The paper is structured as follows. First, we introduce the notion of transferability in robotic construction and then elaborate on this concept through the four major challenges in the LightVault project development: 1) prototype scalability, 2) end-effector design, 3) path planning and sequencing, and 4) fabrication tolerances. To develop and test solutions for these challenges, we iterated through several prototypes at multiple scales, with different materials for the standardized bricks, and at three distinct locations: Embodied Computation Lab, Princeton, US; Global Robots Ltd., Bedford, UK; and Ambika P3 gallery, London, UK. While this paper is specifically tailored to the construction of masonry structures, our long-term goal is to enable more robotic fabrication projects that consider the topic of transferability as a means to develop more robust and broadly applicable techniques.

5.1 Introduction

The last ten years have seen significant growth in the use of industrial robots[210]. In the architecture and construction fields specifically, robotics is most commonly applied to the prefabrication of building elements. However, the disadvantage is that prefabrication cannot occur for structural and material expressions that can only be assembled in-situ (e.g., masonry vaults[211], cast-in-place concrete structures[212,213], and sequentially designed structures[214,26]). We believe that more emphasis on developing generalized and transferable on-site methods is necessary to achieve the goal of widening the applicability of robotic fabrication in the construction industry.

On-site robotic technology was first introduced to the construction industry with a patent for an automated bricklaying robot in the early 20th century[215] and a working prototype of such a machine in the 1960s[216]. However, the building sector has generally benefited much less from robotic technology than other fields like the automotive[217]. Some reasons for this latency in adoption are as follows:

- Technical Challenges: further advancements are necessary in areas such as sensing, path planning, spatial navigation, and communication to ensure a smooth workflow on-site[24].
- Managerial Considerations: efficient and robust robot-human coordination is required to form a safe building environment while maintaining an economic distribution of tasks and decision-making structure between human and robot teams[29,30,218,219].
- Design Philosophy: robotic fabrication processes are often designed for niche applications, so it can be challenging to adapt techniques for broader applications.

This paper addresses the last point by starting a conversation on how a robotic fabrication process can be designed from the outset to consider broader applicability over specificity. The concept of transferability for a robotic fabrication process is a measure of how readily it can be adapted to alternative sites and setups with little adjustments. In general, a transferability-oriented design paradigm is desirable to facilitate the broader adoption of new methods in the construction industry as design possibilities are calibrated to the process rather than a specific setup or site. This emphasis on generality will help bring robotic arms from a prefabrication factory environment to construction sites and enable more freedom in architectural articulations.

Figure 5.1: The full-scale glass LightVault displayed at the "Anatomy of Structure: The Future of Art & Architecture" exhibition at Ambika P3 gallery in London, UK

The proposed method is discussed in the context of LightVault (fig. 5.1) – a building-scale robotic vault where industrial robotic arms alternate between placing bricks and supporting the structure to eliminate the need for formor falsework[220]. This structure was developed with the specific intention of being built robotically with different construction setups because the nature of the project was such that the development lab, testing site, and exhibition space were all in different locations and partially unknown at the onset of the project. We identified the four following considerations as essential to developing a fabrication method that would achieve this goal: 1) prototype scalability, 2) end-effector design, 3) path planning and sequencing, and 4) fabrication tolerances. The following sections present a general discussion of transferability in the context of these features with specific examples of their implementation in the LightVault project. Based on this specific project experience, the scope of the proposed methods is constrained to large-scale robotic assembly processes for vaulted structures.

5.2 Background

Robotic construction of masonry structures was first performed at the architectural scale in the Gantenbein Winery project, where robots were used to construct the undulating brick walls of the structure[221,222]. The LightVault project builds on this methodology by using standardized construction units, but breaks from the layered vertical construction approach to build a spanning masonry structure out of glass bricks.

Discrete element assembly projects that feature three-dimensional geometric complexity often achieve it through a high level of customization on the local scale (i.e., customization of individual building units is used to achieve complexity globally). For example, in the field of glass construction, Gustave Falconnier patented an interlocking construction system using blown-glass bricks that could be used as building blocks[223]. Other examples of customization on the local scale are seen in spanning masonry structures such as the Armadillo Vault[224,225], or in drone-assisted construction of structures[226] as a way to ensure interlocking behavior between units.

Over the past decades, advancements in robotic technology and architectural expression have constantly influenced each other. While novel robotic tools have stimulated new masonry expressions[221,227] and functional performances[228] in architecture, masonry construction in return also informed the development of corresponding robotic fabrication processes and machinery[12]. The introduction of integrative design methodologies suggested the co-development of the design formulation, material experimentation, and robotic fabrication strategy to accelerate the iterative progression between tool and design[229]. However, tools and techniques developed in such a manner may face difficulties due to over-specialization when applied in contexts outside their original intent. Therefore, a balance between generality and integration is desired in developing a transferable robotic fabrication method.

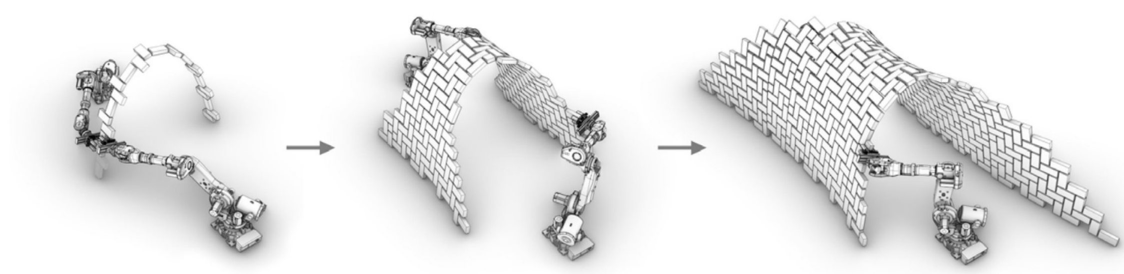
5.3 Methods and Results

The following chapter will discuss four considerations that are essential in developing a highly transferrable fabrication method. A general discussion of transferability in the context of these features is followed by specific examples of their implementation when developing the LightVault project.

5.3.1 Prototype Scalability

Developing new construction methods using robots requires the design team to explore the full range of limitations and abilities of a selected robotic setup for a particular site condition. During the development stages of a robotic fabrication project, it is necessary to verify and solve technical challenges before attempting large-scale construction. As such, it is advisable to aim for a scalable design that does not compromise the overall intent – it allows for both a robust prototyping strategy and final adjustment on site. In LightVault, the structure itself was materially efficient since the shell was form-found to exhibit membrane behavior once fully constructed. The membrane stresses from self-weight in the final state were far below the glass bricks' strength; thus, it was the stability during construction that governed the design. This meant that explorations of stability as a function of sequencing, tessellation, and connection methods could be performed at the smaller scale and then applied to largescale prototypes.

Figure 5.2: Concept diagram showing the distinct construction phases: middle arch (a), strengthened middle spine (b), and full vault (c)



The development of the LightVault project began with three small prototypes built with two UR-5 robots; these prototypes were used to develop the construction sequence logic (i.e., brick tessellation and placement order) and the overall feasible shape based on the robot's position and overlapping reach volume. The next set of prototypes, constructed using two ABB-4600 robots, assessed the overall structural performance at the intended building scale. Figure 5.2 shows schematically how the final vault was planned around a phased construction approach – alternating segments of the vault were built while maintaining both global and local stability at each phase without the need for temporary scaffolding (for further information on developing a scaffold-free cooperative assembly sequence see

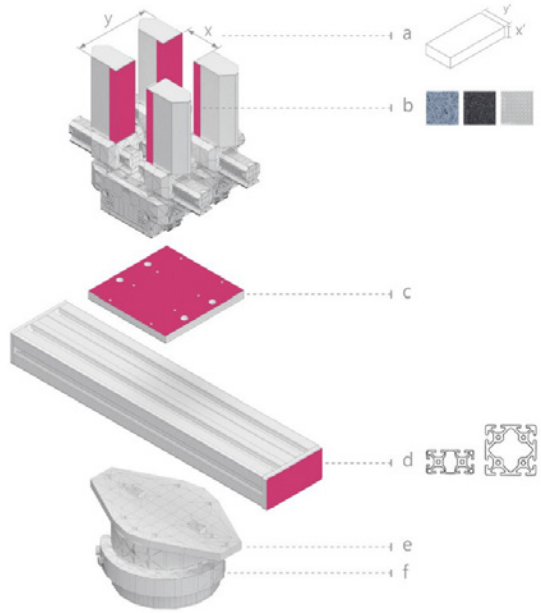
Parascho et al., 2020[20]). The project was then rebuilt with a new setup using two ABB-6640 robots at the final exhibit location. A test construction was first performed at Global Robots Ltd., Bedford, UK, where the grippers and pneumatic systems assembled and tested within ten days. The final LightVault structure was then assembled live at the "Anatomy of Structure: The Future of Art + Architecture" exhibition in London, UK. Unfortunately, the construction of this final vault was cut short due to the COVID-19 pandemic.

In building the LightVault at Ambika P3 gallery in London, we encountered few space and access limitations for on-site masonry construction. Whilst the floor construction was solid reinforced concrete, the gallery operators stipulated that there should be no structural anchoring to the floor, which meant we had to design the robot bases and the arch floor framing with this in mind. The need to prevent movement of the robot bases was of crucial importance. Each robot was bolted down to a relatively heavy (1.8t) reinforced concrete base that was strategically arranged to align flush with the arch plinth. The base design was optimized to resist over-turning, with appropriate factors of safety against the worst-case loading scenarios throughout all building stages. Using conventional timber sections and plywood flooring, we created a raised platform to ensure that the floor was leveled and that the robot arms with attached grippers could reach all areas of the proposed arch geometry. All power cables and air lines were concealed below the floor frame, eliminating potential trip hazards for the operators and ensuring a clean and clutter-free site. Each of these components was developed to be simple to piece together and dismantle, and with sufficient tolerance for a fast in-field and on-the-fly setup.

5.3.2 End-Effector Design

In contrast to a custom-built robot, a robotic arm is a generic tool whose application is mainly defined by the attached end-effector. As such, the end-effector design is crucial in determining what types of material manipulations are possible, which in turn shapes and defines the construction procedure. While more complex material processing such as welding and 3D printing might suggest bespoke end-effectors, over-customization should be avoided as it can result in low overall transferability of the project. Designing an adjustable end-effector that is independent of the robotic system and can accommodate different materials and dimensions has proven advantageous for applications in different environments.

Figure 5.3: Exploded axonometric projection of customized gripper showing: adjustable fingers (a), replaceable finger surface (b), customized plate between finger and extrusion material (c), optional aluminum extrusion to extend reach (d), and quick changer and corresponding plates (e & f)

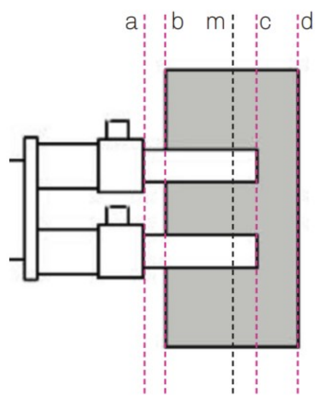


The grippers designed for LightVault consisted of a combination of standard products (fig. 5.3 a, d, f.) and customized interfaces (fig. 5.3 b, c, e.). Standardized SCHUNK PGN, fingers, and optional quick changers simplified the overall process of assembling new grippers at different sites. Their design also made them transferable across projects as they were easily adjustable for use with construction units of different dimensions and materials. Specifically for LightVault, the grippers were designed based on the following fabrication-related requirements:

- The finger spacing (fig. 5.3 x) shall be constrained by the precision tolerance and gripping power associated with the proposed fabrication method – too narrow a gap between finger spacing and brick thickness (fig. 5.3 x and x') can cause collisions, while too wide a distance can result in insufficient gripping power.

- The fingers (fig. 5.4 a-c) shall be longer than the half brick width (fig. 5.4 b-m) plus tolerance gap

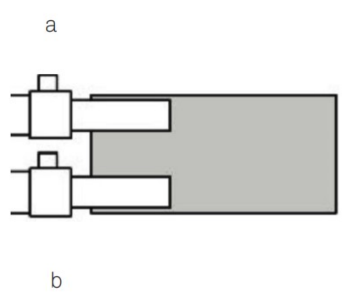
Figure 5.4: End-Effector dimensional constraints: finger base (a), brick's inner edge (b), brick's middle line (m), finger tip (c), and brick's outer edge (d)



(fig. 5.4 a-b) to prevent eccentric loads caused by off-centered gripping. However, long fingers that exceed the brick's outer edge (fig. 5.4 d) should be avoided due to collision risk between the finger tips (fig. 5.4 c) and existing vault structure.

- The distance between the two pairs of fingers (fig. 5.3 y) shall be as wide as possible for stable gripping without exceeding the brick's width (fig. 5.3 y', fig. 5.4 b-d) to allow the brick to be picked up in different orientations.

Figure 5.5: End-Effector with asymmetric pneumatic component distribution: the side with pneumatic extrusions (a) and the unobstructed side (b)



- The pneumatic components shall be oriented in such a way that one side of the gripper is left unobstructed (fig. 5.5 b), which is necessary to avoid collisions in precise placement operations.
- An extension element (e.g., an aluminum profile, fig. 5.3 d) can be used to prevent collisions in cases where the industrial robot's wrist joint is at high risk of hitting neighboring bricks during

construction. However, too long of an extension is not advisable as it results in higher chances of collision during movements and more considerable instability caused by robotic arm deformation.

- The gripper finger surface (fig. 5.3 b) shall be selected based on the type of brick material used for desired performance (e.g., sandpaper with timber blocks or rubber-based tape with glass bricks).

The design of the proposed end-effector is flexible due to its modularized components. We were thus able to use the same end-effector for wooden, concrete, and glass (both textured and glossy) bricks with minimal adjustment.

5.3.3 Path Planning and Sequencing

Defining the assembly and path planning process parametrically, rather than prescriptively, improves the adaptability of the robotic construction process for complex geometries. But for a construction method to be transferable and robust, it should also take into account that robots are wellsuited for a process with repetitive tasks. Therefore, the ideal approach is one that calculates movements parametrically where needed (e.g., for intricate 3D geometric areas) and relies on predefined repetitive movements otherwise.

In LightVault, the bricks were added to the vault following an overall diagonal stepping sequence, which was established to maintain global structural stability[220,20]. Since the general construction sequence was based on growing the vault outwards from the central arch, this allowed for more space to maneuver the robots around the structure without collision. Only when approaching the structure for the final brick placement was it necessary to generate a precise movement path parametrically. This process involved assessing the nearest neighbors for a new brick being placed into the structure and then calculating either a diagonal or orthogonal insertion vector to best avoid collisions with the existing structure.

In contrast to the parametric paths determined for the insertion movements, the pickup location and associated motions were discretely categorized based on the brick type (half and full bricks) and gripping orientation (from the shorter or longer edge of brick). The robot went through a fixed transition pose before moving on to the parametric insertion path steps. Making such repetitive movement explicit from a path-planning perspective greatly simplified the computational component of the project. It also gave the user more control over the robot configurations, which helped mitigate the risk of unexpected collision and robotic singularity errors.

In summary, this hybrid path planning approach allocates computational efforts in areas where it's most needed (i.e., around final brick placements) and uses predefined discrete paths in less critical zones (i.e., around pick up station and areas away from the structure). This hybrid approach was computationally efficient and highly predictable from the perspective of human operators, which is particularly important when developing methods that will be transferred to different robots with different kinematic behavior.

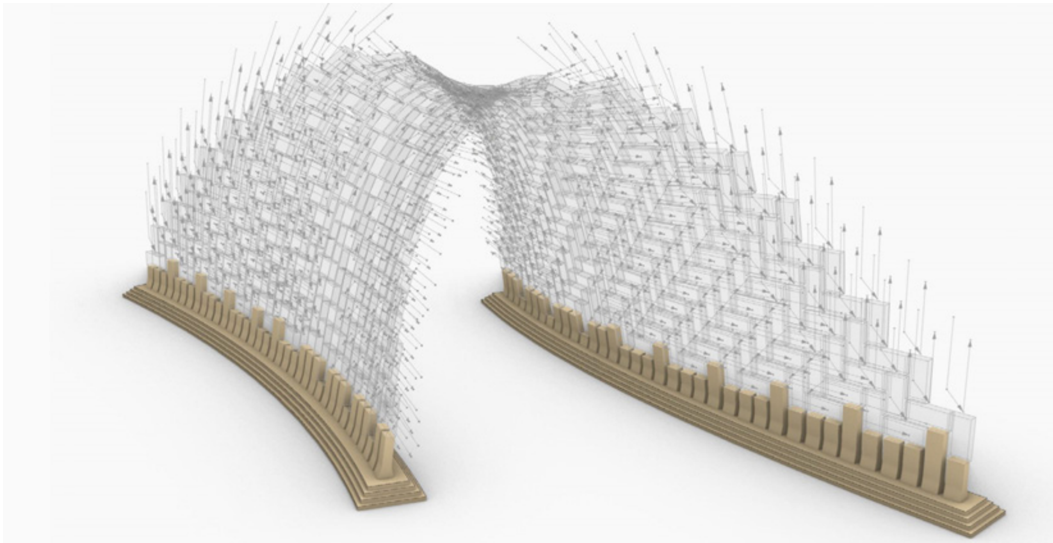
5.3.4 Fabrication Tolerances

Differences between the simulated and physical setups are inevitable in any robotic fabrication project. While certain systematic errors can be corrected when working with a constant setup, this is not always possible when a project is applied to a new setup. Therefore, including a certain level of fabrication tolerance as a design feature is a robust way to improve a project's transferability.

To construct LightVault, we developed an adaptive mechanism for both the brick-to-brick connections and the vault foundation base. We used a flexible epoxy putty and acrylic shims to account for the different gap sizes and connection angles between the bricks. The epoxy putty was manually mixed and placed by a human, and acrylic shims were additionally used in larger gaps to shorten epoxy curing time and lower material cost. In the final placement step, the robot would move the brick into the correct location, compressing the malleable epoxy layer into the best fitting position, forming a solid connection between bricks.

While the epoxy-shim connection absorbed local-scale imprecision, a series of uniquely designed base shoes offered global-scale tolerance for the entire vault (fig. 5.6). These base shoes connected the bottom row of glass bricks with the ground. The tenon and oversized mortise connection allowed the

Figure 5.6: Parametric path planning for brick placement. Base shoes are shown at the bottom part of the structure.



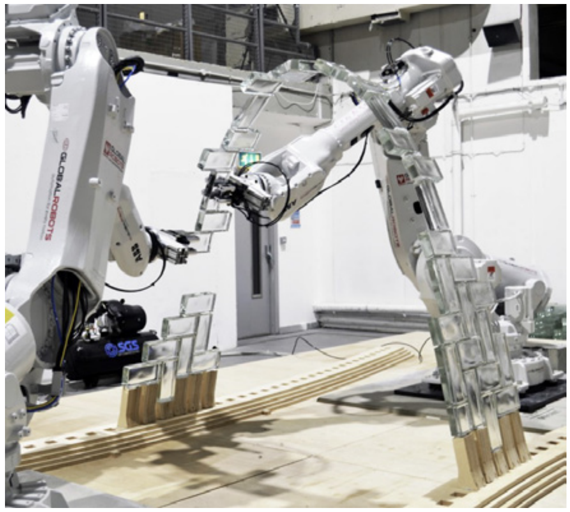
base shoes to slide freely in all directions before being anchored with screws into the floor stacks. The base shoes were prefabricated from high-quality birch plywood with CNC routers.

We performed a few tests before initiating the final construction to assess whether the robotic tolerances were small enough to be absorbed by our construction method (i.e., offsets less than 5mm). Gripping strength, brick slipping behavior, robotic deformation must be checked when a new setup or building unit is adopted. The key parameters for the LightVault were: (1) evaluating the load capacity of the robots and grippers, (2) guaranteeing deformations in the setup were minimized and did not lead to collapse during construction.

With respect to the load that the robot would support, the critical stage was reached in the second-to-last step before completing the middle arch (fig. 5.7). At this point, one robot was required to support a load of 32kg, corresponding to 30% of the partial arch's weight, while the other robot picks up and inserts the last brick to complete the arch.

Several tests were carried out in advance to assess the gripper's ability to hold the required peak load without slip. We conducted these slip tests by hanging a weight on a glass brick that was being held by one robot. We identified the air pressure under which the grippers operate to be a significant factor: a minimum air pressure of 7 bar was needed to withstand the required load with no slippage. Therefore, speed of construction, air-tight connections with no leaks, and air compressor restart/recharge pressure

Figure 5.7: Middle arch construction



became essential aspects in the construction sequence planning.

With respect to deflections in the setup, the base structure stiffness and deformability of the robot arms were of paramount importance for global stability during the temporary construction stages of the central arch. As a robot releases a brick, there was an instantaneous shift of load from one gripper to another as a new equilibrium configuration was reached. During this dynamic load shift, a deformable base or excessive deformations of robot arms under sustained load may cause vibration, which could compromise the structural stability.

5.4 Conclusion

This paper provides a basic framework for developing robotic fabrication projects which are to be executed at different construction sites and using varying setups. The LightVault is an example of such a project, with construction occurring in various locations: several small and large-scale prototypes in Princeton, followed by a test fabrication at the robot factory in Bedford, and the final vault built at a live exhibit in London. This project aims to start a discussion on how to make on-site robotic fabrication more accessible to the construction industry. By invoking a transferability-focused design philosophy and without reverting to using custom, expensive, and time-consuming robotic manipulators, a robotic fabrication project can be explicitly designed to be adaptable to different setups. In developing the LightVault project, we found the following to be important considerations: scalable prototypes, end-effector design, path planning and sequencing, and robotic fabrication tolerances.

Future research will aim to expand the design space of cooperative robotic processes and generally increase the accessibility of robotics in construction. For example, mobile robots could be coupled with stationary industrial robotic arms to expand the application range of cooperative processes to larger fabrication spaces and more complex geometries (i.e., more intricate construction sequences would be possible with an additional robotic agent). To improve the transferability of robotic processes, we aim to address the main challenges that we encountered, namely unpredictable inaccuracies and difficulties in path-planning with a new setup through feedback systems (e.g., force or visual). This information, coupled with results from a structural analysis framework, could be used as the basis for dynamic adjustments to the design and fabrication process to guarantee stability and buildability during construction.

Another approach is to address the used robots themselves by developing new industrial machines based on modularity and standardized components with the potential to customize. Providing easier access to more adjustable machines, rather than more specific ones, could strongly impact the future scale at which robots are employed in architecture and construction. Even though designing and constructing custom robots is an active research field, striving for generality through modular, but still ensuring availability through standardized systems, would simultaneously provide more freedom of construction and easy implementation and operation.

Similar to hardware requirements, we believe that finding the balance between customization and general validity is key for all software components of a fabrication process. Thus, developing new overall design, structural analysis, end-effector design, and robotic control tools that provide a base of knowledge but allow for quick adaptability is crucial for the successful transferability of robotic fabrication methods. As we experienced firsthand through the COVID-19 shutdown, being able to quickly react to unexpected changes even during the construction process is not only helpful, but a necessity to ensure that fabrication processes are successfully advanced.

Acknowledgments

The construction of the LightVault was only feasible through the many people that supported our research through administration, development, and construction. We would like to acknowledge Alessandro Beghini, Samantha Walker, Michael Cascio, David Horos, Mark Sarkisian, Masaaki Miki, Max Cooper, Dmitri Jajich, and Arthur Sauvin (Skidmore, Owings & Merrill), Ian Ting and Lisa Ramsburg (CREATE Lab Princeton), Grey Wartinger and William Tansley (Princeton School of Architecture).

The project was conducted with support from Faidra Oikonomopoulou and Telesilla Bristogianni from Delft University of Technology and sponsorship from Global Robots Ltd., Poesia Glass Studio, and New Pig Corporation. In addition, the project was made possible through the generous support of the Princeton Metropolis Project and Princeton Catalysis Initiative.

Chapter III Improvisation and Collective Creativity

Chapter Overview

The previous chapter established the theoretical foundation of Collective Human-Robot Construction (CHRC). Building on this, Chapter III presents three projects of increasing scale and complexity, exploring Human-Robot Interaction (HRI) methods within an improvisational construction framework.

Unlike a traditional linear workflow, where robotic fabrication begins only after the structural design and robotic sequences are predetermined, the projects in this chapter follow an adaptive, improvisational approach. Instead of relying on a predefined blueprint, the structure evolves on-site as a product of human-robot interaction. Sensing at different frequencies and levels of abstraction are tested with the robots. Humans respond to the robots' physical cues and influence the robots' decisions through the building elements—a stigmergic principle carried over from the previous chapter.

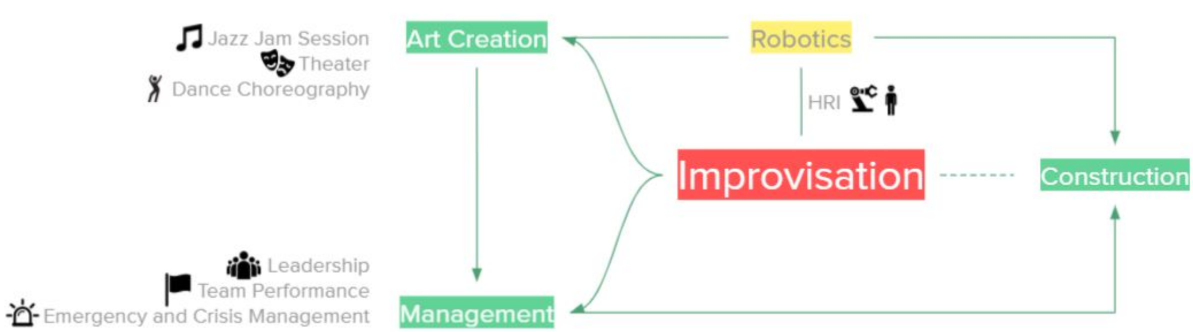


Figure 5.8: Improvisation in art creation, management, and construction

Section 6 reviews literature on improvisation from the perspectives of creativity, team performance, and HRI (Figure 5.8). It then applies these concepts to simple vertical 2D stacking tasks, where humans and robots collaborate in an improvisational workflow. The robot's decision-making is informed by 2D camera data and color sensors. By comparing different team compositions (human-only, robot-only, and human-robot duos), the study reveals that humans generate more unexpected and creative solutions when working with a robotic arm that provides well-designed spatial prompts.

Section 7 expands on this improvisational construction framework and introduces *Improv-Structure*, a proof-of-concept pavilion-scale construction project using bamboo rods instead of predefined geometric modules. In this experiment, two industrial robotic arms and several human participants collaboratively assembled ~500 bamboo rods through a collective decision-making mechanism. The robots provide guidance rods and structural support, while humans determine when to introduce new building units, position filler rods, and apply craftsmanship in tying the rods together. The robots receive their input parameters based on 3D LiDAR scans of the existing structure. The frequency of scanning is every several guiding sticks, initiated by humans.

Section 8 enhances the feedback loop between robots and humans by mounting a 2D camera on the robot's end effector, enabling visual servoing for real-time interaction with the built structure and human operators. The study explores tensegrity structures as fundamental building modules, investigating two key experimental approaches:

- Employing stigmergic mechanisms and visual servoing for robots to adapt to structural changes and human interventions during the fabrication of an X-module tensegrity structure.
- Incorporating several layers of "robot design preferences" to influence the final form of a T3-prism tensegrity structure.

Additionally, the incorporation of audio feedback and direct human-robot interactions, such as material handling, enhances the intuitiveness and user-friendliness of the robotic fabrication process for human designers.

For a detailed discussion on tensegrity structures, refer to Chapter V.

The sections in Chapter III include adaptations from the following papers:

Han IX. Improvisation in Collective Human-Robot Construction. ARC573 Final Paper, Princeton University, Instructors: Prof. Stefana Parascho and Prof. Forrest Meggers. May, 2021.

Han IX and Parascho S. Block Play with a Robotic Arm. In D. Reinhardt, L. Loke, and D. T. Tillman (Eds.), *SHErobots: Tool, Toy, Companion*, 70–73. University of Sydney, 2022. ISBN 978-0-6455400-6-2.

Han IX. Improv-Structure: Exploring Improvisation in Collective Human-Robot Construction. ARC574 Final Paper, Princeton University, Instructor: Prof. Stefana Parascho. December, 2021.

Han IX, Parascho S. Improv-Structure: Exploring Improvisation in Collective Human-Robot Construction. In *International Conference on Trends on Construction in the Post-Digital Era, ISIC 2022*, 2022 Sep 7, *Lecture Notes in Civil Engineering*, vol 306. (pp. 233-243). Cham: Springer International Publishing.

Han IX and Parascho S. Spontaneous Tensegrity: Exploring Improvisational Design and Robotic Fabrication in Tensegrity Structures. *Robotic Fabrication in Architecture, Art and Design ROB|ARCH 2024: Beyond Optimization*. Toronto, Canada. Conference Proceedings. 2024 May 24.

6

Block Play with a Robotic Arm

This section of the dissertation has been adapted from the following course paper and publication:

Han IX. Improvisation in Collective Human-Robot Construction. ARC573 Final Paper, Princeton University, Instructors: Prof. Stefana Parascho and Prof. Forrest Meggers. May, 2021.

Han IX and Parascho S. Block Play with a Robotic Arm. In D. Reinhardt, L. Loke, and D. T. Tillman (Eds.), *SHErobots: Tool, Toy, Companion*, 70–73. University of Sydney, 2022. ISBN 978-0-6455400-6-2.

Overview

The emerging field of Collective Human-Robot Construction (CHRC) opens up more space for human-robot interaction and collaboration in real-time in construction tasks, making the idea of improvisation a critical layer to explore. Although rich literature exists in improvisation under the branch of art performance, management, and robotics, little has been done regarding improvising in construction with a multi-robot-human team. How can human-robot improvisation techniques transfer into the field of architectural design and fabrication? How can robots influence group creativity in real-time improvisational construction? If so, what are some critical research parameters related to human-robot improvisational construction? This project aims to start setting up frameworks where humans and robots can collaboratively construct and improvise. The questions raised above are explored in various collaborative settings where a UR5 robotic arm and a human researcher engaged in stacking toy blocks within a vertical wooden frame. The objective is simple—to stack blocks vertically until they reach the top of a frame. By comparing how different team compositions (e.g., human only, robot only, human-robot duo) and preferences influence the process and the final structure, we observed that humans are inspired to generate more unexpected and creative solutions when paired with a robotic arm that poses good spatial prompts. This project indicates that group creative in construction can be influenced and manipulated by the setup of a heterogeneous human-robot team. Furthermore, the project points towards near-future research focuses on improvisation in CHRC.

6.1 Introduction

Collective Human-Robot Construction (CHRC) is an emerging field that explores new ways of building enabled by multi-human-robot agents operating under flexible team dynamics[230]. In traditional robotic constructions, pre-planned constructions are executed step-by-step, where humans and robots operate under a controller-agent framework. In contrast, CHRC opens up more space for human-robot interaction and collaboration in real-time, making the idea of improvisation a possibility, and further, a critical layer to explore and expand. Improvisation is essential for creativity - it generates new processes and products that were not envisioned before. In addition to improvisational creativity, management studies have also shown improvisation training to positively affect team performance and leadership since it pushes the team members to be more cooperative and use intuition to come up with the best responses in a given context[231,232,233].

Until today, improvisation has been extensively used in artistic contexts, such as theater, music jam, and dance choreography. Besides, improvisation training has been adopted by corporations to enhance team management. Over the past decades, computers and robotics have also been used in improvisation to explore whether humans and robots can collaboratively create inspiring art pieces[234,45,235] or better workflow[73]. However, although there has been rich literature regarding creativity, team performance, and Human-Robot Interaction (HRI) regarding improvisation, little research exists in the realm of improvisation in the architectural field.

With recent advancements in multi-agent robotics and computational fabrication, interacting and creating with robots without pre-planning becomes possible for humans. This allows for reworking existing designs or creating new designs on-site during construction. It also allows for an organic and flexible blending of human and robotic capabilities and captivities. Improvisation also shifts more design weight from architectural studios into construction sites, potentially inspiring more fabrication- and site-inspired structures than ones heavily influenced by representations like drawings and renderings. Therefore, it is time to connect dots across improvisational creativity, team management, and CHRC and rethink the role of improvisation in the design and construction of architecture (Fig. 6.1). The project aims to start setting up frameworks where humans and robots can collaboratively construct and improvise. It indicates improvising with robots can potentially enhance creativity in constructing structures and point out near future research focus in this emerging domain.

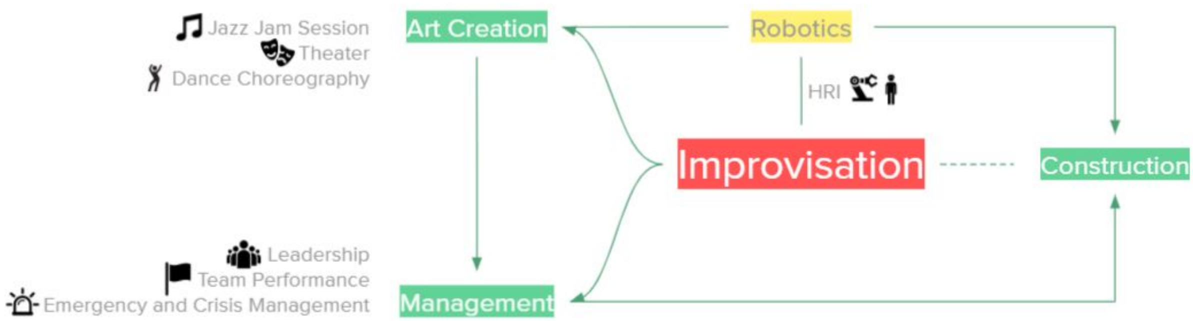


Figure 6.1: Improvisation in art creation, management, and construction

6.2 State of the Art

Collective Human-Robot Construction (CHRC) concerns multi-agent construction involving both humans and robots. It is an emerging researching field bridging Collective Robotics Construction (CRC), Human-Robot Interaction (HRI), and heterogeneous teams. Compared to the direct controller-agent relationship between human operators and robots in a traditional setting, CHRC enables a more complex and dynamic relationship across heterogeneous team members[230]. The process of completing a task no longer needs to be direct and linear. Instead of pre-planned construction steps for a set final structure, the structure can emerge through complex interactions and collective decision-making among multi-human-robot agents with improvisation in construction.

6.2.1 Improvisation, Creativity, and Team Performance

Improvisation, which often appears in music or theater, refers to the act of creating or performing without preparation. In contrast to traditional theater, improvisational creation does not have any predetermined script, props, or roles. The creation during improvisation is, instead, mainly guided by intuition and spontaneity[236,237].

Improvisational Creativity

Improvisation often yields collective results that are fresh but fitting to the progression of events. Therefore, its two major applications are for creativity and management in group settings. Because improvisation involves multiple agents coming up with ideas and creations that correspond to other agents and the larger context, it is a great channel to nurture *group creativity*. In contrast to *product creativity* or *compositional creativity*, where accumulated step-by-step design efforts (e.g., Graham Wallas' four-stage model: Preparation, Incubation, Illumination, Verification[238]) lead to a final product, *group creativity* or *improvisational creativity* stands out by its simultaneous occurrence of the creative process and product[42,239,240,44]. R. Keith Sawyer, an American Psychologist specializing in creativity and innovation, stated that improvisation could bring out the key features in *group creativity*, which are "process, unpredictability, intersubjectivity, complex communication, and emergence.[241]" During improvisation, participating agents can shift roles, tune power dynamics, join and leave at any moment[237]. This helps to merge ideas from multiple agents into one collective creation, although the process of creating itself can be highly unpredictable. In a heterogeneous human-robot team setting, *group creativity* as described above can be an appealing feature where human and robotic capabilities can be organically blended together to come up with something that neither party can create alone.

Improvisation and Team Performance

Other than in artistic disciplines, improvisation also holds great value in management and is broadly recognized and applied in corporations. Improvisation is important in emergency and crisis management where an effective solution is required under time pressure[232,233,231]. In the construction industry, the current planning and management framework does not fully cope with uncertainties and emergencies. Improvisation is starting to inspire better safety measures on-site[242]. In addition to its application in crisis management, improvisation can also enhance team performance in the workplace through real-time communication, rotational leadership, and trust among members[243,244].

Based on literature reviews of music and workplace improvisation, the authors summarized five rules for an improvisational mentality as listed below. These guidelines are closely followed when planning and conducting this project:

1. "Yes, and..."

   Improvisation requires the participating players to have an open mind and be ready to actively respond to whatever challenge that is ahead of them. This demands a positive, open, and flexible mindset which can also facilitate teamwork[245,246].

2. Accept odd pieces.

   Not all acts during improvisation are successful, even in an ideal jam session. Therefore, players need to be tolerant of the "odd" pieces[247].

3. Make connections.

   For multiple players to create one comprehensible and relatively consistent work, it is essential for each player to actively listen to others, interpret the context, and make contributions that respond to the given situations[248,249].

4. Live in the moment.

   The temporal dimension is significant in improvisation. All decisions are made in real-time, and no reworking is possible[250]. Therefore, players need to stay highly focused through the process and put in the best effort and judgment on the spur of the moment.

5. It is okay to change.

   Because improvisation is not pre-planned, players should be very comfortable when things do not go as they envisioned.[251].

6.2.2 Improvising and Robotic Construction

Although improvising with robots is starting to be explored in art creation (e.g., multi-robot-human jazz jam session[45,46], human-robot improvisational dance[252,253], theater improvisation[254,47]), the very idea of "improvisation" is still very new and under-investigated in the collective human-robot construction (CHRC) setting. Existing robotic fabrication methods that involve collaborative building with human constructors usually have the humans fixing connection elements while taking advantage of the robot's accuracy by having them hold building blocks at destination locations[20,255]. These models mainly focus on taking humans' abilities in sensing and manipulating materials at complex non-repetitive connection areas, rather than on humans' creativity in coming up with new designs on the spur of the moment.

By shifting the research focus onto improvisation, many existing techniques in robotic construction and HRI can be easily adapted to explore human-robot improvisational construction. For example, researches on HRI interface in dialogues (e.g., dialogue-based human-robot[256,257]), simulation (e.g., human-robot collaboration through virtual environments[258]), gesture[259], social cues[260], and even brainwaves[261] can be adapted to enhance the communication among players in improvisation. In addition, swarm robotics in construction opens up possibilities for each agent to develop customized solutions for local situations on the fly[262,263]. The swarm robotics control system is also flexible and robust enough to provide creative spaces for humans to step in and modify the structure at any moment without breaking the robotic construction system[35].

When exploring human-robot collaboration in construction tasks, Tuckman's "four subtopics for teams" can be a great reference[264]:

1. Forming: determining who would be on the team.
2. Storming: finding out the strengths and weaknesses of team members and characterizing the tasks to be done.
3. Norming: distributing tasks to the team members for execution.
4. Performing: execution of responsibilities.
5. Adjourning: disengagement; anxiety about separation and termination; sadness; feelings toward the leader and group members.

While "norming" or task assignment is a standard topic explored in some existing collective human-robot construction examples[141], the authors also value the potential of other aspects listed above and extended the discussion in sections 6.4 and 6.5.

6.2.3 Challenges for Improvisation Research

Improvisation is a challenging topic to research for the following reasons. First of all, the standard for evaluating an improvisation session is not apparent. Because improvisation can be "too elusive for analysis and precise description," some researchers said it could be regarded as essentially non-academic[265]. Thus, because both the process and the final product matter in improvisation[241], only evaluating the outcome is insufficient to render a complete picture. Therefore, in this project, a combination of quantitative evaluations of the outcome and qualitative descriptions of the process is presented.

Another challenge when analyzing improvisation, both its product and process, is intersubjectivity. According to Oxford Reference, intersubjectivity can be defined as "the process and product of sharing experiences, knowledge, understandings, and expectations with others"[266]. More specifically, in an improvisation setting, Sawyer describes the issue of intersubjectivity to be a situation where it is "impossible to determine the meaning of an action until other performers have responded to it[241]." The meaning of the product created through improvisation is assigned and interpreted by more than one agent, making it impractical to document and evaluate definitively. However, the good side is that intersubjectivity is also a key trigger for creativity because it leaves interpretation open-ended and provides space for imagination. Thus, intersubjectivity provides a neutral ground for collective creation that mixes perspectives and ideas from multiple agents.

Other challenges in improvisation research include identifying "which can be intuitive"[265] for both robots and humans, how to navigate complex communications between agents that are required for smooth improvisation, how to account for time pressures in task execution, and more. Because improvisation is still a very new idea in collective human-robot construction (CHRC), the lack of precedents also requires researchers to develop effective experiment setups to study this topic. Since improvisation is unpredictable and ever-changing, the dimension of freedom can exponentially scale up if not carefully constrained, making the experiment design even more challenging.

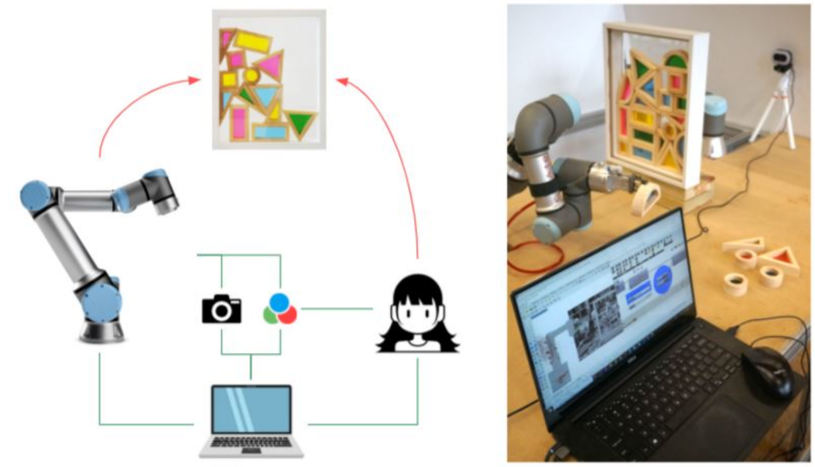


Figure 6.2: Feedback and control setup

Figure 6.3: A human and a robot in the process of improvisational stacking

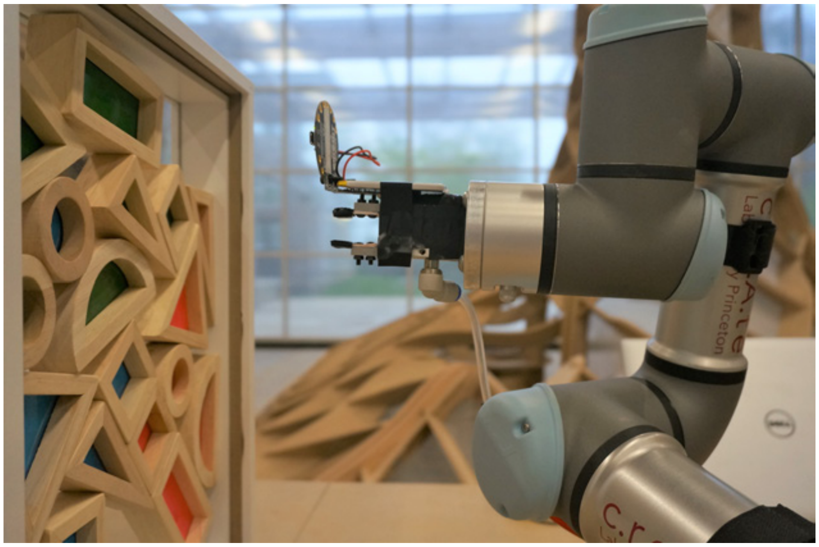


Figure 6.4: UR5 robot with color sensor on the gripper

	Sub-Tests	Agents	Agent 1	Agent 2	Additional Input	Preferences		Goal
						Human	Robot	
Test 00	Test 00 - A	One-Human	Human X	n/a	n/a	Shape (Fit)	n/a	Height
	Test 00 - B		Human Y	n/a	n/a	Shape (Fit)	n/a	Height
	Test 00 - AB	Human-Human	Human X	Human Y	Social Cues	Shape (Fit)	n/a	Height
Test 01	Test 01 - A	Human-Robot	Human X	UR5 Robot	n/a	Shape (Fit)	None	Height
	Test 01 - B		Human X	UR5 Robot	n/a	Shape (Fit)	None	Height
	Test 01 - C		Human X	UR5 Robot	n/a	Shape (Fit)	None	Height
	Test 01 - D		Human X	UR5 Robot	n/a	Shape (Fit)	None	Height
Test 02		Human-Robot	Human X	UR5 Robot	Fine Tuning Position	Shape (Fit)	None	Height; Reduce unsolvable puzzles
Test 03		Human-Robot	Human X	UR5 Robot	Visual Input	Shape (Gap)	Shape(Level)	Fill up the space
Test 04		Human-Robot	Human X	UR5 Robot	Color Sensing	Shape (Fit) and Color	Color	Height; Color Clustering

Figure 6.5: Test setup

6.3 Methods

Framed in the context of Collective Human-Robot Construction (CHRC), this project limits its scope to setting up basic human-robot improvisation scenarios to construct structures collectively. How to set up an improvisation model in construction? How can robots contribute to improvisational creativity in design and fabrication? What are some critical dimensions to consider when humans and robots improvise together to build a shared structure? This project starts thinking about these questions through a series of abstract examples (Fig. 6.5).

To prevent the improvisational construction from being overly complex (see section 6.2.3) yet still consider "gravity" in structures, the task for this experiment was set to be a two-dimensional structural composition in a vertical plane. The construction task is bounded by an 11" wide, 18" high, and 1.5" thick wooden frame. The frame stands vertically within reaching distance in front of a UR5 Robot[267].

The feedback and control system is relatively basic, allowing the robot to respond to geometry and color if needed with a level of randomness (Fig. 6.2). Specifically, a UR5 Robot is plugged into a laptop computer. The robot has a pneumatic gripper that is customized to pick and drop toy blocks from the side. The prefabricated, commercially available toy blocks are 1" thick, with 0.4" wide wooden edges and a colored film (red, green, blue, or yellow) in the middle. These blocks come in standard shapes such as square, rectangle, right triangle, equilateral triangle, circle, and semicircle. Overall, this specific set of blocks allows the researchers to explore preferences on color or geometry when needed. For example, visual feedback is used in Test 03 to give geometry preference for the robot (Fig. 6.2). For color preference, a color sensing device (Circuit Playground Express[268]) is attached to the front end of the robot gripper (Fig. 6.4). Combined with robotic movements, the color sensor allows the robot to detect the most frequently appearing color in the color area.

Because the process is as important as the final product in improvisation, as mentioned in section 6.2.3, both process and result are documented and evaluated in this project. All improvisation test trials are video recorded with the final products photographed in the elevation view (Fig. 6.6).

A total of 10 rounds of improvisational stacking were performed under five major branches of explorations in different team compositions, preferences, goals, and feedback settings (Fig. 6.5). The tests start from a basic setup derived from the typical model where the robot holds pieces at their precise destinations while humans fix the connecting elements in-between (see section 6.2.2). However, as mentioned in section 6.2.2, the focus of exploration shifts onto the topic of creativity in improvisation. Thus, the robot functions as unplanned temporal constraints to give human players more design space and challenging prompts. In addition, throughout all tests, the human participants are committed to keeping a positive "improvisational mentality" as listed in section 6.2.1.

Tests 01-04 are all collectively built by one human and one robot without pre-planning. In contrast, *Test 00* series was created as controlled groups where all constructions are done by humans only, without any influence from robots. *Test 00* series aims to provide a basis for "personalities" or design instructions individually and collectively from two humans. This, later on, serves as a point of reference to extract what the robot's influences are. Specifically, *Test 00-A* and *Test 00-B* are single-person constructions by two different persons. *Test 00- AB* is conducted by the two human agents working together. Human Y holds blocks of their choice in the air to indicate anchor points, and Human X comes up with a supporting solution for Human Y's anchor block. The goal of improvisational construction in the *Test 00* series is to reach the top of the construction frame.

Test 01 keeps the same setting as in *Test 00-AB*, but replaces human Y with a UR5 robot to hold the anchoring block mid-air while the same Human X from *Test 00* finds supporting solutions on the fly. By contrasting *Test 01* and *Test 00-AB*, one expects to see whether the UR5 robot can do as good a job as Human Y. In addition, the different experiences and final products between the two tests can also help the researcher analyze how the "personality" of humans and robots matter in CHRC improvisation scenarios. Specifically, in *Test 01* series, the robot does not have a preference over shape or color. Instead, within a reasonable height in the construction frame, its block shape and color, location in the horizontal direction, and angle of relation within the vertical plane are randomly generated. This randomization also created situations called "unsolvable puzzles" in this paper, where it is nearly impossible for a human agent to develop a doable supporting configuration.

Although the "improvisational mentality" summarized in section 6.2.1 instructs the players to be tolerant of the "odd pieces," however, having a higher chance of "solvable puzzles" can help create a smoother and encouraging improvisation session. Therefore, a "fine-tuning" feature was added and tested in *Test 02*. This "fine-tuning" feature allows the human agent to give the robot quick and simple commands to shift or rotate "a little bit" so that a supporting block can fit in.

So far, in *Test 00, 01, and 02*, there is much randomness but very little feedback for the robots. With the help of visual and color feedback, *Test 03* and *Test 04* explore the topic of preference separately over shape and color. In *Test 03*, based on the uppermost outline of the existing geometry, the human would try to fill in gaps with a new block, while the robot would prefer horizontal flat surfaces and try to fit an orthogonal block on top. It is worth mentioning that, instead of the robot-holding-human-connecting model, the two parties alternatively contribute one piece at a time in *Test 03*. Thus, *Test 03* differentiates from *Test 00-AB, 01, 02, and 04* in the improvisational procedure, giving a good reference to study

Figure 6.6: Improvisational Construction Results (Elevation View)

how the procedure setup influences the entire experience and outcome.

In *Test 04*, both robot and human aim to create color clusters where blocks with the same color would be stacked close to each other as long as the geometry works to create an equilibrium state. Specifically, to decide the color of a new piece, the robot would do a color scan around the last location it was at and suggest a color that is detected the most in that local region.

Among the five sets of tests, *Test 01* is repeated four times (*Test 01-A, B, C, D*). This is because *Test 01-A* yields a formal composition that is interesting and delicate with small gaps and odd angles. The author would like to check with more trials to assess if this level of creativity produced under this setup is consistent.

Overall, this collection of tests provides references to study how the presence of a robot (*Test 00* as opposed to *Test 01*), personalities (*Test 00 and 01*), communicating small adjustments (*Test 02*), feedback (color in *Test 03* and geometry in *Test 04*), and procedure setup (*Test 03*) would influence a collective human-robot improvisational construction.

6.4 Results and Discussions

This project presents a first step towards setting up an improvisational construction framework where the human and robot build and create structures together without pre-planning. However, it is challenging to analyze an improvisation session due to intersubjectivity and its emphasis on process and product, as mentioned in section 6.2.3. Therefore, results for this project are provided and analyzed in both quantitative and qualitative manners through visual, numerical, and verbal descriptions.

- The result shows that how the improvisation procedure is set up can significantly influence the outcome. Looking at the outcomes, the formal and connection analysis in Fig. 6.7 and 6.8 provide a quantitative description of the compositional characteristics of the final product. *Test 03* in Fig. 6.8 renders a polyline that's drastically different from the rest of the tests, showing that procedure setup can influence the outcome of the improvisation. In terms of procedure, Test 03 also feels very different from the rest - the building process was less engaging because both the human and robot have pre-assigned preferences over geometry.

- In an outcome-oriented scenario, a robot, when properly set up, can potentially replace humans in improvisation because the connection analysis for *Test 00-AB* and *Test 01* yields almost overlapping poly-lines in Fig. 6.8. However, the experience of improvising with robots and humans is very different based on this project. The human collaborator stands out in communicating, including the use of subtle social cues. For example, when Human X said, "That piece is high," Human Y instantly lowered the piece in hand without any further communication needed. In contrast, the robot collaborator excels in precision and "patience." It was able to hold one piece steadily for a theoretically infinite length of time, giving the human player minimal time and social pressure to come up with a solution. Therefore, both humans and robots have their benefits and drawbacks to collaborate with, which corresponds to the "Storming" and "Adjourning"

	Test	00 - A	00 - B	00 - AB	01	02	03	04
Shape	Total # of Blocks	9	6	18	15	13	18	18
	Square	0.0%	0.0%	11.1%	18.1%	15.4%	22.2%	16.7%
	Rectangle	33.3%	33.3%	16.7%	15.5%	23.1%	22.2%	16.7%
	Right Triangle	11.1%	16.7%	16.7%	25.3%	15.4%	16.7%	16.7%
	Equilateral Triangle	33.3%	50.0%	22.2%	20.4%	15.4%	16.7%	16.7%
	Circle	0.0%	0.0%	22.2%	10.8%	7.7%	5.6%	16.7%
	Semicircle	22.2%	0.0%	11.1%	10.0%	23.1%	16.7%	16.7%
Connection	Total # of Connections	14	5	24	21	18	25	27
	Aligned	7.1%	40.0%	16.7%	15.5%	22.2%	52.0%	18.5%
	Small offset (<=10°)	14.3%	0.0%	12.5%	11.8%	11.1%	16.0%	14.8%
	Point-to-surface (>10°)	78.6%	60.0%	70.8%	72.6%	66.7%	32.0%	66.7%

Figure 6.7: Formal Analysis

points covered in section 6.2.2

- Human and robot's inherent "personalities" can influence the outcome. "Personality" in the context refers to individual differences in characteristic patterns for kinematic movement and composition. The difference between *Test 00-A*, *Test 00-B*, and *Test 03* in Fig. 6.8 illustrate this point.

- Human and robot's preferences can influence the final result. This is illustrated in the formal composition in *Test 03* and color clustering in *Test 04*, as shown in Fig. 6.6.

- The proportion of how much each player influences the improvisation process and outcome can be manipulated by the procedure setup. For example, in Fig. 6.8, *Test 00-AB*'s poly-line resembles more that of *Test 00-A* than *Test 00-B*, because Human X, the builder of *Test 00-A*, plays a more important role in collaboration with Human Y. Human X actively builds more blocks, while Human Y statically holds constraining pieces. Similarly, *Test 02* resembles *Test 01* for the same reason. In contrast, in *Test 03*, the two players almost hold equal weights in defining the final shape. That's why its poly-line in Fig. 6.8 differentiates drastically from the Human X-oriented settings in *Test 01, 02, and 04*.

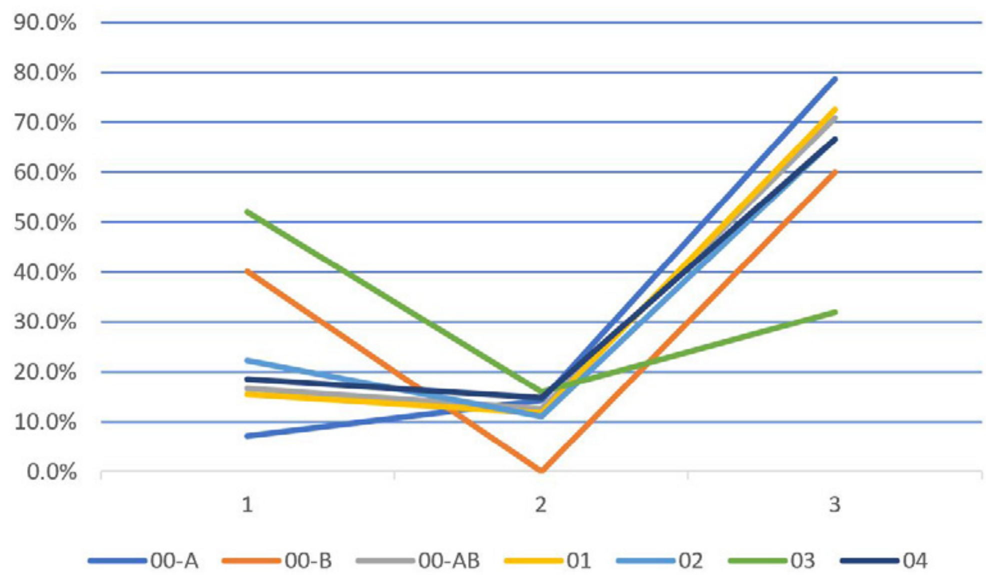


Figure 6.8: Connection Analysis: 1) Aligned, 2) Small offsets $\leqq 10^{\circ}$, 3) Point to Surface $> 10^{\circ}$

6.5 Limitations and Outlook

Overall, this project set up a straightforward and initial framework to explore topics on improvisation in CHRC setting. The feedback and sensing in this project are very fundamental. In future research, more advanced elements can be added on top of this basic framework, such as topics involving learning, social cues, HRI, sensing, control, and team dynamics (see section 6.2.2). In addition, the sample size of small in this project, so the data collected may not be representative. The next step can be to verify the findings in this project by repeating each test for more rounds. Besides, since the temporal dimension is vital for improvisation, constraints to add time pressure can be included in future tests.

In the future, improvisational creativity should be further explored in collective human-robot construction (CHRC). Based on this project, we can conclude that how the improvisational construction is set up significantly influences the process and outcome. This means that, by carefully defining the team composition and roles of each player, we can boost or tune down the influence of different human or robot players. With a flexible management framework, we can also allow for rotational leadership, where major influences are led by robotic or human players on a dynamic basis. It allows for a more integrated design with both human and robotic contributions organically blended together.

Furthermore, we would like to invite the readers to rethink the architectural industry to be less linear and more flexible, thanks to new building workflows inspired by improvisation with heterogeneous human-robot teams.

7

Improv-Structure: Exploring Improvisation in Collective Human-Robot Construction

This section of the dissertation has been adapted from the following course paper and publication:

Han IX. Improv-Structure: Exploring Improvisation in Collective Human-Robot Construction. ARC574 Final Paper, Princeton University, Instructor: Prof. Stefana Parascho. December, 2021.

Han IX, Parascho S. Improv-structure: exploring improvisation in collective human-robot construction. In *International Conference on Trends on Construction in the Post-Digital Era, ISIC 2022*, 2022 Sep 7, *Lecture Notes in Civil Engineering*, vol 306. (pp. 233-243). Cham: Springer International Publishing.

Overview

The emerging field of Collective Human-Robot Construction (CHRC) opens up vast space for human-robot interaction and collaboration in real-time for construction tasks, making the idea of improvisation a critical layer to explore. Compared to the traditional linear workflow of pre-planned structures, improvisational construction allows for a real-time collective building experience, giving the build team more space for creativity, flexibility, and immersive design. However, the concept of improvisation in an architectural context has not been fully explored yet, especially with a multi-robot-human team, despite rich literature on improvisation in art performance, management, and robotics. In this paper, we present *Improv-Structure*, a proof of concept for improvisational construction, where ∼500 bamboo rods were assembled by two industrial robotic arms and several humans using a collective decision-making mechanism.

7.1 Introduction

With the introduction of robotic tools into architectural fabrication processes, computational designs can be manifested in the physical world more easily than before. An example of this can be seen in the Gantenbein vineyard[11]. However, robotic systems also have their shortcomings. Since every construction site and building project is different, it is more challenging to calibrate robots to suit new construction sites and building materials compared to setting up a production line for a repetitive task[269]. Additionally, complex sensing systems (e.g., with reinforcement learning[270]) and tighter tolerances are needed to work with materials possessing non-standard geometries, such as natural elements (e.g., bamboo rods), or building blocks with manufacturing inconsistencies. Thus, it is essential to consider the transferability of robotic assembly systems across different projects involving distinct environments, building materials, and robot models[146].

In addition to the technical challenges faced by robotic construction systems, there has also been a growing trend for segregation and specialization between *design* and *construction* disciplines. In most cases, construction only begins after the design is finalized. Even with the development of notions such as building information modeling (BIM)[271] and robot-oriented design (ROD)[55], the role of robots in today's construction techniques is mainly categorized as a passive element of fabrication rather than an active element integral to the design process.

The relationship between humans and robots in construction settings is of concern as well. We ask: How can humans, both as designers and construction workers, best collaborate with robots so that the strengths of both sides can be amplified? How can humans' design-construction experience be altered and improved by the introduction of robotic tools? The emerging field of collective human-robot construction (CHRC)[230] has begun to explore these questions by pointing researchers towards a wide range of possibilities for human-robot team creativity. It is primarily concerned with investigations and explorations into how design decisions can be distributed across robotic and human agents in order to enhance the collective performance.

In this work, we introduce the concept of improvisation to the human-robot design-construction process. *Improv-Structure*, a 7' x 14' x 7' bamboo structure consisting of ∼500 4' long and 3/8" wide bamboo rods, was designed and constructed by two ABB IRB 4600-255/40 robots and several humans over the span of 5 days. The robotic arms functioned as guidance and structural support, while the humans led the design and construction process. This led to an immersive and improvisational experience for the human builders that was profoundly different from the cut-and-dry experience typically encountered when building a structure from a pre-prescribed design. Since no planning occurred and no expectations were made with regard to how the final structure would look, collective design decisions were made solely by humans based on observing the built portion of the structure. Throughout the process, the robot received its input parameters based on LiDAR scans of the existing structure into the 3D computer model. *Improv-Structure* serves as a proof of concept for improvisational construction with an immersive design process in the CHRC setting.

7.2 State of the Art

7.2.1 Improvisation and Robotics

Improvisation refers to actions (e.g., art performance, emergency response) made without advance planning. This method is often adopted in musical and theatrical settings to nurture group creativity[45,43], in corporate management to enhance team performance[231], and in emergency scenarios to maximize the effectiveness of decision-making under time pressure[232,233]. In recent years, the notion of improvisation has been introduced into the context of robotics, for example, in robotic teams that improvise jazz music with human musicians[45,234] and human-robot improvisational dance[252,253]. However, the concept of improvisation is still very new in the design-construction field.

Improvisational skills can be divided into two categories - *open* and *closed skills*[272]. According to Jeff Pressing's article in 1988, *open skills* "require extensive interaction with external stimuli," meanwhile *closed skills* "[rely] only on self-produced stimuli."[272] In a heterogeneous human-robot team, we expect humans, robots, and the built environment to act as external stimuli for each other. Inherent qualities such as intuition and stylistic preferences will be key aspects of the agents' *closed skills*. We expect improvisation to enhance creativity and construction efficiency as shown in researches from adjacent fields (e.g.[233,45,231]).

7.2.2 Segregation Between Design and Construction

Since the Industrial Revolution, design and construction have become increasingly segregated and specialized. Nevertheless, a harmonious collaboration between these disciplines (i.e., architects and engineers) is essential for the development of quality structures[273]. The introduction of robotic tools has provided a means to bring complex parametric designs into the physical world. However, most robotic fabrication processes in the building industry regard computational design and robotic construction as two distinguished steps. In other words, despite the fact that computational design allows for a large number of quick iterations before a design is finalized, we expect robots to follow pre-planned assembly steps to achieve a pre-determined geometry once the construction phase begins (e.g., Gantenbein vineyard[11]).

In order to better integrate design and construction processes, several solutions have been proposed and implemented. From the industrial point of view, BIM[271] intends to more effectively connect designers with relevant construction disciplines through consistent data gathering and representation. Similarly, ROD[55] emphasizes the consideration of robotic parameters when designing robotic construction processes. Examples such as the ICD/ITKE Research Pavilion 2016/2017[?] and the Light-Vault[220] have also shown the importance of considering robotic kinematics and workspace when designing robotic fabrication processes. Even with BIM and ROD, however, design and fabrication processes are still segregated in the majority of construction projects.

7.2.3 Human-Robot Interaction and Immersive/Participatory Design Using Robots

Recent developments in human-robot interaction (HRI) and immersive design with augmented and virtual reality (AR/VR) have brought forth new possibilities for integrating design and fabrication processes. Evidence shown by Paes et al. has proven the cognitive benefits of immersive design with VR for 3D perception and presence[274]. Additionally, he adoption of HRI and HCI (human-computer interaction) has enabled co-design through fast and cheap physical prototypes[275,276]. Despite these obvious advantages, there are few examples of co-designing and co-constructing architectural-scale structures in real-life immersive design settings that are not enabled by virtual or augmented reality.

A key question faced in participatory design involving high tech is whether the technology itself imposes another layer of segregation and bias. For instance, how can we involve people without a background in robotics (i.e., community members) into a participatory design process that uses robotic arms? In the *Improv-Structure* project, we aim to open up new channels for design decision making so that they are less centralized and have lower technical barriers.

7.2.4 Collective Human-Robot Construction (CHRC)

Collective Human-Robot Construction (CHRC) "concerns multi-agent construction involving both human and robotic collectives. It is an emerging interdisciplinary field that combines collective fabrication, human– robot interaction, and heterogeneous teams. Research focused on CHRC spans from autonomy to collaboration, indicating novel ways of designing and fabricating."[230] Building on top of cooperative robotic assembly, where multiple robots can achieve complex structural compositions by alternating between placing new elements and holding existing structures[26], CHRC brings humans into the loop for enhanced design-construction experiences, creative formal expressions, and building efficiency.

7.3 Methodology

In the project *Improv-Structure*, we introduced the concept of improvisation into construction through the design-construction process of a bamboo structure carried out by two ABB IRB 4600-255/40 robots and several humans. As described in Section 7.2.1, we took advantage of robots' *closed skills* in strength and precision, as well as humans' closed skills in sensing and flexibility. By creating feedback channels using a LiDAR scanner (for robots) and real-life observations (for humans), we triggered agents' *open skills* to improvise based on external stimuli. Specifically, we built a human-scale structure made of 4-foot-long bamboo rods with an average diameter of 3/8" and connected with zip tie knots by alternating the placement of rods between robots and humans. Our two main goals were to 1) combine the strengths of robots and humans and 2) distribute design decision-making through the proposed improvisational building framework in CHRC.

7.3.1 Combining the Strengths of Robots and Humans

The distribution of design-construction roles across agents was based on each agent's strengths. To build the *Improv-Structure*, the two robotic arms were responsible for placing guiding rods, which pro-

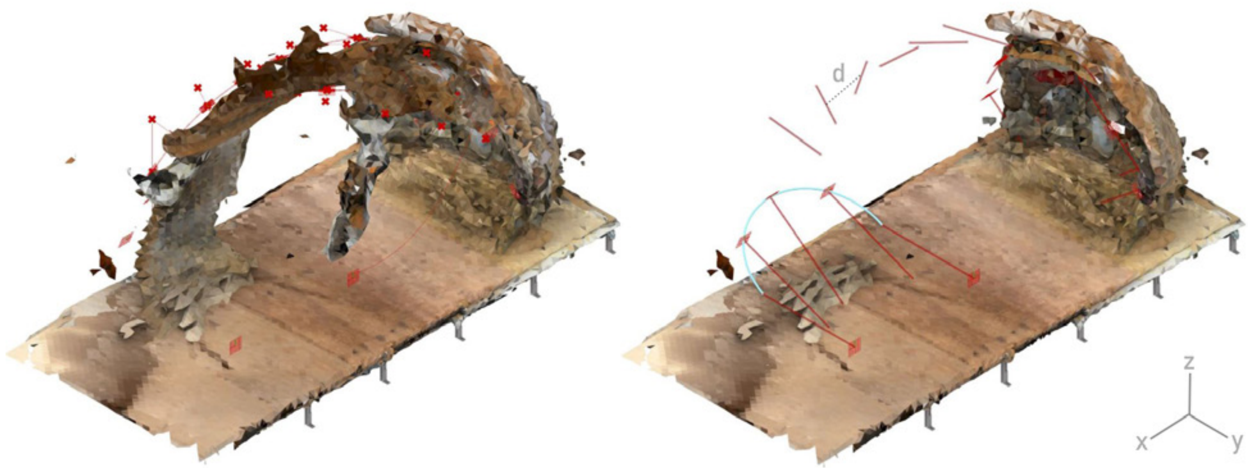


Figure 7.1: Guiding rods marked in red color; world X-Y-Z axis defined at the bottom right corner; **d** = gap size between guiding rods.

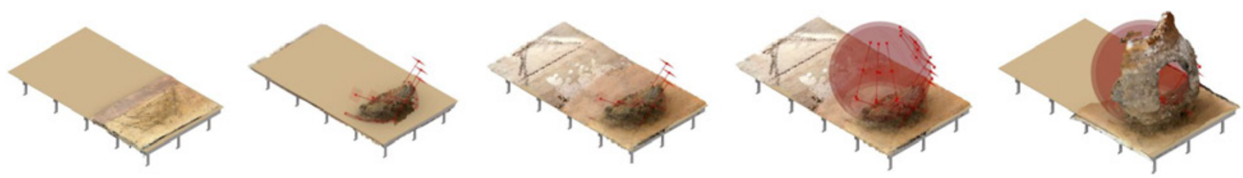


Figure 7.2: LiDAR scanning of existing structure into 3D models to inform robotic movements

vided temporary structural support and enhanced the alignment between the physical construction and the computational design intent. Specifically, in this prototype, the pre-defined Grasshopper[277] algorithm took in 1 to 2 curve geometries each time and generated the guiding rods' location for the robotic arms accordingly. The tunable factors included the distance between adjacent guiding rods (**d** in Figure 7.1) and the rods' rotation angles around the curve input, mainly within the YZ plane (Figure 7.1). Orienting the guiding rods around the YZ plane was a simple way to ensure that they were not connected to each other. In other words, a new guiding rod was held in mid-air, detached from the main structure. Here, **d** was bounded within a range of 0.65∼0.85 times the rod's length, which the authors observed to be a good gap size to catalyse humans' creativity for finding bridging solutions while the robotic arms provided efficient temporary point support.

The human's role was to 1) connect the guiding rods (marked in red in Figure 7.1) held by the robots into the existing structure, 2) make design decisions on the fly based on the immersive physical experience in and around the partially-built structure, and 3) translate that design into 1 to 2 curves that help

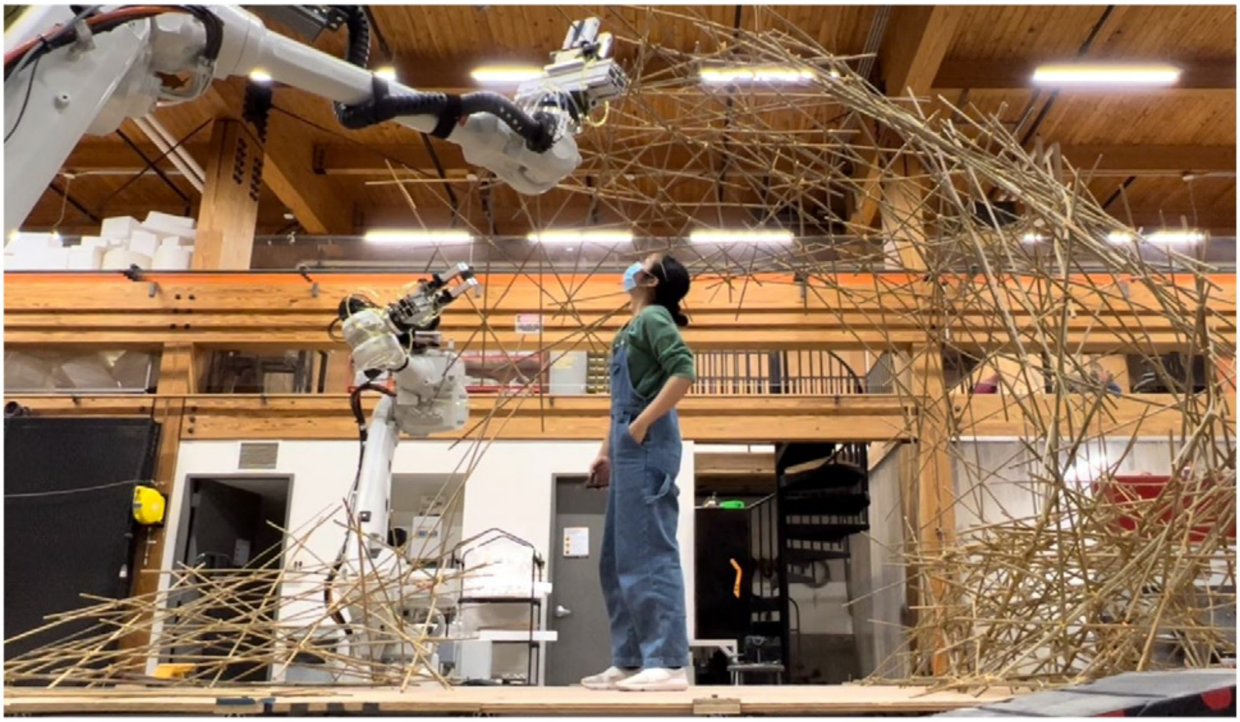


Figure 7.3: Designing on the fly by observing the built proportion

define the guiding rods based on the LiDAR model. This way, we utilized the robot's precision and strength without worrying about the complex sensing and tolerance problems caused by organic building elements (i.e., bamboo rods). Similarly, humans were freed from the highly specialized position of either designer or constructor and formed a co-design, co-fabrication relationship with the robotic arms.

For communication between the virtual and physical world, the robots received information about the ongoing building process through LiDAR scanning (Figure 7.2). Compared to AR/VR, this allowed humans to observe and experience the 3D structure in real life to inform future design decisions (Figure 7.3).

It is worth mentioning that the mechanism presented here is just one version of how design decisions can be distributed between robots and humans. One could shift the level of autonomy between humans and robots towards either direction in future iterations.

7.3.2 Distributing Design Decision-making

The design-construction process was divided into multiple action units to distribute decision-making across time. Each action unit consisted of the following steps:

1. **Robots** LiDAR scan the existing structure
2. **Humans** observe and experience the existing structure and discuss what the next design features could be. Designers need not be trained in robotics to carry out this step
3. **Humans** input parameters (i.e., 1 to 2 curves) needed for robotic movements based on the LiDAR model
4. **Robots** place the next guiding rod in mid-air next to the existing structure (Figure 7.4)
5. **Humans** propose structural solutions on-the-fly to extend the existing structure towards the guiding rod held by the robot

The execution of the design-construction action units is flexible. Based on the humans' observations on-site, it is possible to quit the action unit mid-way and change plans on the fly. The design-construction action unit is repeated until the humans decide to stop the construction, assuming the structure can stand alone without external support. In other words, it is arbitrary whether the construction is finished or not. One can always restart the building process and continue adding to the structure.

7.4 Results

The final product of the *Improv-Structure* is 7'x14'x7' in dimension and was constructed within a timespan of five days. It consists of around 500 bamboo rods that are 4' in length and 3/8" in diameter, of which ∼30 guiding rods were inserted and temporarily supported by the ABB IRB 4600-255/40 robotic arms.

Figure 7.4: Robotic arm (right) holding guiding rods in mid-air

The design construction process was divided into 5 design-construction action units, between which the existing structure was re-scanned by LiDAR sensor and updated in the 3D Rhino/Grasshopper model. New design decisions and adjustments were made between each action unit. Two out of five action units experienced change-of-plans that were influenced by the human's observation of the constructed portion of the structure. *Improv-Structure* provides a proof of concept example for using improvisation as a framework for CHRC.

7.5 Discussion, limitation, and outlook

7.5.1 Discussion

Flexibility and Tranferability

The improvisational construction in CHRC combines the strengths of robot and human agents and considerably reduces the problem of tolerance. Because the robots are only placing and supporting geometry-defining elements in mid-air next to the structure, we replace the need for a complex robotic

Figure 7.5: Improv-Structure, Photo credit: Michelle Deng.

sensing system with craft from human designers/constructors. This also eliminates concerns related to material inconsistency due to manufacturing defects or organic geometries (i.e., bamboo rods). Thus, the method for *Improv-Structure* is highly flexible and transferable.

One can argue that replacing the mechanically challenging proportion of the task with human craft is not a permanent or automated solution. As a response, we would like to clarify that the essence of our proposal is to take advantage of a heterogeneous team composition and allocate the tasks in a way that triggers collaboration and maximizes the strengths of the agents. Accordingly, the role of human agents in the *Improv-Structure* project could theoretically be replaced in the future by robots that specialize in sensing the local environment and connecting material elements. In other words, the improvisational construction framework is not only designed to be applicable to human-robot heterogeneous teams, but also to teams with multiple types of robots. However, going back to the topics mentioned in Section 7.2.2 and 7.2.3, we may also want to include more humans (e.g., designers, engineers, community members without robotics backgrounds, etc.) in a participatory design-construction process. In such scenarios, a completely automated design-fabrication method may not be desirable. While robots

Figure 7.6: Detailed view of Improv-Structure. Photo credit: Michelle Deng.

are taking over more and more design-construction tasks in the building industry, it is important to remain mindful of how we would like to leverage human intelligence and creativity as well.

Reducing the Segregation between design and construction

Improv-Structure provides a unique design-construction experience that's not comparable to immersive AR/VR or non-immersive CAD modeling or rendering. Designers and builders can physically interact with the built proportion, observe the structure from different angles in real life, and imagine the following design steps according to the full-scale structure.

This design-construction model is not only immersive but also participatory. One doesn't need a robotics background to be able to play a part in crafting the structure. Thus, the shape of the structure emerges throughout time based on the dynamic decision-making among multiple agents. To illustrate this point, multiple humans participated in proposing the potential following design features in *Improv-Structure*. It is worth noticing that, for people with expertise in both design and construction, the same improvisational model only requires a minimum of one human and two robots to finish similar tasks. Thus, the *Improv-Structure* design-construction method encourages a more collaborative and interdisciplinary building process.

7.5.2 Limitations

Even though the robotic arms acquired data necessary for motion planning based on existing structures' spatial parameters from LiDAR scanning, the robots could have had more agency in deciding what the structure would look like.

Additionally, although it is easier to design/build on the fly on a full scale, the cost of corrections is higher. For example, it is much more time- and labor-efficient to prototype intensively using simulations and computer models. Once a construction is completed in full size in the physical world, it is more difficult to erase or redo a part to correct mistakes, not to mention that some material processing systems are non-reversible. However, such an improvisational approach can reduce the overall time and cost by shortening the design-construction period for building processes that are well-studied and easily disassemblable.

7.5.3 Outlook

In the future, the following aspects of *Improv-Structure* can be further developed: 1) enhanced agency for robots, 2) heterogeneous team compositions, 3) decision-making mechanisms, 4) tunable levels of autonomy, and 5) design-construction experiences.

Firstly, more agency can be given to robotic arms by developing robotic control systems to respond autonomously to the LiDAR scanning model and human inputs. Secondly, human constructors with different craft styles and robots with varied specialization (e.g., securing joints, transporting materials, etc.) can be invited to the building of future versions of *Improv-Structure* to explore how different compositions of heterogeneous teams can influence the improvisation process and the final product. Thirdly, how exactly design decisions are made can be further explored. For example, one may use machine learning to train "design intuitions" for robotic agents. On another note, a library of spatial features (e.g., seats, spanning shell, planter, tables, etc.) can be used to offer many pre-defined design choices and further accelerate the decision-making process. Fourthly, *Improv-Structure* is only one version of how design-construction tasks can be distributed among multiple agents. In the future, one may look at all agents' autonomy as a tunable dial and adjust the levels of autonomy to suit the needs of varied construction tasks. For example, one may tune down the robots' autonomy to achieve a structure closer to a desired end result or tune up the autonomy for a more unexpected or creative design. Yet another potential extension to this project can be to use augmented reality to assist humans in better imagining and visualizing design sketches in a hybrid environment. In this scenario, further efforts can be put into creating a more intuitive user interface and experience tailored for spatial design and human-robot collaboration.

Improv-Structure is a proof of concept to bring improvisation into construction with a heterogeneous team. We can imagine this framework being applied to the building of community sculptures or urban furniture to enhance the sense of belonging and collective identities. In an industrial setting, improvisational construction can potentially improve the efficiency of the design-build cycle by compressing the design and construction phases into one. Methods for creating a more diverse and tunable human-robot team composition for new design-construction experiences are yet to be explored.

8

Spontaneous Tensegrity: Exploring Improvisational Design and Robotic Fabrication in Tensegrity Structures

This section of the dissertation has been adapted from the following publication:

Han IX and Parascho S. Spontaneous Tensegrity: Exploring Improvisational Design and Robotic Fabrication in Tensegrity Structures. *Robotic Fabrication in Architecture, Art and Design ROB|ARCH 2024: Beyond Optimization*. Toronto, Canada. Conference Proceedings. 2024 May 24.

Overview

Over the last two decades, significant progress has been made in multi-robot systems (MRS) and human-robot interaction (HRI). In architectural applications, however, robots have mainly served as fabrication tools rather than design collaborators. Integrating robots into the design and fabrication processes can yield numerous advantages, including enhanced adaptability at dynamic construction sites and more efficient and creative construction processes. This paper showcases how robots can cooperate with humans through visual computing to design and build X-module and T3-prism tensegrity structures. Instead of following predefined blueprints, the human-robot team relies on generalized procedures and spontaneous decisions, resulting in greater flexibility and an expanded design space. The experiments include: 1) Employing stigmergic mechanisms and visual servoing for robots to adapt to structural changes and human interventions during the fabrication of an X-module tensegrity structure. 2) Incorporating so-called "robot design preferences" to influence the final form of a T3-prism tensegrity structure. Audio feedback and direct human-robot interactions, such as material handling, make the robotic fabrication process more user-friendly and intuitive for human designers. The presented prototypes illustrate how robots can autonomously adjust during fabrication, promoting collective decision-making between robots and humans in the design process. The paper's contributions encompass four key aspects: 1) a novel robotic end effector design for manipulating X-module and T3-prism tensegrity modules; 2) a computationally inexpensive visual servoing method for robotic arms to track and interact with building elements; 3) human-in-the-loop improvisational workflows for the design and fabrication of tensegrity structures; 4) proof-of-concept prototypes.

8.1 Introduction

Robotic technologies are adopted in the architectural field to enhance efficiency, enable new forms of expression, and automate the industry. Nonetheless, the currently dominant approach adheres to a linear design-fabrication workflow, where designers create digital models, programmers execute robotic path planning and sequencing, and fabrication takes place in a controlled factory or construction site. While this traditional approach has introduced notable advancements in robotic assembly processes[21], there remain drawbacks to the linear robotic fabrication workflow. First, traditional robotic fabrication processes often lack robustness against external factors such as material variations and structural deformations. Second, making design changes during the construction phase becomes prohibitively complex and costly due to the need to reprogram robots. Integrating these changes into a partially built structure also demands meticulous calibration, which is time-consuming and challenging. Third, the technical complexities surrounding robotic fabrication present a significant obstacle for architectural designers looking to fully explore the creative potential of this technology in their designs. Consequently, a substantial yet untapped potential exists for integrating robots into the design cycle in a user-friendly and intuitive manner[230], enhancing efficiency and expanding the design space.

This research paper aims to elevate the agency of robots in architectural design and fabrication by positioning them as active collaborators rather than passive tools. Specifically, we introduced computationally inexpensive vision-based robot control to two ABB IRB 2600 industrial robotic arms (12kg payload with 1.85m reach). This technology enables these robots to make context-aware decisions rather than to adhere rigidly to predefined paths resulting from construction blueprints. Using a rule-based generalized procedure, robots and humans collaboratively design and fabricate tensegrity structures in a dynamic and flexible process.

Experiment I demonstrates how robots can adapt to external influences, such as structural deformations and human interventions, using local sensing and stigmergic mechanisms. Experiment II integrates various design influences, including robot preferences, human input, environmental variables, and structural constraints, throughout the construction process with an improvisational design-fabrication approach.

8.2 Related Work

8.2.1 Improvise with Robotic Arms

Breaking away from the traditional linear workflow, we can draw inspiration from improvisation to envision a dynamic human-robot design-fabrication process. Improvisation is characterized by spontaneous decision-making and action devoid of pre-planning. This approach finds relevance in various creative domains, including theater[278], dance[252], craft[279], and music (G. Hoffman and Weinberg 2010). Notably, architectural-scale projects, such as "Improv-Structure"[280] and "Tie a Knot"[281] experiment with human-in-the-loop co-design with robotic arms, marking a departure from conventional robotic construction practices.

Improvisational techniques can be categorized as "open" and "closed skills"[272], or "external" and "emergent" approaches[282]. The former involves responses to external stimuli, while the latter refers to self-produced movements or decisions. Various models for human-robot improvisation have been proposed. Troughton et al. combine both "external" and "emergent" techniques to create rule-based improvised robot movements that are playful and open-ended[282]. Hoffman builds upon related concepts such as "inner monologue"[283] and "responsiveness" and maps such skills onto the application to robotics[284].

In this paper, we integrate both internal (e.g., robot's design preferences) and external stimuli (e.g., human intervention, structural deformation, and environmental variables) to robotic arms to inform the improvisational design of tensegrity structures (see Section 8.4.2).

8.2.2 Collective Human-Robot Building Sequence

Research in multi-agent construction draws inspiration from nature to devise flexible assembly sequences. For instance, Werfel et al. replicated stigmergic construction principles inspired by termite behavior, where simple robots with minimal onboard sensing collectively achieve specific human-designed goals, such as 3D stacking, without human intervention[35]. Stigmergic construction means the agents do not directly communicate with each other but leave cues (physical or chemical) in the environment and make construction decisions according to such cues. Stigmergy is known for its robustness against external interventions. This concept serves as the foundation for our exploration of human-robot interaction in Experiment I (Section 8.4.1).

Conversely, another research trend focuses on a structured rhythm of human interventions, exemplified in projects like "Tie a knot"[281], where human and robotic arms each contribute one rod to form a unit triangle to extend the existing structure. In "improv-structure"[280], a new building cycle involves a robot placing rods in mid-air adjacent to the existing structure, with a human bridging the gap using bamboo rods to create organic weaving shapes. Experiment II (Section 8.4.2) delves into a more structured collaborative sequence.

8.2.3 The Assembly of Tensegrity Structures

Buckminster Fuller coined the term "Tensegrity," derived from "tensional integrity," to describe structures that combine compression elements (struts) and tension elements (tendons) to create stability in space[285]. Unlike construction methods like stacking, casting, and spanning, where the relationship between each building block is tightly coupled, tensegrity structures exhibit strict topological rules while offering significant flexibility in geometric forms. This inherent flexibility fosters design versatility and expressive formal possibilities, making it an ideal candidate for improvisational structural design.

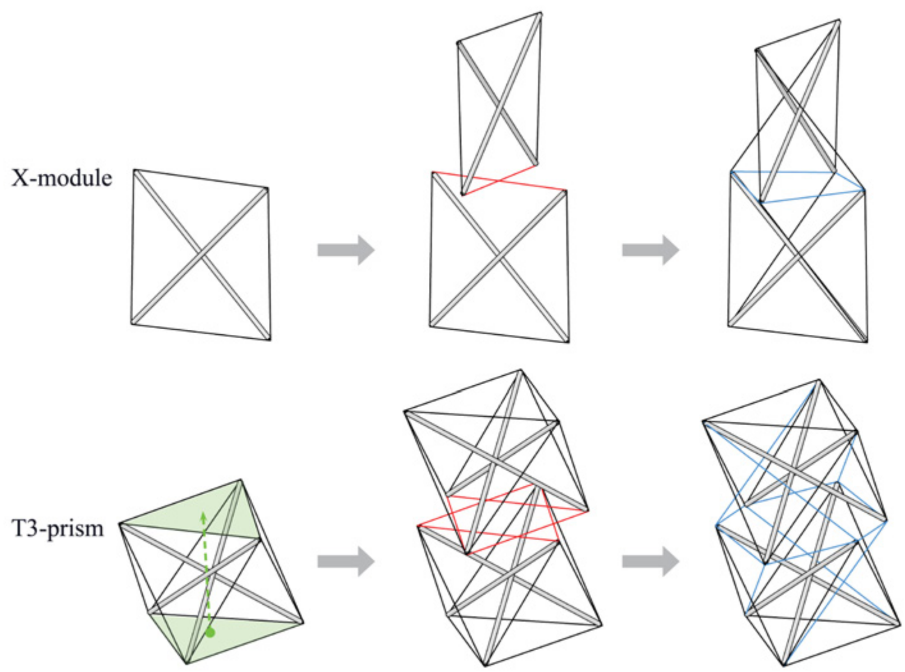
This paper focuses on two tensegrity unit types: the X-module, originating from Kenneth Snelson's X-piece sculpture of 1948[286,287], and the T3-prism, the simplest prismatic tensegrity structure in 3D[288]. T3-prism also finds its root in Snelson's patented design, the three-way tower[289].

The assembly of a tensegrity structure is intricate. It typically involves a large team of human constructors holding elements until stability is achieved, as evidenced by projects like the MOOM Pavilion[290] and Snelson's Soft Landing installation[291]. There are a handful of robotic assembly processes developed for pre-defined tensegrity structures. Vasey et al. describe a process that "utilizes the human's dexterity and the robot's precision" to collaboratively fabricate pre-designed tensegrity units to form a large-scale structure[292,293?]. Nurimbetov et al. present a motion-planning strategy for robotic tensegrity assembly of a T3-prism unit with inverse kinematics[294]. To the best of the authors' knowledge, our research paper marks the first endeavor in the field to improvise the design-fabrication of a tensegrity structure through collaboration between robots and humans.

8.3 Methods

8.3.1 Material System and Gripper Design

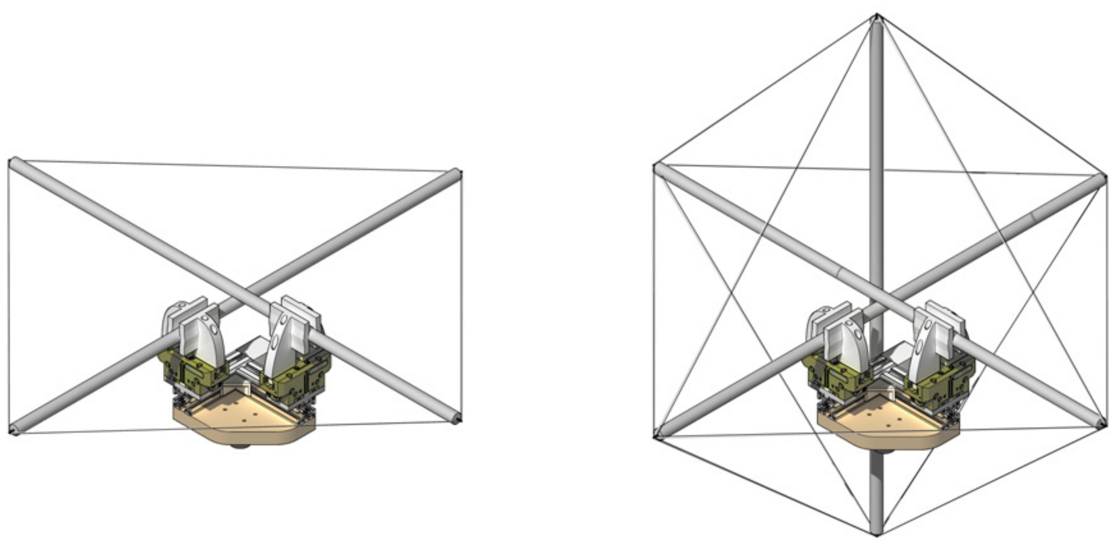
Figure 8.1: Tensegrity modules and their aggregations: X-module and T3-prism



The tensegrity experiments covered in this paper consist of two unit types: X-module and T3-prism (Fig. 8.1). These units are individually stable but can also be combined. Once aggregated with additional tendons (marked in blue in Fig. 8.1), strategically removing selected tendons that support the original units (indicated in red in Fig. 8.1) reduces the redundancy of tension members in the combined structure. To facilitate this process, we employ two different materials for tendons. Nylon strings are used as temporary placeholders to indicate segments that can be removed after unit aggregation. Meanwhile, stainless steel ropes with diameters ranging from 1 to 1.5mm serve as the more permanent tension members. The struts in the experiments are made of wooden rods with diameters ranging from 20-28mm. One screw is drilled into each end of the strut with the stainless-steel rope wound around it to provide tension. Aluminum crip sleeves and tensioners are used to secure the tendons in place.

The customized end-effector we have designed (Fig. 8.2) is a pneumatic gripper-based tool engineered for handling X-module and T3-prism tensegrity units. The gripper features a unique perpendicularly positioned dual-jaw design with 3D-printed custom-shaped fingers that conform to rods of 24±4mm diameters. This perpendicular position is achieved by mounting two SCHUNK JGP 100-1 grippers onto an L-shaped aluminum profile, which is then affixed to the ABB IRB 2600 robot with a customized hardwood plate. A camera is mounted onto the L-shaped aluminum for 2D visual feedback. The control system utilizes computer vision algorithms to coordinate the robotic arm's movements (see details in Section 8.3.2).

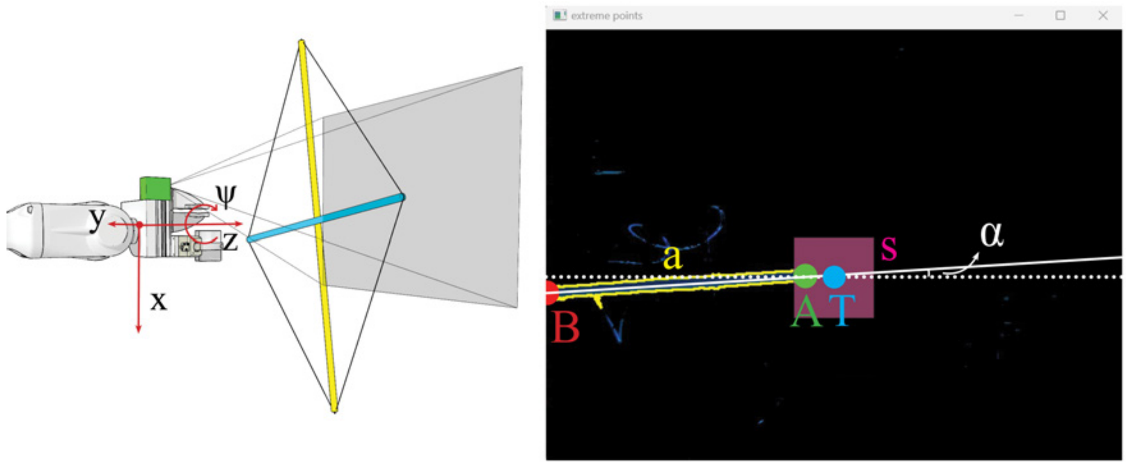
Figure 8.2: Customized end effectors holding X-module and T3-prism tensegrity units



8.3.2 Visual Servoing

In the context of extending a tensegrity structure, knowledge of the location and orientation of a single rod at a specific topological position of an X-module or T3-prism unit can be sufficient to inform subsequent decisions. We mark these key struts in blue for ease of sensing and identification. The programs are written in Python using the OpenCV[295] library for computer vision and COMPAS RRC[296]

Figure 8.3: Key parameters for visual servoing



for robot movements. In order to balance context awareness and information overload, we process and analyze only the 2D visual data to track and inform the robot's relative positions to the key strut.

Calibration of the servoing system happens once at the beginning of the construction for each robot, given that the lighting conditions of the construction site don't undergo drastic changes. To calibrate the system, the human operator needs to manually guide the robotic arm to a preferred relative position to the key strut for future reference. For example, in this paper, the calibrated relative location is for the robot to face the right-most end of a strut at roughly 35cm away in -z direction of the tool-center point (TCP) coordinate system (Fig. 8.3, left), with the strut appearing entirely horizontal in the camera's view. We document the area of the key strut, denoted as a0, and the coordinates for the right-most strut end in the camera frame as point T. To create a target region s in the camera frame for tracking future key struts (Fig. 8.3, right), we assign a buffer distance of p for the horizontal direction and q for the vertical direction, resulting in a $2p \times 2q$ rectangle s centered at T. Additionally, we define the upper and lower bounds of the HSV color range for the key strut's color (in this case, blue) as it appears in the camera for color filtering.

With this information on hand, we can initiate the visual servoing process to track the key struts (in blue). This process begins with either manually positioning the robotic arm approximately 1m away from the existing structure or directing the robot to move back 0.5m in -z direction (TCP, Fig. 8.3, left) from its last building frame. These distances are relative to the scale of the building units. The main goal is to ensure the robotic arm has a clear view of the existing structure and sufficient space for location adjustments.

We isolate the struts of interest by employing a color filter with the preset HSV bounds. By selecting the region with the maximum area from the filtered regions, we focus exclusively on the nearest key strut. Our process begins by evaluating whether the right end of the key strut, denoted as point A (Fig. 8.3, right), falls within the designated regions. If it does not, the robotic arm makes a 1-step adjustment in the ±x and/or ±y direction (Fig. 8.3, left) to approach T in the next time frame, t+1. If point A is within region s, the program proceeds to assess angle alignment, which is to minimize α (the angular difference between the strut segment AB and the horizontal direction in the camera frame, Fig. 8.3, right). This is achieved by adjusting the value ψ (rotation around z-axis, Fig. 8.3, left). In the z direction, distance is estimated using the area of the closest strut, a (Fig. 8.3, right). $\Delta a = a - a0$ informs the displacement in z at the upcoming time frame. This method does not consider the rotation of the blue strut around the yellow strut for simplicity.

Through the iterative application of the steps above, α, Δa, and distance(T, A) are gradually reduced to a preset tolerance (e.g., buffer p, q) over time. This process can be adapted to moving targets, allowing the robot to actively track a strut in a human's hand. Eventually, the program exits the loop when the robot reaches the same relative location to the key strut as defined during calibration. This relative location forms the basis for any forthcoming robotic movements, whether it's proposing the next building frame or retrieving the key strut of interest from a human's hand (Sections 8.4.1 and 8.4.2).

8.3.3 Design Influencers: Human, Robot, and Environment

Even though tensegrity structures have specific topological rules (Fig. 8.1), there remains significant room for design freedom, with human, robot, and environmental factors collectively shaping the ultimate form of the structure. In Experiment II (Section 8.4.2), for instance, robots are entrusted with the autonomy to define two perpendicular struts within a T3-prism module (in blue and yellow), while humans dictate the placement of the third strut (in orange). Moreover, each robot can be programmed with distinct "design characters" (Fig. 8.7, right), resulting in a multitude of design proposals. Furthermore, the environment itself is preconfigured with a vector heat map (Fig. 8.7, left), exerting influence over each frame within the spatial context. The precise implementation of these influential factors will be expounded upon in Experiment II in Section 8.4.2.

8.3.4 Human-Robot Interaction

Multiple means of human-robot interaction are integrated into the experiments:

- Vision: Robots, with cameras and computer vision systems, can react to building elements within existing structures and to humans holding construction units.
- Audio: Human operators receive real-time updates about the robots' status through audio cues played via a laptop speaker, informing them of the robots' actions and providing instructions, such as "Please feed rods into the gripper."
- Direct Physical Contact: Using computer vision, robots can physically interact with building elements, directly grasping them from a human's hand when instructed. This collaborative potential enhances design interaction; for example, in constructing tensegrity structures, humans can summon a robot for on-the-spot assistance.

8.4 Experiments

Two experiments in this paper explore building tensegrity structures with various complexities, including variations in geometry, agency distribution, and collaboration modes between humans and robots. To enhance clarity, a color-coding system was employed for the wooden struts: pink for the initial seed strut, blue for key struts guiding robotic actions, yellow for neutral struts aiding in forming X-modules with blue struts, and orange for manually placed struts by humans.

8.4.1 Experiment I: Stigmergic Construction of an X-module Tensegrity Structure

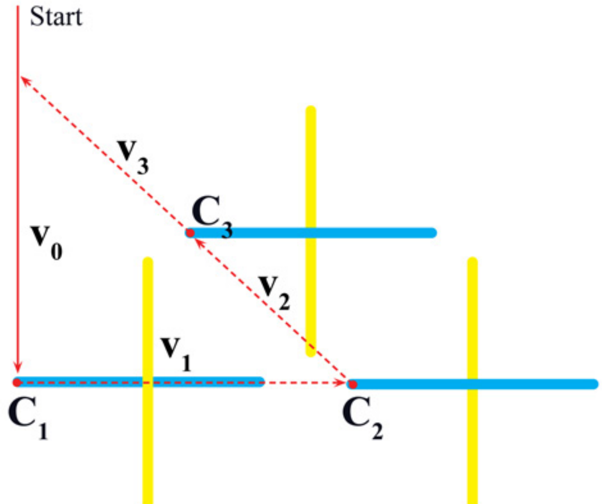
Experiment I drew inspiration from Kenneth Snelson's "Self-Portrait" in Pendleton, Oregon, in 1948. Experiment I explores the flexibility of construction sequences involving both humans and robots.

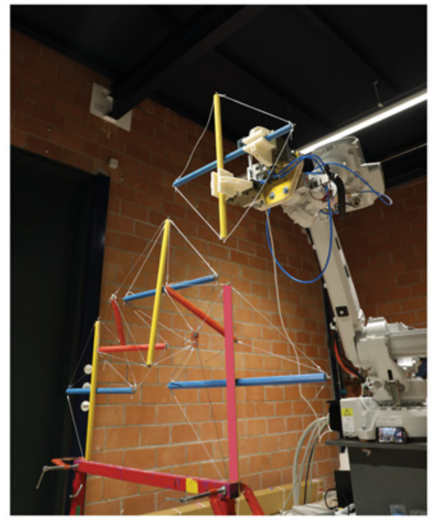
This investigation relied on a stigmergic logic (see Section 8.2.2) applied to a thick vertical 2D structure. Within this framework, robots exhibit adaptive responses to existing structures and adjust to tolerate local inaccuracies.

The construction of this structure only requires the robot to execute a simple program repeatedly for the placement of each new unit. Initially, the camera undergoes calibration following the procedure in Section 3.2, with reference to one end of the blue strut in an X-module unit. Additionally, three predefined vectors, namely v1, v2, and v3, guide the robot in searching for struts within the general regions around C1, C2, and C3 (Fig. 8.4). At the beginning of the program, the robot starts from one preset point (Fig. 8.4) and moves downwards following direction v0. While in motion, the robot scans for the presence of a blue key strut. Upon detecting a key strut, the robot fine-tunes the end-effector's location to align precisely with the strut's position (Section 8.3.2). The robot then checks regions C2 and C3. If a key strut is not detected, the robot places a new X-module unit at that location. If both C2 and C3 are occupied, the robot places a new strut unit at a displacement of v3 from C3. While the robot securely holds the X-module unit in place, the human builder inserts the connection rods (in orange) in the diagonal direction. The human also removes temporary nylon ropes and connects new steel cables according to the topological relationship illustrated in Fig. 8.1. Since the robot consistently fine-tunes its position in response to the presence of a key strut in the area of interest (e.g., C1, C2, C3), this process enables the robot to efficiently adapt to any deformations or minor changes in the existing structure, whether they result from material tolerance, human inaccuracies, or purposeful design intentions.

Stigmergic construction exhibits robustness against external disruptions. For example, if a human inserts a new X-module, it will not adversely impact the robot's subsequent actions. The robot will proceed to add new pieces to the structure. This enhances design flexibility; for instance, humans can intentionally extend the structure in a particular direction, which the robot will seamlessly adapt to as structural tolerance.

Figure 8.4: Stigmergic construction for X-module tensegrity structure





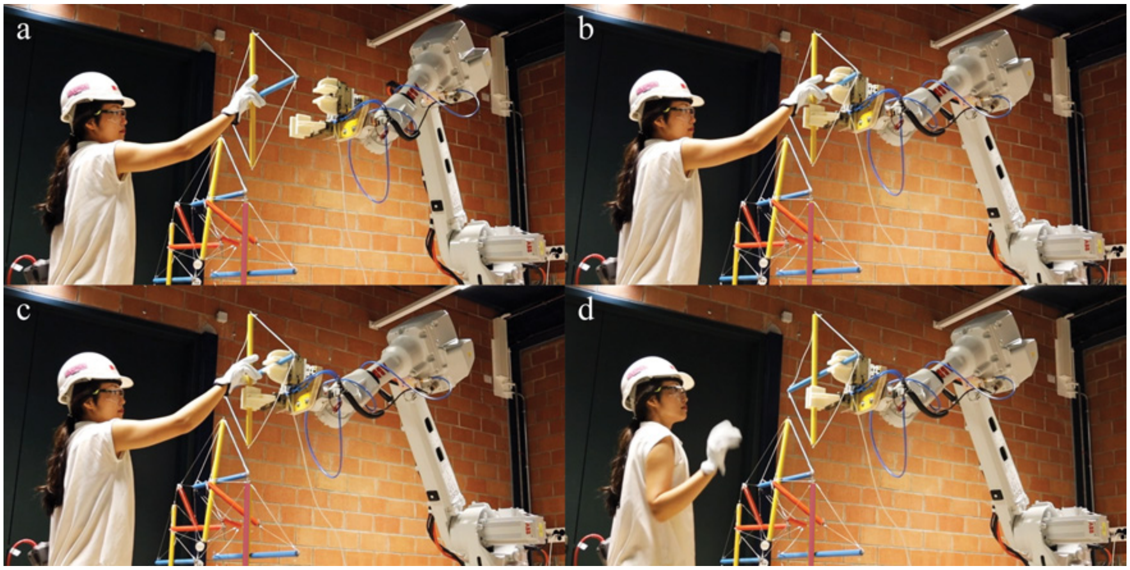
Handover

In the same setting, we also test out an additional function that asks the robot to take a building unit from a human's hand and hold it in place. This "handover" mode entails the robot tracking, approaching, and grasping the key strut of interest (Fig. 8.5), after which it maintains the unit in position for the humans to work on. By occasionally employing the handover function within the context of stigmergic construction, humans can introduce design interventions not only through the placement of orange connectors but also by directly positioning the blue-yellow struts with the robot's assistance.

8.4.2 Experiment II: T3-prism Tensegrity with Multiple Design Influences

Experiment II extends the design space from regular thick vertical 2D into irregular 3D tensegrity. The general goal is to build a cantilevering T3-prism tower (refer to Fig. 8.1 for T3-prism connection logic). Unlike a conventional T3-prism tower with uniformly sized components and consistent rotation angles between stacking units, Experiment II grants the robot autonomy to determine the orientation of two struts while allowing human placement of one strut within each T3-prism unit. On a high level, Robots 1 and 2 take turns extending the structure from the central seed unit towards opposite sides. They locate the nearest blue key strut, propose a relative displacement, and suspend two out of three

Figure 8.5: Hand over a building unit to a robot. a) The robot detects the unit. b) The robot approaches the unit. c) Grippers close. d) The robot holds the unit in place.



struts (blue and yellow) in mid-air within a T3-prism unit. The human then inserts an orange strut at their preferred location and orientation to complete the unit and connects tendons to integrate the new unit into the existing structure, following the logic in Section 3.1 (Fig. 8.1).

The experiment setting involves two ABB IRB 2600 industrial robotic arms positioned 3 meters apart, facing each other on elevated platforms 0.725 meters high. The pink seed strut is 2.4m tall with a 28mm radius. It is anchored to a metal block on the ground, positioned equidistant between the two robots. Along with two additional struts (including one blue key strut), the pink strut forms the seed T-3 prism unit. The two robotic arms initiate the design process by utilizing this seed unit as a reference point for sensing and generating proposals for the placement of new units.

To start the building process, each robot first locates and fine-tunes its end effector's position in reference to the blue key strut of the last placed module using the method in Section 3.2. Once the key strut is located, the robotic arms advance toward a new frame. This frame is the result of three vectors, namely:

1. **A constant vector** addressing topological requirements, predetermined according to the height of a typical unit when uniformly stacked. This vector originates from the centroid of the bottom triangles and extends to that of the top triangles, highlighted in green in Figure 8.1.

Figure 8.6: Human designer connecting steel cables

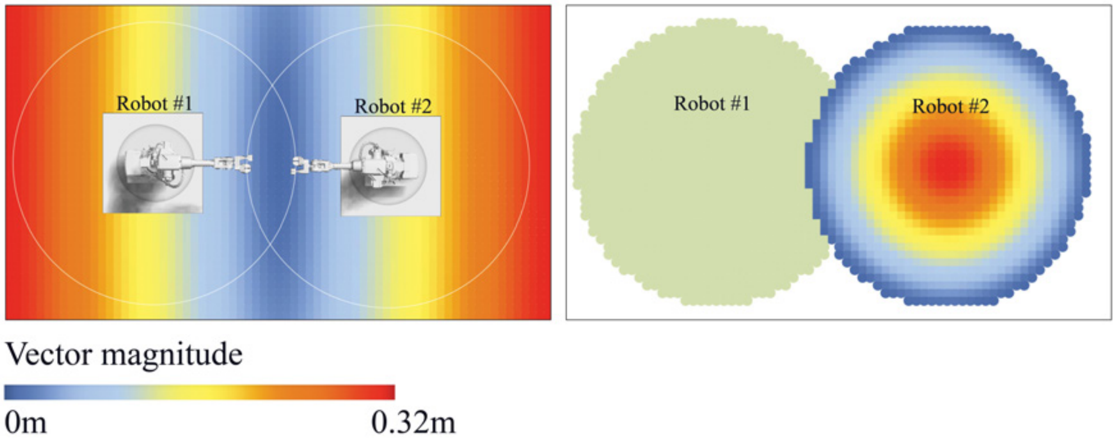
2. **An environmental vector** based on the end effector's location within a predefined 3D vector heatmap in the world coordinate system (Fig. 8.7, left). This environmental vector, continuously applied across the entire structure, ensures uniformity of design language. In Experiment II, the heatmap imposes fewer displacements in the central area of the site, thus aiding in aligning suggestion frames from two robots positioned on opposite sides. This heatmap can be easily adapted in future construction to reflect various design constraints.

3. **A robot preference vector** determined by the gripper's position relative to each individual robot's base frame coordinate system (Fig. 8.7, right). In this case, robot 1 adopts a uniform vector across its reachable zone, while robot 2 employs vectors pointing outward from the robot's base to create more space for movement and reduce the risk of collisions. These preferences, though relatively straightforward in this preliminary experiment, have the potential for enhancement in future iterations, for example, by incorporating visual inputs for more sophisticated design suggestions.

The weight of the three influences can be tuned within the Python program to achieve the desired balance of design influences.

The design fabrication process emphasizes human participation by allowing human constructors to manually insert the third orange strut into the T3-prism unit at their desired position and orientation.

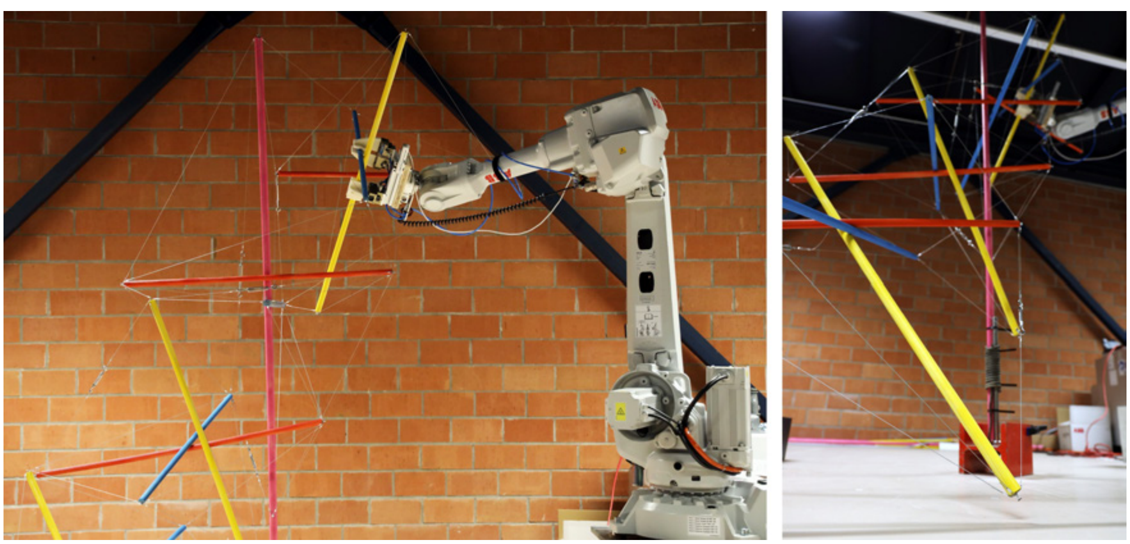
Figure 8.7: Influencing vectors – a horizontal section view. Left: Heat map of the environment vectors. Right: Heat map of the robot preference vectors.



Humans also have the flexibility to adjust the structure by tightening tendons.

In this experiment, a total of two T3-prism units are added by robot 1 and one unit by robot 2, with human involvement in cable connection, detachment, and placement of the orange struts. The resulting structure (Fig. 8.8), measuring 2.5m x 1.6m x 2.5m, exhibits asymmetry due to angular variations and positional adjustments introduced by both humans and robots. Additionally, the system demonstrates a degree of flexibility in accommodating variances in rod radius and length.

Figure 8.8: Spontaneous Tensegrity - Prototype II



8.5 Conclusion and Outlook

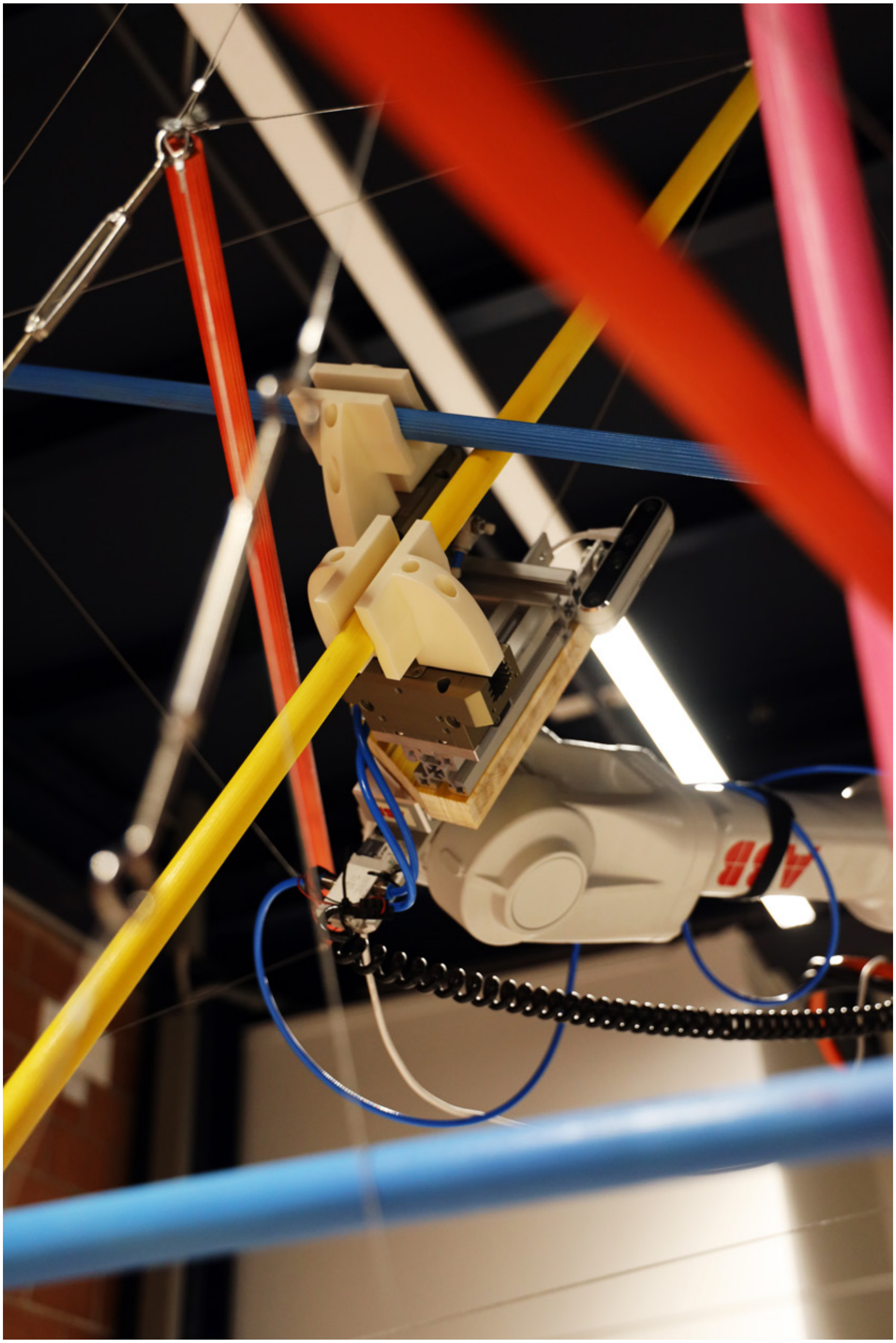
Through two prototypes, this paper introduces novel ways for humans and robots to collaborate in designing and constructing complex tensegrity structures characterized by simplicity in logic rather than precise blueprints for element placement. Experiment I involves creating a thick vertical 2D tensegrity structure comprising X-modules, following a stigmergic logic, allowing room for human-driven variations while ensuring robotic adaptability to changes and sequencing disruptions. Experiment II elevates the agency of both humans and robots in design by constructing a T3-Prism structure, resulting in a blend of environmental, human, and robotic influences. Overall, this paper presents human-in-the-loop improvisational design and fabrication techniques specific to tensegrity structures alongside a novel end effector design and visual servoing methods for robotic arms, supported by preliminary proof-of-concept prototypes.

The current methods exhibit several limitations. As the robots only track selective local information (e.g., the nearest blue key struts) and lack an internal model of the existing structure, their proposed building frames do not consider the structural performance of the entire structure. Thus, human judgment is required to determine the viability of robot proposals. Despite Experiment II demonstrating humans and robots creating an irregular T3-prism tower, adherence to strict topological relationships persists. In experiment II, the structure quickly reaches its limits, as evidenced by the second unit proposed by Robot 2 nearly touching the ground and tilting at an angle that precludes adding another unit. Despite the prototypes laying the groundwork for integrating robot information into the design-fabrication process alongside human choices, there is a need for enhancements to enable robots to generate proposals that better consider surrounding obstacles and their own reachability constraints.

Looking forward, we envisage several potential advancements:

- The development of a computationally inexpensive structural simulator utilizing existing key strut data to enhance predictions of structural performance and limitations;
- The integration of a more context-aware environmental and robotic preference vector, for example, vector displacements in response to visual inputs instead of pre-defined heat maps;

Figure 8.9: Spontaneous Tensegrity - Prototype II, Detailed View



- The potential development of a secondary mobile robot to adjust tension cables within the constructed structure. Given the directional nature of tensegrity aggregation, these minor adjustments can facilitate the extension of the structure in specific directions.

Chapter IV Design Agency, Communication, and Intelligence

Chapter Overview

This chapter of the dissertation delves into topics of ambiguity and agency in human-robot interaction (HRI). Section 9 expands on the interaction between humans and construction robots by developing a large language model (LLM)-enabled HRI workflow. This approach focuses on the collaborative design and assembly of tensegrity structures using ABB robotic arms. Leveraging OpenAI's GPT model, robots respond to verbal commands from human operators to position building elements. Prompt engineering techniques, such as step-by-step instructions and few-shot examples, are used to update robot movement parameters, achieving an average accuracy rate of 92.31% from text command to code update. This LLM-driven approach offers several advantages:

- Lowering the technical barrier for robotic construction
- Freeing up the operator's hand during assembly
- Providing more precise control compared to traditional jogging methods with a teach pendant
- Enabling the robots to also interpret vague and ambiguous languages
- Enhancing adaptability in construction workflows
- Making the design-fabrication experiences with robots more fun and engaging for human operators

However, significant drawbacks remain within such an LLM-enalbed HRI workflow, including:

- Lack of accuracy guarantee
- AI's limited ability to handle complex tasks
- Safety concerns
- Energy and monetary costs associated with AI implementation

Section 10 further expands robots' roles from being design collaborators or assistants on physical tasks into an integral part of the environment. In this section, *Rhythm Bots*, a custom-designed swarm robotic system, position themselves as active agents that shape the spatial and multi-sensory experiences together with human participants in real-time. Grounded in the research on collective behaviors, Section 10 describes the development of *Rhythm Bots*' body structures and their digital twins. *Rhythm Bots* serve not only as an art installation but also as a research platform for the Nonlinear Opinion Dynamics (NOD) model[22]. Rather than constructing fixed forms, robots influence and redefine the space through coordinated movements.

The sections in this chapter include adaptations from the following papers:

Han IX and Parascho S. From Words to Actions: A Large Language Model (LLM) Approach forHuman-Robot Interaction in Design-Fabrication Settings. The *29th Annual Conference for Computer-Aided Architectural Design Research in Asia, CAADRIA 2025*. Tokyo, Japan. Conference Proceedings. 2024 March 26.

Leonard NE, Cox J, Trueman D, Santos M, Wantlin K, Han IX, Witzman S, James T. *Rhythm Bots* (2024): A Sensitive Improvisational Environment. The 38th Annual Conference on Neural Information Processing Systems, NeurIPS, Creative-AI Track. Vancouver, Canada. 2024.

9

From Words to Actions: A Large Language model (LLM) Approach for Human-Robot Interaction in Design-Fabrication Settings

This section of the dissertation has been adapted from the following publication:

Han IX and Parascho S. From Words to Actions: A Large Language Model (LLM) Approach for Human-Robot Interaction in Design-Fabrication Settings. The *29th Annual Conference for Computer-Aided Architectural Design Research in Asia, CAADRIA 2025*. Tokyo, Japan. Conference Proceedings. 2024 March 26.

Overview

With recent advancements in Large Language Models (LLMs), workflows have emerged to integrate LLMs into Human-Robot Interaction (HRI), enabling more intuitive robotic manipulation. This paper investigates LLM-enabled HRI in a design-fabrication context, focusing on collaborative design and assembly of tensegrity structures with ABB robotic arms. Using OpenAI's GPT model, robots interact with human operators through verbal commands to position building elements. Prompt engineering techniques, including step-by-step instructions and few-shot examples, are employed to update robot movement parameters, achieving an average accuracy rate of 92.31% from text command to code update. Challenges observed during implementation include reduced audio-to-text accuracy due to construction site noise, an additional 0.6–0.7s response time per AI request, and inconsistent accuracy influenced by task complexity. To address safety concerns, AI reiteration for human confirmation is incorporated before task execution. Despite these challenges, LLM-enabled workflows offer advantages, such as freeing one hand during operation for human users, reduced technical barriers, adaptability for customized tasks, and greater precision than traditional pendant controls. This study provides valuable insights into optimizing LLM-enabled design-fabrication workflows for construction applications, highlighting both the potential and limitations of natural language robotic control in enhancing human-robot collaboration.

9.1 Introduction

With the advancement of robotic technology, the role of robots in construction has evolved from automation in assembly to a more interactive and assistive collaborator for human builders. This role shift highlights the growing importance of designing effective human-robot interaction (HRI) within the design-fabrication process, where robots and humans work collaboratively[230,21,297]. Recent breakthroughs in artificial intelligence (AI), particularly with the transformer model in Large Language Models (LLMs)[298], have enhanced communication between humans and robots, positioning LLMs as a promising tool for improving HRI.

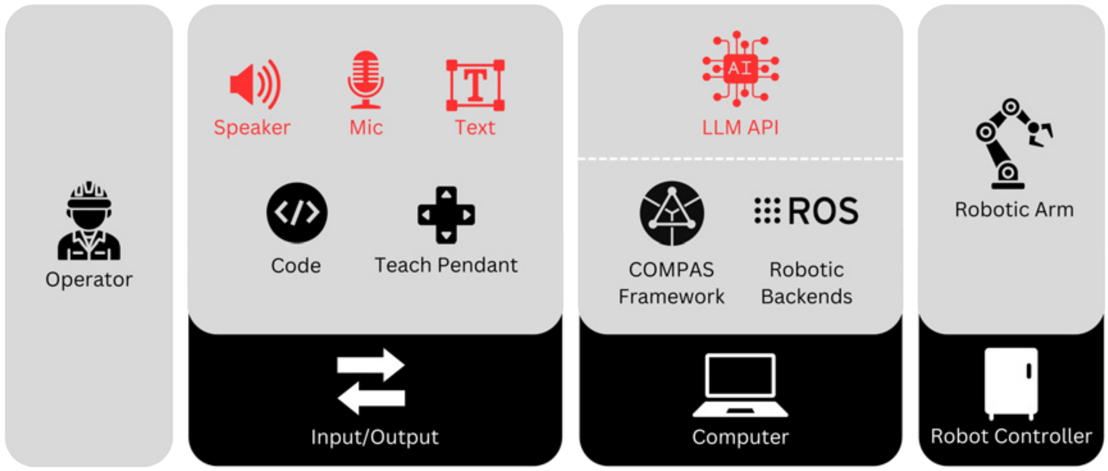
This paper explores the potential of LLMs to facilitate HRI in collective human-robot construction, using a case study on collaborative tensegrity structure assembly. It details the development of a functional LLM-enabled HRI workflow with ABB robotic arms, its implementation in construction environments, and prompt engineering techniques to enhance performance. The paper also evaluates performance parameters, including average execution speed, cost, and accuracy rates, offering valuable insights into the challenges and opportunities of LLM-enabled HRI in design fabrication.

9.2 Related Work

9.2.1 Collective Human-Robot Construction

Collective Human-Robot Construction (CHRC) is an emerging field that combines collective robotic construction with HRI[230]. Unlike conventional robotic workflows with pre-programmed assembly sequences for finalized designs, CHRC leverages human-robot interaction to reveal the design space during fabrication. This improvisational approach merges human decisions and robot agency, resulting in structures that embody co-intelligence and co-creativity. Notable examples of such design workflows include Improv-Structure[280], Spontaneous Tensegrity[299], Tie-a-Knot[281], and Prototype as Artefact[61]. This project situates itself under the field of CHRC and explores how LLMs can facilitate design-fabrication processes within such collaborative frameworks.

Figure 9.1: Workflow Diagram



9.2.2 Large Language Models in Design Fabrication

The transformer model[298] has recently propelled LLMs to achieve human-level performance on various tasks[300]. In architectural design, Li et al. leveraged a pre-trained LLM to generate floor plan diagrams from natural language descriptions, yielding results comparable to human designers[301]. In construction, Kim et al. proposed an LLM-based robot task planning framework incorporating natural language inputs from building information models (BIMs), construction schedules, robot task specifications, and onsite instructions[302]. Additionally, prompt engineering for ChatGPT has been experimented with to interface with BIMs for more effective and versatile information searches[303].

Several recent projects have realized the implementation of LLMs on industrial robotic arms. Dimitropoulos et al. validated the effectiveness of an LLM-enabled HRI approach in a case study involving a UR-10 robot assembling induction kitchen hobs with a human operator, using GPT-3.5-turbo without fine-tuning and achieving results comparable to fine-tuned models[304]. Building on this, our paper explores LLM-enabled HRI with a focus on prompt engineering and user experience design tailored for collective human-robot construction applications.

9.3 Methodology

9.3.1 HRI Models

In conventional robotic fabrication, human operators interact with robotic arms through either: 1) teach pendants for direct control, or 2) computer programs. This paper explores novel interaction methods using natural language via text and audio (Fig. 9.1). The workflow involves the following transformations between audio, text, and code:

Text-to-Audio

Text-to-audio enables the robot to "speak," facilitating intuitive communication with human operators. This project employs OpenAI API's speech endpoint[305], derived from the TTS (text-to-speech) model. When the text-to-audio function is invoked, a temporary .mp3 file is generated at a designated location, which is then played aloud via the Playsound package[306].

Audio-to-Text

Audio-to-text transcribes human speech into text for further processing. Testing of OpenAI API's large-v2 Whisper model[305] reveals that local computer processing is faster and sufficient. Thus, the voice typing feature in Windows 11, powered by Azure Speech Services[307], is chosen for this project.

Text-to-Code

Text-to-code converts natural language into executable code for robot control, a task well-suited to LLMs. We chose OpenAI's GPT-3.5-turbo model[305] due to its ease of implementation, affordability, capacity, and speed.

Prompt engineering and fine-tuning are two common approaches for adapting an existing LLM to specific tasks. Prompts refer to input queries provided to the LLM, typically limited to a few thousand words. Prompt engineering refers to "the process of designing and refining input queries, or 'prompts,' to elicit desired responses from Large Language Models (LLMs)"[308]. Fine-tuning, by contrast, requires additional task-specific data, making it more resource-intensive. In Dimitropoulos et al.'s paper[304], they mentioned that prompt engineering alone is enough to achieve comparable results as a fine-tuned model for LLM-enabled HRI tasks. Following this, we employed prompt engineering with the GPT-3.5-turbo model, which successfully met project goals.

While LLMs can directly generate code, the output can have errors and bugs[309]. This poses significant risks in HRI scenarios, where safety is critical, as faulty code could endanger human operators. To address this, we propose:

- LLM-Generated Parameters: LLMs to set customized parameters, such as the distance and direction for robot movement before triggering the displacement.
- LLM-Triggered Functions: Use LLMs to call pre-written functions, such as activating a robotic arm to 3D scan objects along a designated path.

The LLM-generated outputs are converted into executable code and sent to ABB robots using online control via COMPAS RRC[310].

9.3.2 Design Considerations

Completion for Robots vs. Humans

When designing the interaction between LLMs, robots, and humans, it is important that the LLM-generated outputs or "completions" for robots remain stable and accurate for functionality and safety, while the completions for humans should vary to create an engaging and interactive experience.

To achieve this, we employed two methods: 1) modifying the prompt to incorporate the corresponding instructions, and 2) adjusting the LLM's "temperature" parameter, which controls response variation. For robots, we set the temperature to 0 to eliminate variation and ensure stability. For human interactions, we set the temperature to the default value of 1, allowing for creative and dynamic responses.

Voice Choice for the Robots

When assigning voices to robots, two key questions arise: which voice to choose and why, and whether to use the same or different voices for multiple robots.

While people may have drastically different ideas of what a robot should sound like, we want to emphasize several considerations. For safety, the voice must be clear and articulate to ensure accurate communication. The voice should also be comfortable for operators to work alongside, and it is essential to avoid voices that may consciously or unconsciously reinforce biases.

In living creatures, voice is a significant aspect of identity. Similarly, commercial AI products like Siri or Alexa often use a single, uniform voice. However, in heterogeneous robotic teams, where robots may have different functions despite being the same model, distinct voices can help humans differentiate the robots, enhancing clarity and reducing errors. In our case study, we assigned two distinct voices to two robots to facilitate this differentiation.

Reiteration and Confirmation for Safety

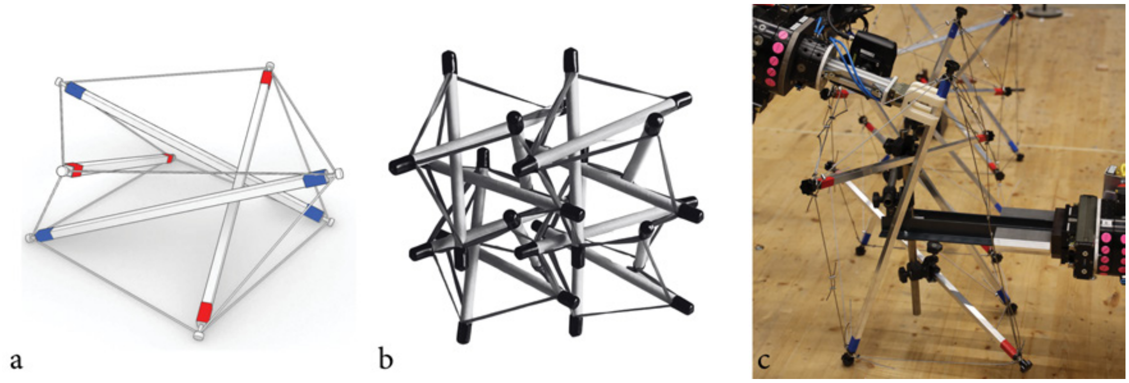
To enhance accuracy and safety, we added two extra steps between a human command and the corresponding robot execution. First, the robot verbally reiterates the request. Then, the human confirms the command by pressing a physical button. These steps enhance transparency, helping the human operator better understand the robot's state and catch potential errors.

9.4 Case Study: LLM-Enabled HRI for Tensegrity Assembly

We formulated a multi-agent system comprising two ABB IRB 6700 robotic arms on track and a human operator, who alternately places new tensegrity struts. This workflow followed an improvisational approach, rather than a pre-defined blueprint, where both humans and robots observe the evolving structure, via human vision or the robot's 3D scan, and make on-the-fly design decisions during construction.

We selected the T-4 Prismatic (T-4 Prism) tensegrity unit as a base topology, which can be aggregated

Figure 9.2: a) T-4 Prism Tensegrity Unit, b) T-4 Prism Lattice, c) Robot 2 (left) with a scanner places blue struts, while Robot 1 (right) with long fingers assists in positioning red struts.



in two directions (Fig. 9.2-b). For each new T-4 Prism unit, the first two struts are placed by the human operator, who verbally instructs Robot 1 (the assistant robot). Robot 2 then scans the workspace using a 3D Zivid Scanner, reconstructs an abstract representation of the existing structure, and proposes the next two strut placements to complete the unit (Fig. 9.2-c). Despite both robots being the same model, their distinct roles and programs make them functionally heterogeneous. This paper focuses on the design and evaluation of HRI with Robot 1.

9.4.1 Text-to-Code Accuracy

This case study enables Robot 1 to make linear adjustments based on natural language commands from a human operator, assuming the operator faces the robot with the X-axis to the right, Y-axis forward, and Z-axis upward. While this setup is specific, the AI can be re-prompted to adapt to other settings. The goal is for the AI to process commands, from simple ones like "Move up a little bit" to more complex ones such as "Lower by 0.1 m, shift right by 0.2 m, and move closer by 10 cm," returning a completion in the format "delta_x, delta_y, delta_z = a, b, c" for precise displacements. The temperature is set to 0 to ensure no variation in the output (Section 9.3.2), which is then directly converted into code to update the robot's movement parameters.

Two key prompting techniques are used: step-by-step instructions and few-shot examples. The complete code and prompts can be accessed on GitHub[311]. A brief summary of the key instructional steps is provided below:

- Convert units based on specified rules.
- Convert units based on specified rules.
- Use a default unit, e.g., millimeter, if no unit is specified.
- Define values for vague terms like "a little bit" or "slightly."
- Ensure no movement for commands lacking meaningful instructions.
- Accurately interpret X, Y, and Z directional inputs.
- Clearly specify the output format.
- Apply magnitude and direction separately for multi-directional commands.
- Eliminate any unwanted characters, such as semicolons and quote marks.

Eleven example commands are provided in the prompt to cover a range of cases, from single- to multi-axis instructions, vague to explicit terms, and scenarios with or without unit conversions. The refined prompt uses 1,239 tokens, with a 24-token completion. Each instruction costs $0.0019 and takes 0.6 seconds with GPT-3.5-Turbo.

We tested the prompt on 130 sample commands: 40 single-axis instructions, 40 two-axis, 40 three-axis, and 10 irrelevant inputs (Fig. 9.3). Each category is further subdivided to test varying complexities: 1) Default unit without direct mention of axes, 2) Other units without direct mention of axes, 3) Default unit with axes explicitly mentioned, and 4) Other units with axes explicitly mentioned.

The overall accuracy in translating natural language commands to correct robot parameters is 92.3%. The model achieves 100% accuracy for single-axis movements, commands with explicit axes, and ignoring irrelevant inputs. While it handles unit conversions well, performance decreases when multi-axis instructions are combined with unit conversions.

Figure 9.3: Model Performance

AXIS NO.	UNIT	AXIS	EXAMPLE INPUT	ACCURACY RATE
1	mm	Implicit	Lift the arm for 45 mm	10/10
		Explicit	Move along the negative x-axis for 33mm	10/10
	Others	Implicit	Lower the arm down for 2 inches	10/10
		Explicit	Shift along the z-axis for 0.6 m	10/10
2	mm	Implicit	Move up 5 mm and forward 4 mm	10/10
		Explicit	Adjust the position by moving 10 mm along the Y-axis and 35 mm along the Z-axis.	10/10
	Others	Implicit	Shift left 7 centimeters and upward 1 meter	8/10
		Explicit	Displace 50 cm along positive x and 0.3 m along positive y	10/10
3	mm	Implicit	move to the left for 10 mm, upwards for 12 mm, and away for 13 mm	6/10
		Explicit	Move along negative x direction for 10 mm, negative y for 32 mm, and positive z for 69 mm	10/10
	Others	Implicit	shift to the left for 0.2 m, and upwards for 0.1 m, and away for 0.3 m	6/10
		Explicit	Shift in x-axis for 1 ft, negative y for 10 cm, and positive z direction for 0.6 m	10/10
0	N/A	N/A	Stay still	10/10
TOTAL				120/130 (=92.31%)

9.4.2 Audio-to-Text Accuracy at Construction Site

We tested twelve examples (one from each subcategory with meaningful commands from Fig. 9.3) in two noise environments: urban ambient noise at 40 dBA and construction site noise at 80 dBA. The test assesses voice typing[307] accuracy, with success defined by the correct transcription of the human command, including direction and magnitude. At 40 dBA, two critical words were misinterpreted, resulting in an 83.33% (=10/12) success rate. At 80 dBA, seven critical words were incorrect, reducing the success rate to 75% (=9/12).

9.4.3 Reiteration and Confirmation with Human Operators

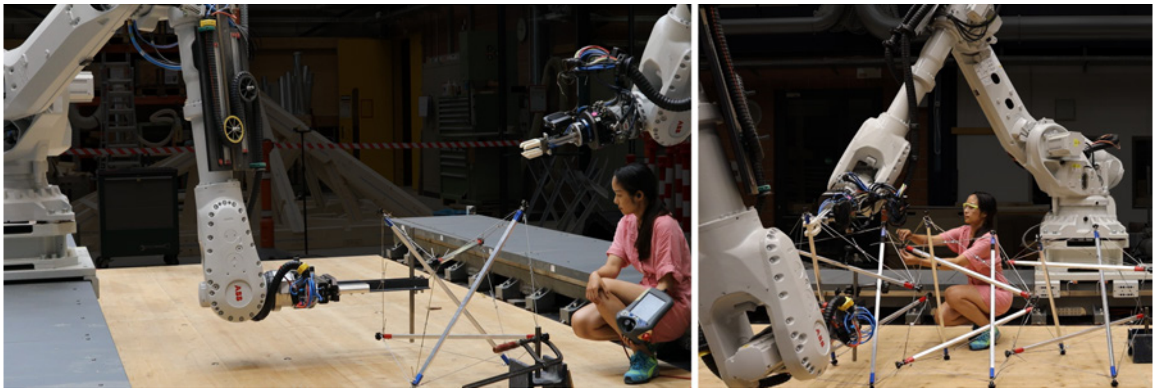
To avoid amplifying the errors between audio-to-text and text-to-code, we highly recommend AI reiteration and physical button confirmation procedures with the human operator to prevent incorrect robot movements. For this function, the LLM is trained to respond in the following structure: 1) reiterate the transcribed audio command, 2) specify the parameter updates, and 3) ask a confirmation question.

As in Section 9.4.1, the LLM is prompted with three-step instructions and two examples. The temperature is set to 1.0 to introduce variety in phrasing, making interactions with the human operator more conversational. The prompt uses 318 tokens, with an average completion of 47 tokens. The average execution time is 0.7 seconds per response, costing $0.00058. In 20 test examples, repeated twice to evaluate performance under varied phrasing, the accuracy rate was 95%.

9.5 Conclusion and Outlook

This paper explores the use of LLMs to enable more intuitive HRI in collective human-robot construction via a case study on improvisational T-4 Prism tensegrity assembly. In this scenario, a human operator verbally instructs the featured robot to place two struts at specified locations for each new T-4 Prism unit (Fig. 9.4). By employing prompt engineering techniques, such as step-by-step instructions and few-shot examples, we achieved an overall text-to-code accuracy rate of 92.31%, with perfect per-

Figure 9.4: a) A human agent interacting with Robot 1 (left) via voice control. b) A human fastening tension cables while robots secure the struts in position.



formance for commands with a single-axis or explicitly defined axis. Accuracy decreased when unit conversions were combined with implicit axis references. Additionally, at 80 dBA construction site noise, audio-to-text accuracy dropped from 83.33% to 75%. To reduce errors, we implemented AI reiteration and physical button confirmation. Based on our findings, we identify the following benefits and drawbacks for LLM-enabled HRI in design fabrication:

9.5.1 Benefits

- Lowering Tech Barrier: LLM-enabled HRI makes robot operation accessible to individuals without a robotic background, enabling intuitive interaction.
- Temporarily Freeing Up the Hands: Verbal commands allow operators to free at least one hand for other tasks.
- Precise Control: Compared to jogging with a teach pendant, verbal control makes it possible to define the movement magnitude precisely.
- Adaptability: AI can be prompted for customized tasks, making it versatile for a range of scenarios.

9.5.2 Drawbacks

- No Guarantee of Results: AI can only provide a most-of-the-time correct answer but cannot guarantee absolute accuracy.
- Limited Handling of Complexity: As shown in Section 4.1, with just prompt engineering, the accuracy of AI declines with more complex commands.
- Safety Concerns: AI inaccuracies can pose safety risks, which we mitigated by adding a human confirmation step before robot execution. However, this process can slow down operations.
- Cost: AI requests incur time, financial, computational, and energy costs, in addition to the need for human and computational resources for testing and refining the model.
- Affected by the Environment: Factors such as background noise, human accent, and voice volume can impact audio-to-text accuracy.

Looking forward, we suggest further research into microphone and speaker hardware options, as well as noise-filtering software, to enhance sound capture and output in noisy environments like construction sites. Additionally, while prompt engineering has yielded functional results in this project, experimenting with fine-tuning LLMs for robotic design-fabrication workflows could potentially improve performance. From an application standpoint, exploring the creative potential of LLMs in conjunction with improvisational design-fabrication settings could yield valuable insights.

10

Rhythm Bots and Their Digital Twins: Swarm Robot Design and Virtual Reality for Improvisational Immersion

This section of the dissertation includes subsections adapted from the following paper:

Leonard NE, Cox J, Trueman D, Santos M, Wantlin K, Han IX, Witzman S, James T. *Rhythm Bots* (2024): A Sensitive Improvisational Environment. The 38th Annual Conference on Neural Information Processing Systems, NeurIPS, Creative-AI Track. Vancouver, Canada. 2024.

10.1 Introduction

Positioned at the intersection of engineering and the arts, the *Rhythm Bots* project has been an interdisciplinary collaboration since 2021. Its goal is to create a collection of kinetic sculptures—rhythmically moving robots that form an immersive, interactive environment capable of influencing audiences in profound and beautiful ways[312]. Inspired by *Rhythm Bath*, Susan Marshall's (Professor of Dance) "dance-installation" that surrounds the audiences with "rhythm—visual, aural, and kinesthetic"[313], the project was conceived by Naomi Leonard (Professor of Mechanical and Aerospace Engineering) as a way to further explore the complexities of group dynamics through robots rather than dancers[312]. Over the years, we have also collaborated with Dan Trueman (Professor of Music) and Jane Cox (Professor of Theater), enriching the project to become even more multi-sensory and immersive.

In this section of my dissertation, I will focus on my contributions to the project, specifically the design and construction of the robot's body and the latest work-in-progress developments in the multi-sensory *Rhythm Bots* experience in virtual reality (VR). Rather than adhering to traditional notions of architectural or environmental design, I'm interested in exploring the integration of swarm robotics as an active, spatial medium. By reframing these autonomous agents as architectural elements rather than discrete objects, the project expands the discourse on spatial design, incorporating dynamic and ephemeral conditions—movement, soundscapes, and light—as fundamental components of environmental composition.

10.2 Related Work

10.2.1 Artistic Inspirations

Rhythm Bot's formal design is inspired by the rich body of prior work by kinetic artists such as Alexander Calder, Panagiotis 'Takis' Vassilakis, Jean Tinguely, and studio DRIFT[314]. Our creative exploration of light - its impact on human behavior and sensory experience - draws on the work of visual artists such as James Turrell, Mary Corse, and Olaffur Eliasson, as well as on a rich theatrical tradition exploring the relationship between changing lighting states and audience responses[314]. Additionally, we reference the immersive and contrasting work of Brian Eno and Pauline Oliveros, along with contemporary sound artists like Camille Norment and Seth Cluett, as key points of reference[314].

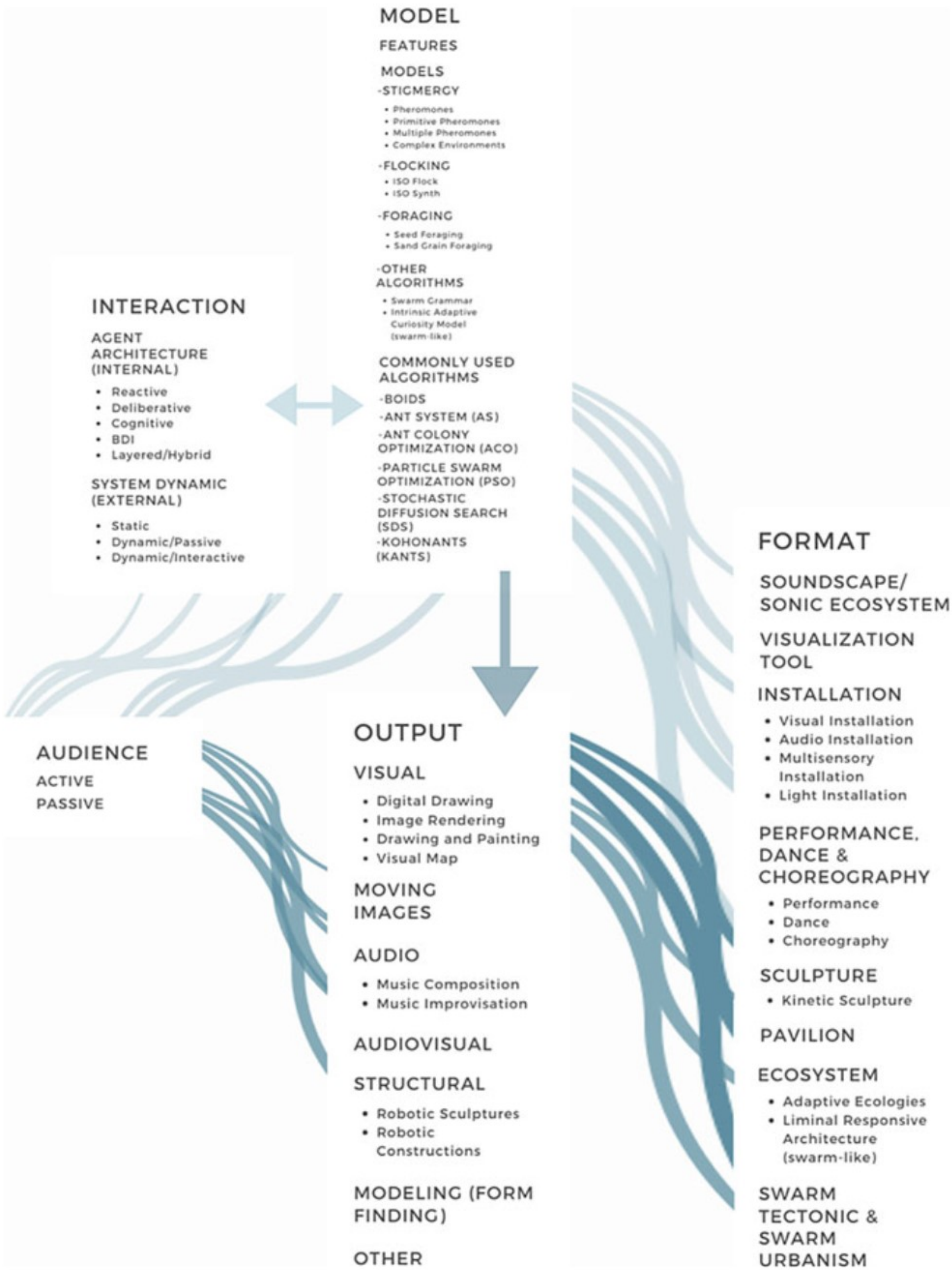
10.2.2 Swarm Systems for the Art and Space Making

In the book "Swarm Systems in Art and Architecture: State of the Art", Mahsoo Salimi reviewed over one hundred swarm-based artworks between 2000 and 2021[315]. In her analysis, she developed a taxonomy of key concepts in the field (Fig. 10.1) and identified four recurring themes[315]:

- Naturalness – The artistic recreation of behaviors and visual patterns that evoke natural systems that are reminiscent of nature[315].
- Interaction – Engagement between audiences and the artwork, often shaped by social principles[315].
- Immersion – Swarm spatial phenomena conveyed through immersive experiences, including perception and potential interaction[315].
- Adaptability – The simulation of swarm interaction's flexibility and responsiveness[315].

Several recent projects operate within a similar research intersection. *I Am Storm*[316] developed by Studio Drift in collaboration with the TextielMuseum – Tilburg draws inspiration from the rhythms

Figure 10.1: Taxonomy of artistic and architectural swarm systems by Mahsoo Salimi [315], 2021, reproduced with permission from SNCSC.

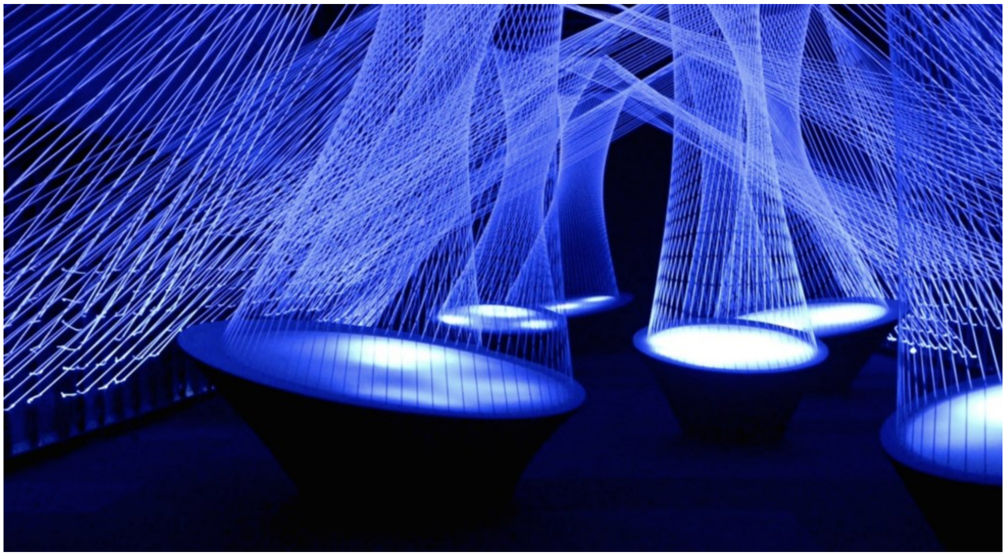


in nature. This installation employs an analogy between grass swaying in the wind and robotic modules responding to human movement. In this interactive environment, the robotic elements represent "grass," while human participants act as the "wind," influencing their motion. The project aims to evoke the feeling of being surrounded by, and responding to, nature"[316], fostering an immersive and responsive experience.

In addition to custom-designed robots, drones represent another widely used method for exploring synchronized movements. For instance, the SwarmGPT-Primitive framework[317] employs a Large Language Model (LLM)-driven choreographer, which can be applied to a multi-agent drone performance team. Similarly, 2047 Apologue[318] showcases a visually striking choreography of 100 synchronized drones, created in collaboration with Ars Electronica Futurelab. Directed by Zhang Yimou, this performance delves into the complex relationship between humans and technology[318,315].

Situating the *Rhythm Bots* project within Salimi's theoretical framework[315], the *Rhythm Bots* project explores synchronized oscillating patterns as an emergent phenomenon. Designed to be both immersive and responsive, the environment consists of a swarm of *Rhythm Bots* that interact with audiences in varying capacities. At times, viewers can actively engage through "triggers" that shape the artwork's behavior, while at other times, they become passive observers of the evolving system. The latest physical realization of *Rhythm Bots*[314], showcased at the Wallace Theater in 2024, employed the nonlinear opinion dynamics (NOD) model[22]. In this implementation, every bot was a decision-maker with three evolving opinion states, each controlling the position of an actuator and activating its associated movement, light, and sound[314]. The output is inherently multi-modal and spatial, creating an engaging and interactive sensory experience. What sets *Rhythm Bots* apart from other swarm-based art installations is its grounding in cutting-edge research into the bottom-up mechanisms that enable animal groups—and neural networks—to act with speed, flexibility, and adaptability in complex, changing contexts[314]. As such, *Rhythm Bots* serves both as an exhibition piece and as a research platform for studying how the dynamics of collectives evolve.

Figure 10.2: *Resonate*[320] © 2014 Knichel and Reckter



10.2.3 Multi-modal Interactive Art Installations

In the physical space, although there are many emerging interactive art projects focusing on sound, movement, and light, there are fewer examples when it comes to multi-modal interactive art.

When sound and light converge, they can produce highly engaging interactive sculptures. One such example is *Resonate*[319,320] (Fig. 10.2), an interactive light and sound installation created as part of a "master course in interior design "Kommunikation im Raum" at the Mainz University of Applied Sciences and emerged from a cooperation with the master study course "Klangkunst-Komposition" of the School of Music at the Johannes Gutenberg University of Mainz[319]". *Resonate* consists of several kilometers of sound strings and seven interactive bodies, where the audience can plug the suspended elastic strings between metal rings with a piezo pickup system to create sound and lighting effects[319,320]. A design aspect that their team was particularly testing is the threshold of noise filtering and the degree of control given to the participants[320]. In the movement segment and human-robot interaction (HRI) design of *Rhythm Bots*, we encountered similar challenges, particularly in determining the frequency and time windows during which humans can trigger responses within the swarm system.

There also exist precedents of multi-modal art installations that involve sound, light, swarm systems, but lack the interaction feedback from humans. For example, *The Day We Left Field* by TUNDRA

Figure 10.3: *The Day We Left Field* by TUNDRA collective[321], photo by Sinitsa Alexsndr, redistributed under CC BY-NC-ND 4.0[322].

collective (Fig. 10.3) is a dynamic art installation featuring 144 square meters of artificial grass suspended from the ceiling. The space is activated by pre-choreographed lighting on the grass, paired with a quadraphonic sound system[321,323].

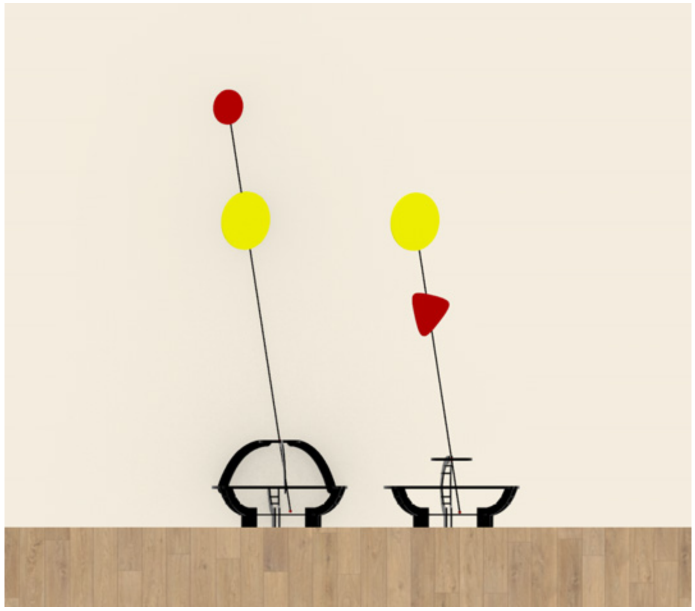
10.3 The Physical: Material choice, Structural Design, and Fabrication

10.3.1 Design Influences

The design of *Rhythm Bots* is strongly inspired by the kinematic sculptures of American artist and sculptor Alexander Calder. For instance, *Rhythm Bots* incorporates elements such as a slender oscillating "torso" and a flat, geometric-shaped "head" in primary colors like shades of yellow and red (Fig. 10.4), reflecting Calder's minimalist and dynamic aesthetic.

The form of the robot base draws from these influences, with key themes of suspension, geometric shapes, and the intersection of 2D shapes. These aesthetic considerations are integrated with engineering perspectives, balancing both form and function. For example, elements are grouped in threes, a formal language drawn from the three actuators. The rotational center of the torso is suspended at a specific height above the actuators, a distance determined through multiple rounds of testing and simulation.

Figure 10.4: A tall version (left) and a short version (right) of the *Rhythm Bots*



Two versions of the frame were created: a short version and a tall version (Fig. 10.4). The primary difference between the two is the height of the rotational center and the method used to support it. The height of this point directly correlates to the maximum weight of the torso that the robot can support, as well as the range of motion of the head. While the cantilevered support method for the short version is visually appealing, the taller robot requires additional structural considerations for stability. Despite these differences in structural design, we decided to maintain both versions to emphasize the diverse character of the robots regardless of their existing in the same swarm.

10.3.2 Material Choice

The material choice of the *Rhythm Bots* was driven by four primary considerations:

- Speed and Cost of Fabrication and Prototyping: Since the *Rhythm Bots* were developed from scratch, the initial versions served both as prototypes and showpieces. While it was important for them to be visually appealing and polished, it was equally crucial to ensure that we could rapidly iterate and prototype when necessary, while keeping time and costs manageable. Medium-density fiberboard (MDF), an industrial wood product made from wood fibers bound together with resin through heat and pressure[324], was chosen for the base frames. A thickness of 1/4" was chosen for its stiffness and ease of cutting with laser cutters. MDF also proved highly suitable for spray testing colors and finishes.

- Structural Limitations: The main structural considerations in this project are stiffness, buckling, and weight. We selected carbon fiber for the thin pole supporting the "torso" due to its high strength, stiffness, and lightweight. Foam core was used to frame the "head," with further carving to reduce weight. Colored vinyl and color-plotted thick poster paper were spray-glued onto the foam core to create the colored "head." Thin color strips were pinned to the sides to conceal the thickness of the foam core frame. However, we observed issues with buckling of the colored material over time, primarily due to the hollow cutouts in the frame for weight reduction. We have tested other lightweight materials for the frame and backing of the colored sheets, such as thin balsa wood, but tests on the short bots revealed insufficient support for the weight of the balsa head.

- Electronics: The dimensions and placement of the electronic components, as well as wire management, were crucial factors in the frame design. The initial design accommodates a Raspberry Pi, drivers, and power cables underneath the base plate near the floor, with wires running to the three actuators through the center of the three base supports.

- Aesthetics: The material finishes, such as matte, hammered, or glossy, were chosen based on aesthetic considerations and how the bots were envisioned in a theater or exhibition setting. These decisions were the result of team discussions and iterative testing.

10.3.3 Fabrication and Assembly

The fabrication and assembly of the initial version of the *Rhythm Bots*'s body frame involves the following steps:

- Laser Cutting: requires approximately sheets of 1/4" thick MDF boards (one 16" x 24" sheet and four 14" x 24" sheets). The cutting files and machine settings are documented in the project's GitHub repository.

- Spray Painting: The interlocking slots in the cutting files are designed specifically to accommodate the thickness of the three layers of spray paint, including one layer of matte black followed by two layers of hammered black.

- Assembly: The assembly process begins by gluing the largest, double-layered ring together using Quick Dry Tacky Glue. The ribs are then assembled without gluing, and everything is hammered into place except for the top ring. For the top ring, the bottom layer is placed first, followed by the top layer, which is secured with three sets of screws and bolts to maintain alignment without using glue. The assembly prioritizes an interlocking method over gluing to facilitate potential part replacement during prototyping.

The assembly of the torso of the bots involves the following steps:

- Coloring: The color scheme of each Rhythm Bot varies according to the design goals. The team collaboratively discusses color distribution, randomization, and hues. Once the exact color assignment is finalized, colors are applied either through pre-printed vinyl or custom printing on thick bonded paper. We tried to reduce repetition in color and shape combinations for each robot to give them distinct characters. Some bots feature identical colors on both sides of the head, while others intentionally differ.

- Shape Frame: The shape frame is constructed from two or three layers of 1/4" foam core. These layers are precision-cut using the ZUND cutting machine, with hollow areas to reduce the overall weight.

- Assembly of the Torso: The foam frame layers are glued together with wood glue, while strong double-sided mounting tape is used to secure the stiff pole to the frame. The bottom portion of the pole is made from carbon fiber for its strength, stiffness, and lightweight properties. To further reduce weight in taller torsos, the top portion of the pole, between the two shapes, is made from lightweight wooden dowels sprayed black. The color shapes are attached to the foam frames with spray adhesive, and the sides of the shapes are covered with color strips pinned to the frame.

The connection between the torso and the frame presents a unique challenge, as the torso must be suspended and allowed freedom for rotation and up-and-down fluctuation. To achieve this, three rubber bands were employed to provide tension force, with each rubber band positioned 120° apart from the others. The bottom end of the pole is inserted into a small metal ring, which is connected to three springs, each linked to the three linear actuators.

10.3.4 Discussions

The *Rhythm Bots* at several events: 1) the IEEE International Conference on Robotics and Automation (ICRA 2022) Workshop on Robotics and Art in Philadelphia, PA, 2) the Lewis Arts Center in 2023, 3) the F-Wing Robotics Lab at Princeton University's Engineering Quad in 2023, and 4) the Wallace Theater at the Lewis Center for the Arts in Princeton, NJ, in 2024. Additionally, the Wallace Theater version was selected for the Creative AI track at the 38th Conference on Neural Information Processing Systems (NeurIPS 2024).

At the first three events, we set up a qualitative feedback board as part of the exhibition, where attendees could anonymously write and hang their responses to the question, "What was the experience with *Rhythm Bots* like for you?" We also collected verbal feedback from visitors at our NeurIPS project table. Common themes that emerged from this feedback include:

- Resemblance to Nature: "Bots sway like blades of grass." "Feels like a robotic forest." "I felt like a plant in the wind!" "I felt like I was in a grassland, where the blades of grass were as tall as me and blowing in the wind" "I enjoyed seeing the robots sway - like grass in savannah" "Moving with the flow like seaweed..."

- Being Present: "The experience reminded me to stay in the moment. Be present. Treasure the 'now'." "It's cool not to be able to put words to everything ... just getting lost in abstraction" "moving...red light, yellow light..." "RYTHMIC"

- Perceived Calmness:v "The bots feel very organic in their motion and had a calming effect on my day." "I feel inspired, empowered, wowed, calmed, relaxed, and most of all impressed." "Very peaceful.' '"It felt very relaxing & smoothing." "The synchronized motions are mesmerizing." "CALMING, especially after a particularly tough day."

- Impersonation: "It's very cute and makes me feel curious how many kinds of reaction pattern it has." "I had to fight a desire to 'figure out' an algorithm and assert some control"
- Impersonate: "I made friends with the robots, and although I'll never know their names, I'll never forget the moment and motion we shared." "human, until...they stopped"
- Other Forms of Expression: we have seen several drawings of the *Rhythm Bots*. Additionally, there was an audience that voluntarily danced around the bots as a form of self-expression.

Since the tags are publicly displayed for other audiences to view, the feedback may be biased toward the positive side. However, it is still interesting to observe some common trends, especially those that were not part of the original design concept, such as the resemblance to nature. In contrast to Studio Drift's *I Am Storm*, which was intentionally designed to resemble grass, *Rhythm Bots* was conceived more abstractly, with an emphasis on synchronized oscillating movements and the possibility of rhythmic entrainment, which would serve to make audience members feel good, as was explore in *Rhythm Bath*[313]. The fact that audiences perceive the movements as resembling natural elements is an intriguing aspect worth further exploration. Overall, the feedback aligns with Salimi's summary of the four recurring themes in swarm systems: naturalness, interaction, immersion, and adaptability.

From a design and engineering perspective, the initial prototypes of the *Rhythm Bots* effectively demonstrated synchronized movements. The system allows for low-cost changes and testing of torso colors for various showcases. Thanks to the efforts of generations of students and lab members, we expanded from the original four bots featured in the Pink Noise Project gallery in Philadelphia to twelve bots at the Wallace Theater. Additionally, the *Rhythm Bots* serve as a platform for interdisciplinary collaboration, where partnerships with the music and theater departments have enriched the environmental and sensory landscape[314].

Throughout the iterations, we encountered several recurring challenges and identified areas for future improvement:

- Wire and Electronics Organization: The current design requires flipping the bots to access the electronics hidden at the base, making hardware troubleshooting difficult. A more user-friendly configuration that allows for easy access to the electronics without flipping the bots would be ideal. Additionally, a slightly larger space and better wire organization would improve the setup.

- Suspension Mechanism: The current method of suspending the torso with three rubber bands can be tricky to manipulate and set up. Alternative methods of suspension or a more straightforward way to attach the rubber bands would be preferred.

- Sturdiness: While MDF was chosen for its rapid prototyping benefits, it sacrifices sturdiness. As the bots evolve and the need for showcases increases, the focus should shift from speed and cost to durability and longevity. Exploring alternative materials, such as acrylic, may be beneficial for the next iteration.

- Transportation and Storage: Collapsible versions of the Rhythm Bots are needed for transportation to showcases, along with improved storage and deployment strategies to accommodate the growing number of bots.

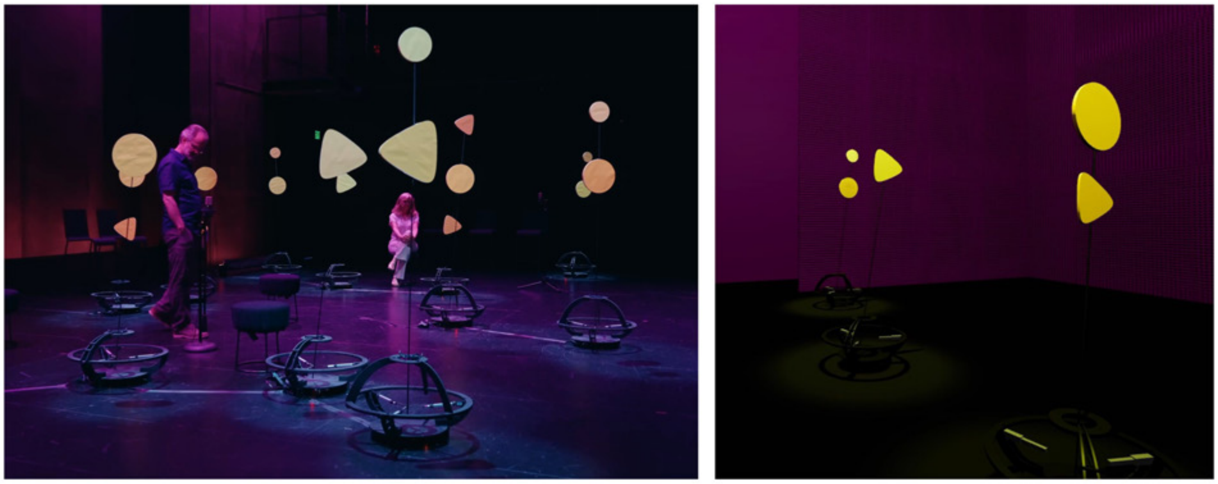
- Documentation: Due to the interdisciplinary nature of the project and its long timeline, comprehensive documentation is essential. Clear documentation will facilitate setup, troubleshooting, and future development, ensuring smooth communication across disciplines and generations of researchers.

10.4 The Digital Twin: Virtual Reality Setup

10.4.1 Motivation and Objectives

The main motivation for developing the VR version of *Rhythm Bots* is to address situations where deploying multiple physical robots is not feasible due to limitations like international travel, time constraints, or insufficient technical support. In the absence of the physical swarm, VR offers a more effective medium to convey the immersive and interactive nature of the *Rhythm Bots* experience com-

Figure 10.5: Left: *Rhythm Bots* exhibited in the Wallace Theater at Princeton University's Lewis Arts complex in May 2024. Right: Rhythm Bots' Digital Twin



pared to traditional representation methods like posters or videos. Thus, the VR version is primarily designed as a presentation tool, with key objectives including the accurate depiction of the robots' collective movements and the integration of interactive elements—in this context most easily with light and sound—that emulate real-world human-robot interactions.

A secondary motivation for the VR version is to serve as a simulation tool for researchers developing the design of the parameters in the responsive dynamics (improvisational rules) of the bots and interaction sequences. Deploying physical robots requires interdisciplinary expertise and specific spatial conditions, making it time-consuming and labor-intensive. A VR-based simulation provides a more efficient way to visualize large-scale swarm behaviors and emergent patterns, facilitating faster experimentation and iterative development.

10.4.2 Design Considerations

The design of the first *Rhythm Bots* VR experience is a constant negotiation between quality and speed, replication and interaction, accuracy and abstraction.

First, for an exhibition-ready VR experience, we aim to export the software as a standalone application on the Meta Quest 3, without the need for a PC connection. This requires the experience to be compact and efficient to avoid glitches or overheating of the headset. Therefore, balancing high-quality visuals with performance optimization is crucial for smooth execution.

Second, while the project aims to document real-life events with accuracy, *Rhythm Bots* is inherently improvisational. A direct replay would fail to capture the interactive essence of the experience. Therefore, a key challenge is balancing faithful documentation with the dynamic, real-time nature of improvisation. In the first version of our VR experience, most robot movements are based on a replay of events from the Wallace Theater, with movement resets simulated by the physics engine. The lights and sounds, however, are more interactive. In addition to being controlled by the actuator data, they can also be triggered by the user's location in VR, as detected by the headset, and respond dynamically in real-time.

Lastly, VR representations do not always need to perfectly replicate real-world functionality. Abstraction can often enhance performance and reduce computational demands. Deciding what should be precisely represented and what can be simplified remains an ongoing design consideration.

10.4.3 Methods

The *Rhythm Bots* VR experience is developed using Unreal Engine 5.3.2, with deployment on the Meta Quest 3 (512GB) headset.

Movement

The oscillating movements are achieved by using actuator data from a five-minute movement segment from the Wallace Theater *Rhythm Bots* Showcase[22] in 2024. The raw data is a NumPy array with the shape (2544, 12, 3), representing 2,544 time stamps across 12 robots, each with three actuators. To animate the *Rhythm Bots* in VR, we first set up a robot model with tunable pivot points and then process the data to directly control the angles of these movable components.

Rather than using traditional 3D rigging—where a skeletal structure controls movement—we implemented a hierarchy of actors in Unreal Engine to define anchor points for transformations. The approach was chosen due to the "floating" nature of many elements enclosed in the robot's concave frame. The suspension and potential need for physics simulation make traditional rigging less applicable since they are mainly meant to animate rigid bots. Additionally, the concave shape complicates collision event calculations. By structuring the robots as separate actors—simulating only key convex elements while treating the static frame as a non-interactive mesh—we achieved a more efficient and flexible animation system.

To drive these animations, custom Python functions were developed to process the raw actuator data, converting values from the normalized range (-1 to 1) into rotation angles in degrees for the "torsos". The final dataset, formatted as a CSV table, contains X-Y-Z rotation values for each actuator across 2,544 timestamps, ensuring precise movement replication in VR.

Sound

A spatial soundscape is essential for an immersive VR experience. The project's sound sources were collected or produced by Prof. Dan Trueman's team. We implemented five categories of sound elements:

- Ambient Background Sound: In the Wallace Theater showcase[314], actuator-clicking sounds were processed live to create a dynamic spatial soundscape. In the VR version, rather than processing sound in real-time, we use a pre-recorded track that replicates the original theater experience. This track plays consistently throughout the VR environment, ensuring an immersive yet computationally efficient audio experience.

- Actuator Clicking Sounds: Each actuator produces a clicking sound upon movement at every time stamp, creating an intricate white noise effect. These sounds were recorded using high-quality microphones and integrated into the VR experience as spatial sound spheres positioned at each robot's base. The inner sound sphere roughly covers the bot's width, while the outer sphere extends three times that width. As a result, when the audience moves closer to a robot's base, the sound intensifies, while at a short distance, they hear a blended soundscape of multiple nearby bots.

- Local Soundscape: A 3D audio source with a filtered soundtrack is placed near the head of each robot, creating a more defined contrast between areas close to the robots and other regions in the space. This enhances the sense of proximity and movement within the VR environment.

- Interactive Trigger Sounds: To simulate interactivity from the physical experience, trigger boxes are placed around each bot, activating pre-paired robots with sound cues. These triggers function in specific time windows, remaining inert at other times. The triggered sounds rotate randomly, making it unpredictable when and what sound will be activated.

- Reset Phase: Every five minutes, the robots return to their initial position and restart the movement segment. This reset sequence is accompanied by a dramatic sound effect, combined with real recordings of the actuators' sounds during the process, enhancing authenticity and immersion.

Lights

In the Wallace Theater *Rhythm Bots* showcase[314], there was background lighting on three sides of the stage, and each bot was assigned three spotlights. However, in VR, rendering lights can be computationally expensive, given that we also have multiple moving actors that constantly change shadows. Therefore, optimizing the lighting setup was crucial for a smooth VR experience.

To maintain the environmental ambiance while reducing computational load, we replaced the background lights with dynamic emissive materials on the three walls. These custom-created digital materials shift colors over time to replicate the real theater's lighting effects. Though counterintuitive, using color-changing emissive materials is far more efficient in VR than rendering multiple light sources. Additionally, textures were applied to simulate the real theater's wall panels.

We added three overhanging point lights with large spherical reach to provide low-intensity front and back illumination across the stage. Each robot, instead of having three individual spotlights, is lit from above by a single spotlight. The light's color is dynamically determined by actuator data, scaled to the (0, 255) range, where the three actuators separately control RGB (Red, Green, Blue) values. The light interacts with the robot's existing head colors, preserving visual differentiation among bots while

Figure 10.6: Audiences experiencing Rhythm Bot through a VR headset during the Galileo Week Collateral Exhibition hosted by *American Academy in Rome*, Rome, Italy, 2025. Photos by Naomi Leonard.

ensuring a cohesive color transition.

Interaction with lighting is achieved through trigger boxes on each robot. When the audience's headset position intersects with a trigger box, it subtly increases the lighting intensity and introduces slight color shifts, enhancing immersion through dynamic environmental feedback.

10.5 Conclusion

This section presents the design and development of Rhythm Bots—a swarm robotics art installation and research platform—alongside their digital twins in virtual reality. Centered on the study of collective behavior, the project employs the NOD model[22] to implement a bottom-up approach for coordinating robotic movement in response to human activity within the space. From a spatial design perspective, Rhythm Bots blurs the line between robotic agents and architectural elements, integrating robotic movement as an active component of the spatial experience and allowing the robots themselves to become part of the environment.

Chapter V The Craft of Tensegrity

Chapter Overview

One of the primary goals of human-robot collaboration is to leverage the strengths of both parties to achieve outcomes that neither could easily accomplish alone. While previous chapters have explored varied modes of human-robot interaction (HRI) in construction and spatial formation—demonstrating robots' ability to make decisions, communicate verbally, and perceive environments in both 2D and 3D—it is equally important to examine the role of humans in this partnership. Beyond their capacity for complex tasks such as achieving intricate force balance, tying and fastening tension cables, and making design decisions, humans contribute a crucial element: craftspersonship.

Previously in projects Block Play (Section 6) and Improv-Structure (Section 7), human workers were involved in stacking blocks or interlacing bamboo sticks; however, these structures required relatively low expertise or specialized training. To further emphasize the craftsmanship aspect of human-robot collaboration, we chose a more intricate structural system for demonstration: tensegrity. Unlike stacking, tensegrity structures demand a highly coordinated interconnection of tension and compression elements to achieve a balanced configuration. The intricate nature of these forms necessitates human expertise in attaching and tensioning cables to achieve structural equilibrium. Thus, a deep understanding of tensegrity principles and hands-on experience with its construction are critical for effective human-robot co-creation.

This chapter provides an exploration of the 3D modeling, engineering principles, and optimization of tensegrity structures. Conducted alongside the tensegrity projects (Sections 8 and 9) discussed in earlier chapters, these studies present a human-centered perspective on the challenges of understanding, designing, and constructing such systems across multiple scales—spanning from assembly techniques to computational modeling to material properties. Readers are encouraged to refer to this chapter when engaging with tensegrity-related HRI fabrication sections in previous chapters.

The chapter is structured as follows:

- Section 11 presents a computational modeling approach for generating tensegrity structures using Grasshopper in Rhino. The parametric definitions developed here allow for flexibility and adaptability, enabling users to create custom tensegrity models efficiently for a better understanding of such structures.

- Section 12 focuses on the compression elements within tensegrity systems, introducing a computational method for optimizing structural and material performance.

Although this chapter primarily examines tensegrity from a human perspective, independent of robotic intervention, it contributes to human-robot collaboration in the HRI projects discussed earlier from the angle of tensegrity craft. Additionally, this work lays the foundation for future research directions, including:

- Training machine learning models for tensegrity generation, incorporating both structural functionality and aesthetic considerations.

- Developing methods for abstracting tensegrity structures from 3D scans.

- Designing robotic assistance techniques to support humans in acquiring and refining tensegrity assembly skills.

The sections in this chapter include adaptations from the following course papers:

Han IX. Dinosaur: A Grasshopper Plugin for Generating Parametric Tensegrity Structures. CEE545/MAE556/MSE535 Final Paper, Princeton University, Instructor: Prof. Glaucio H. Paulino. December, 2023.

Han IX. Macro- and Micro-Level Optimization for the Compression Units in a Two-Element Tensegrity Structure. MSE517/CEE517/MAE571 Rapid Prototyping for Structure Engineering Project Paper, Princeton University, Instructor: Prof. Glaucio H. Paulino. May, 2024.

11

Parametric Modeling of Tensegrity Structures

This section of the dissertation has been adapted from the following course paper:

Han IX. Dinosaur: A Grasshopper Plugin for Generating Parametric Tensegrity Structures. CEE545/MAE556/MSE535 Final Paper, Princeton University, Instructor: Prof. Glaucio H. Paulino. December, 2023.

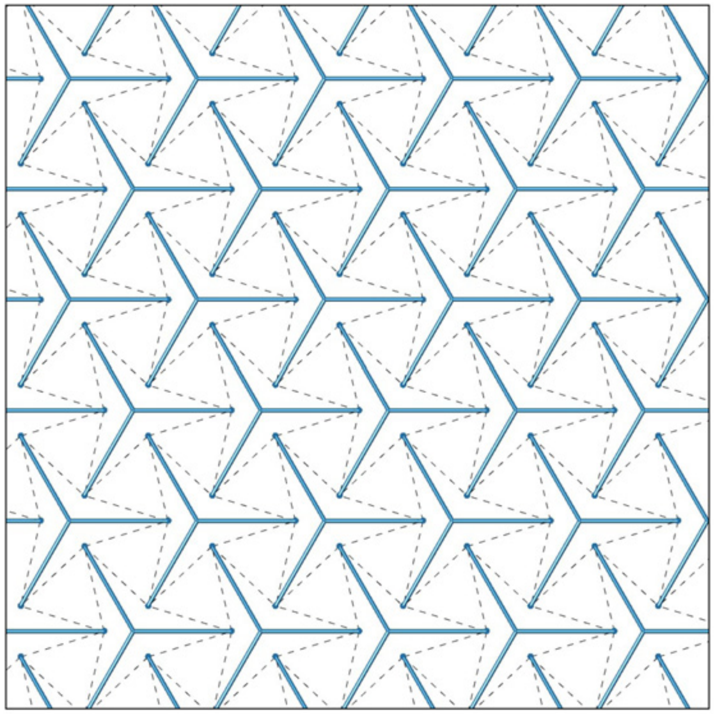
11.1 Introduction

Tensegrity structures consist of both compression and tensile components, which work together to establish a stable system. It has the advantages of being lightweight, robust to impact, and with compelling visual appeals. Despite their growing popularity in various fields such as art, civil engineering, and robotics, there is a lack of user-friendly tools for modeling tensegrity structures, particularly for designers with limited computational backgrounds.

The existing computational plugins for spatial designers, specifically on the food4Rhino platform, offer only one outdated and limited Grasshopper plugin for integrating tensegrity structures into 3D models in Rhino software. Recognizing this gap, the primary objective of this project is to develop tensegrity Grasshopper definitions to enhance the accessibility and craft of tensegrity structures for designers. In pursuit of this goal, the initial development phase consists of various tensegrity types, such as membrane tensegrity (both forward and backward generated), prismatic tensegrity, and polyhedron tensegrity. At least one function in each of the categories mentioned above has been developed. The following subsections present a range of tensegrity types, detailing the computational definitions for each and illustrating the corresponding physical model assembly process.

While this project establishes a foundation for more accessible tensegrity modeling, additional typologies—such as position-based tensegrity[325] and spherical tensegrity—remain promising directions for future research and development.

Figure 11.1: Forward generated 2D strut pattern for membrane tensegrity



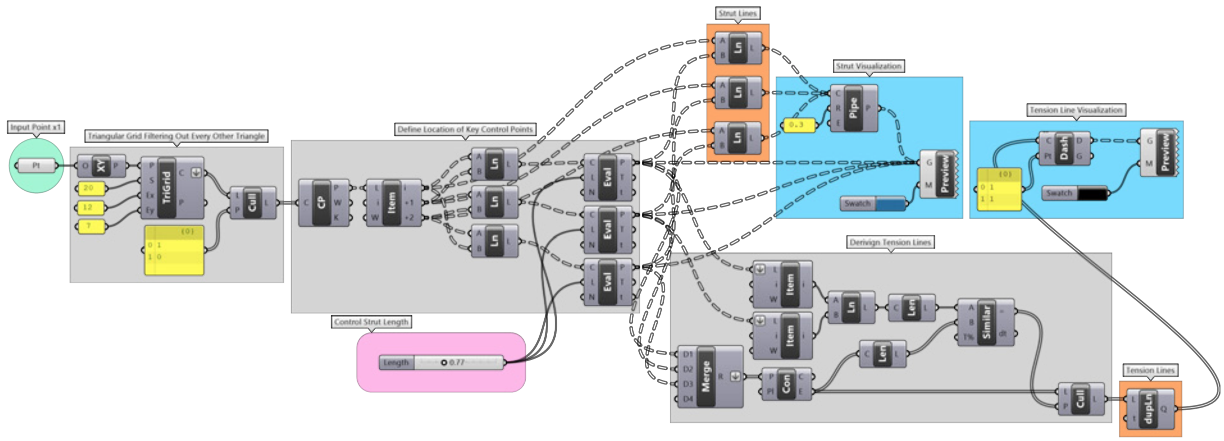
11.2 Membrane Tensegrity

Membrane tensegrity research unfolds in two primary directions: forward and backward design of tensegrity patterns. Backward design [326] initiates from a non-planar mesh surface, retracing steps backward to generate patterns that ultimately result in the desired final form. On the other hand, forward design commences by crafting design patterns in 2D. Subsequently, either through computer simulation software employing a physics engine or by crafting physical models [327], researchers explore the final form that emerges from the 2D patterns.

Figure 11.2 presents the detailed Grasshopper definition used to generate the tessellation pattern shown in Figure 11.1. This definition includes a tunable strut length parameter, which influences the force distribution along the tension lines. Spatially, the pattern of the rigid struts bends the elastic membrane material to form a synclastic shell. Nagano and Nagai [328] recently published an analysis of the physical properties of a comparable membrane tensegrity structure in 2024.

Regarding the human-robot collaboration experiments in previous chapters, we did not select the

Figure 11.2: Grasshopper definition for forward generation of the strut pattern for a membrane tensegrity



membrane tensegrity structure as a base model. While it is capable of forming double curvature, its assembly process primarily takes place on a flat surface, which does not align with our design and testing goals for a spatial structure. Additionally, its design parameters are largely constrained to a 2D surface, extending along the *u* and *v* directions, which can be limiting.

11.3 Prismatic Tensegrity

Prismatic Tensegrity is one of the earliest forms of tensegrity module patented in the mid-20th century[329,289,330]. Certain prismatic tensegrities (e.g., T-4 Prism) have the potential to be neatly expanded in *uv* directions into a "thick surface," as shown in Liapi and Kim's computational model[331] as well as Liapi's physical pavilion[332] and installation[333] work. More interestingly, all prismatic tensegrity also allows for vertical stacking along the *w*-axis—orthogonal to the *u*-*v* surface—by alternating the direction of the twist in adjacent layers, as seen in art sculptures such as Snelson's Needle Tower in 1968[334].

Prismatic tensegrity is intensely studied by Connelly and Terrell in the 1990s[288]. They showed the super stability characteristics of prismatic tensegrity structures where the horizontal cables are connected to adjacent nodes[335].

Prismatic tensegrity resembles a unit cell in a Kresling origami pattern but is made from two tension rings on the top and bottom with an alternation of compression and tension elements in the middle.

Figure 11.3: Grasshopper definition prismatic tensegrity units with customizable control parameters.

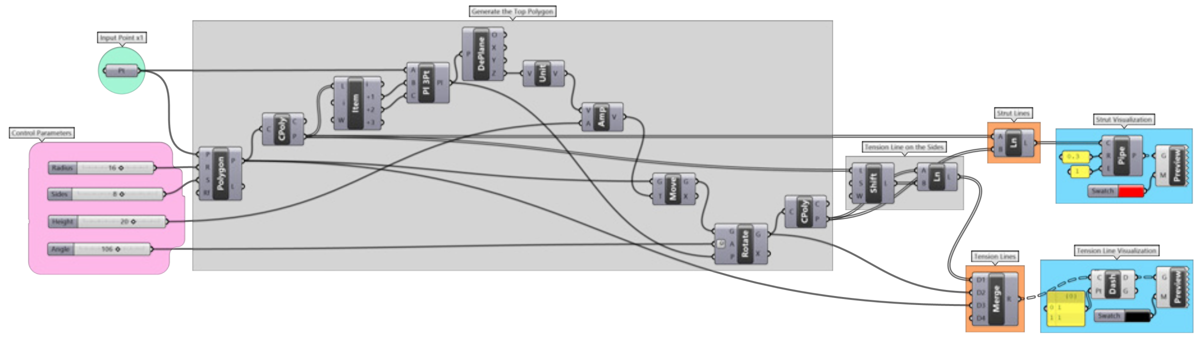
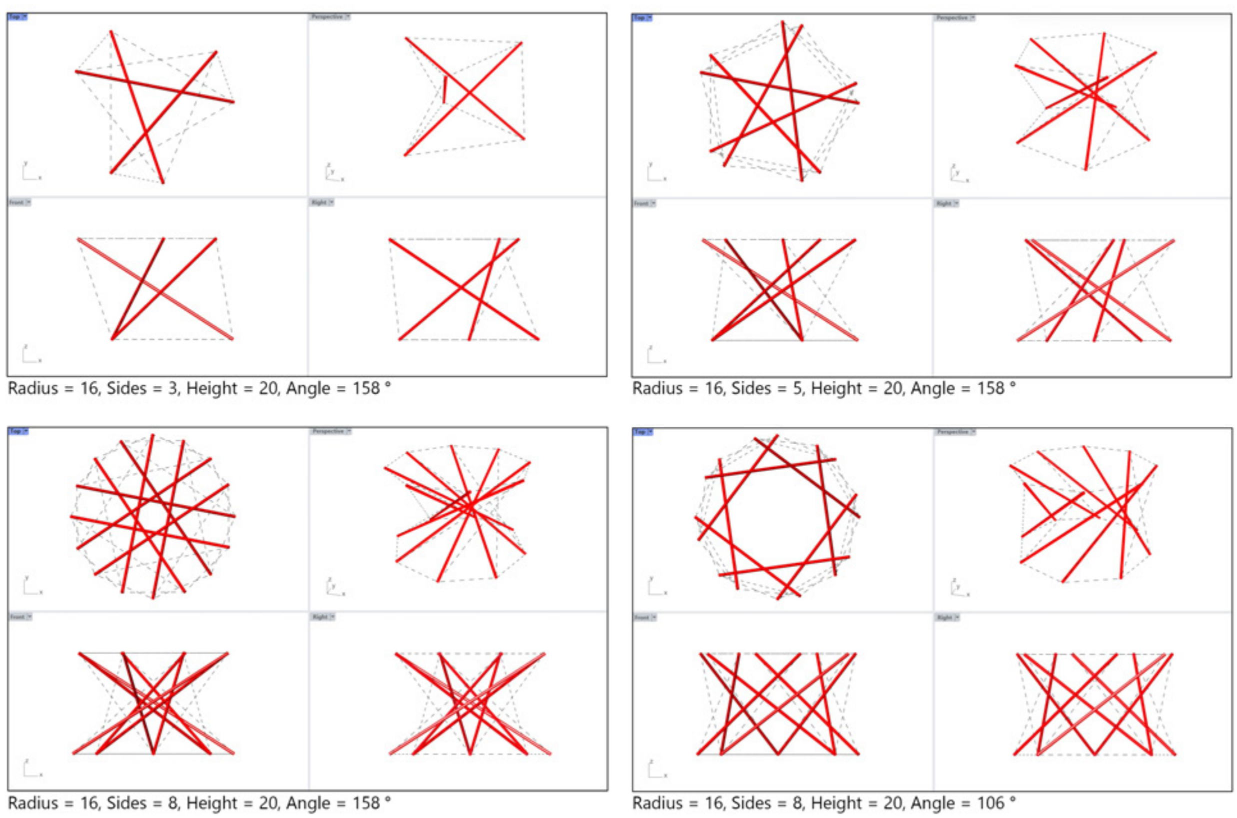


Figure 11.4: Three strut prism tensegrity



Alternatively, to put it more concisely, one can switch mountain creases into tendons and valley creases into struts in a Kresling origami and get a prismatic tensegrity unit.

In the presented grasshopper definitions (Fig. 11.3), prismatic tensegrity units can be easily generated with adjustable parameters such as unit height, radius, number of struts, and twisting angles between the top and bottom polygons. While the definition includes visualization clusters shown in Figure 11.3, the strut and tension lines in orange clusters can be used to plug into physics simulations plugins such as Kangaroo Physics[336] and Karamba3D[337] to observe structural behaviors.

11.3.1 Prismatic Tensegrity Assembly Processes and Considerations

For the assembly sequence, if no additional assistance is available to hold the struts in fixed positions for tension cable attachment (e.g., robotic assistance as discussed in Sections 8 and 9), the 3D form can still be achieved incrementally through the following steps:

1. Wrap a tension cable in a circular loop along the length of each strut, securing it at both ends. Repeat this step to prepare all the struts required for the prismatic tensegrity.

2. Attach one end of a new strut to the tension cable of the previously prepared strut on one side. Repeat this process to create the flat, interlocking ring structure shown in Figures 11.5-left and 11.6-left.

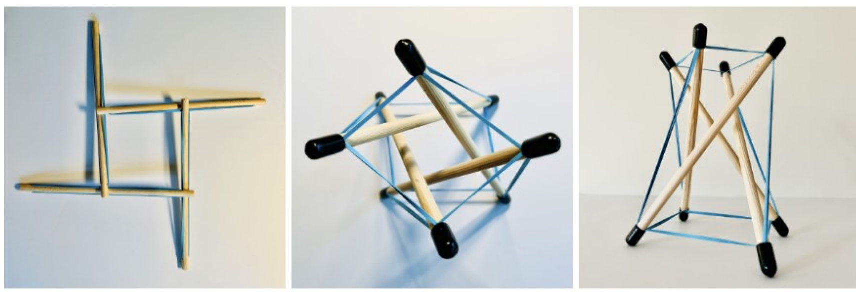
3. Fold the flat interlocking ring, bringing the loose ends of the struts on the outer edge closer together to form the three-dimensional shape.

4. Complete the structure by attaching the free ends of the remaining tension cables (those not yet connected to any strut) to the loose ends of adjacent struts.

For small-scale prototypes, several types of struts were tested: (1) wooden dowels, (2) plastic straws, and (3) paper straws—all combined with rubber bands and end caps. Slots were cut at the ends of each strut to allow rubber bands to slide in, while the rubber caps provided additional security at the end of the assembly.

Figure 11.5: Three strut prism tensegrity - wooden struts

Figure 11.6: Four strut prism tensegrity - wooden struts



Wooden dowels offer the advantage of stiffness, making the structure more stable. However, cutting slots into the ends of wooden dowels is time-consuming. While commercial wooden dowel tensegrity kits with pre-cut slots are available, they are not the most economical solution for early-stage prototyping.

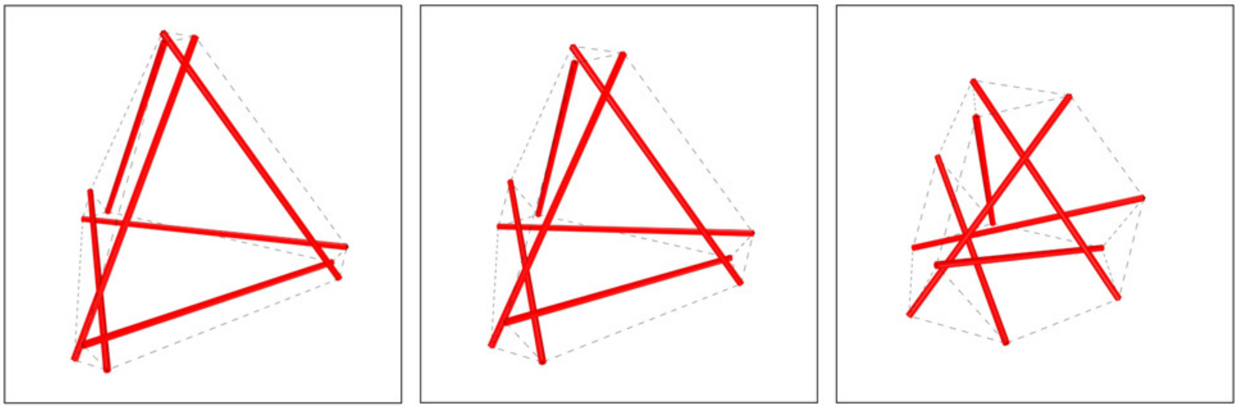
Plastic straws, in contrast, are the cheapest and easiest to modify—slots can be cut quickly. However, they lack structural strength and bend easily. In addition, their sharp edges can gradually wear down or snap the rubber bands, reducing structural longevity.

Paper straws offer the best balance among the three. They are affordable, easy to cut without their edges damaging the rubber bands, and strong enough for small-scale assemblies.

The choice of rubber bands is also important. Thin or small-diameter bands in relationship to the strut length tend to degrade or snap over time. In contrast, industrial-grade rubber bands with proper thickness, width, diameter, and elasticity can maintain tension and structural integrity for extended periods.

For material choices in larger-scale tensegrity structures, refer to Section 8 for an example using

Figure 11.7: Truncated tetrahedron tensegrities with a range of truncation parameters



wooden rods and steel cables, and Section 9 for one using steel rods and steel cables.

11.4 Truncated Polyhedron Tensegrity

Truncated Polyhedron Tensegrity is another type of tensegrity structure "with topology based on polyhedra with truncated vertices."[338,285] The truncated polyhedron tensegrity units can be aggregated in 3D lattices for applications such as tensegrity metamaterial[339].

Figure 11.7 illustrates a series of truncated tetrahedron tensegrities generated in Grasshopper with tunable levels of truncation.

Figure 11.8 and 11.9 show a step-by-step assembly process for small-scale truncated tetrahedron and hexahedron tensegrities.

11.5 Lessons Learned

Key insights and reflections that I learned from this include the following:

Correct mathematical theorems are beautiful, so are correct tensegrity structures. Well-balanced tensegrity structures are beautiful. Beyond mere correctness, the visual appeal of these structures is accentuated by the presence of rotational symmetry. This symmetry not only adds to the overall aesthetics but also serves a practical purpose, guiding the assembly process by providing a sense of order and balance.

Figure 11.8: Truncated tetrahedron tensegrity - plastic straw struts

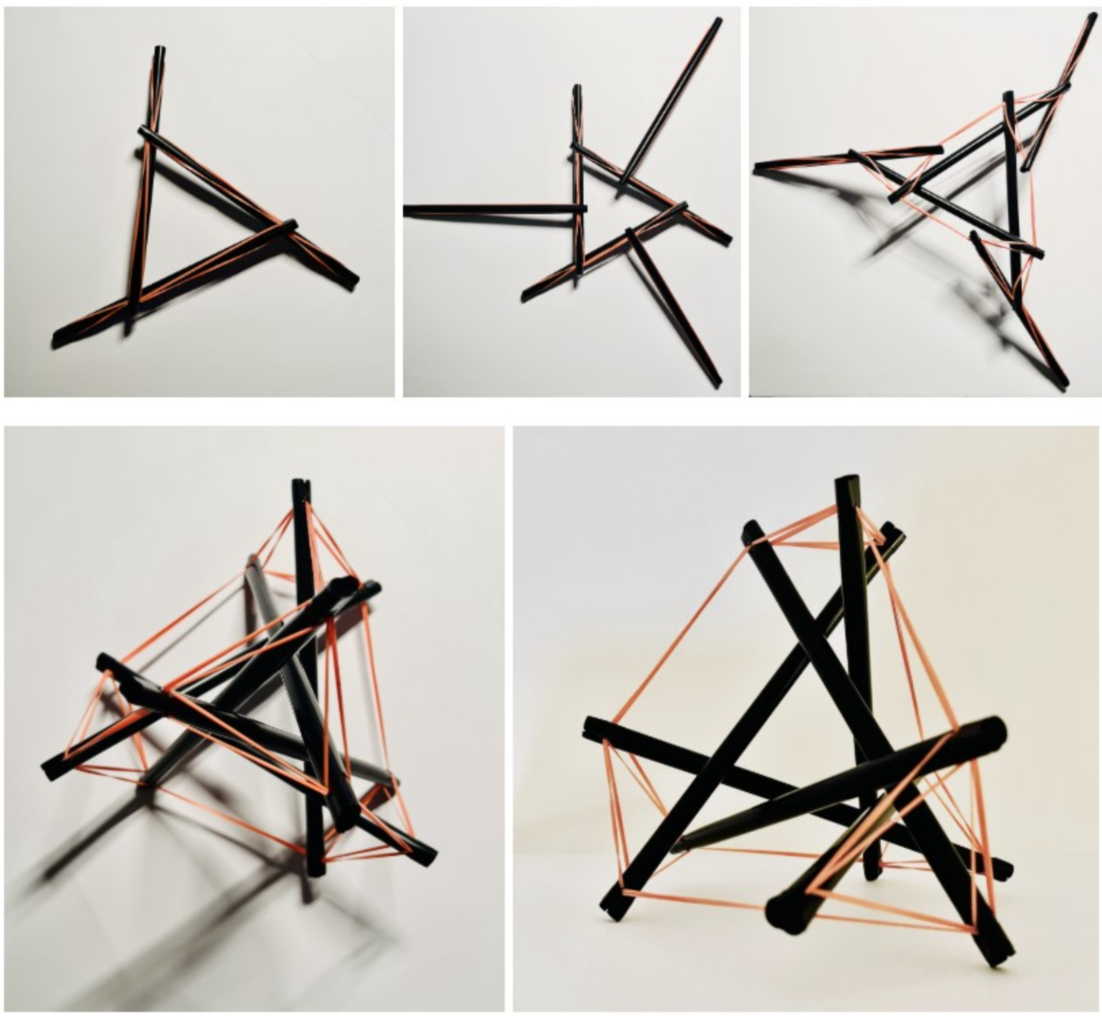
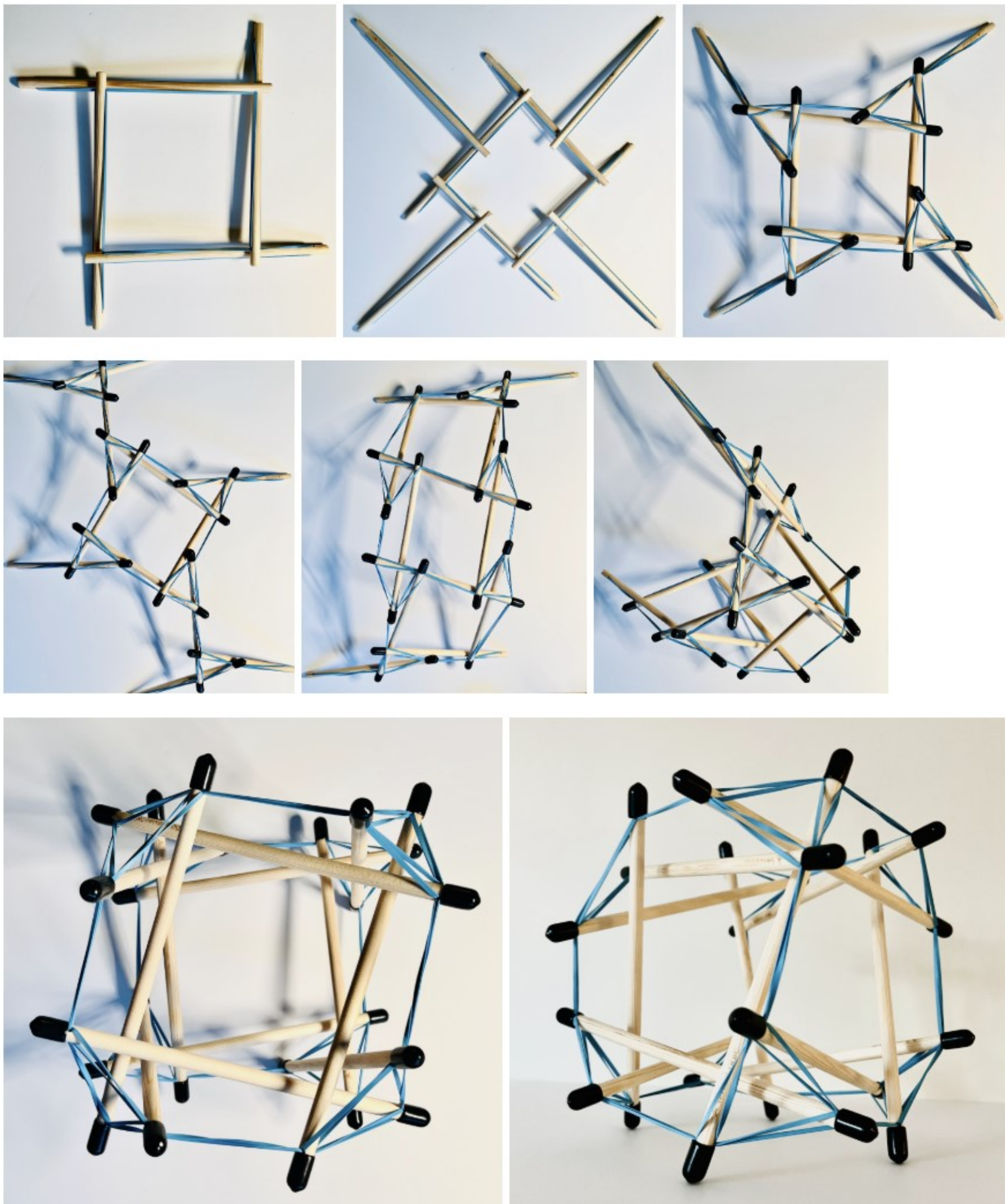


Figure 11.9: Hexahedron tensegrity - wooden struts



Temporal states and sequences also matter for the manual assembly of tensegrity structures. The manual assembly process involves a profound understanding of how temporal sequences align with rotational symmetry. Here is a practical tip learned from the process: capping the strut ends with rubber or tape after attaching tension elements. This precautionary measure, especially during the transition from planar to spherical configurations, prevents tension elements from unintentionally popping out from the ends of struts. This tip might be counterintuitive, as all tension members exert an inward force rather than an outward one in the final state. However, during intermediate states, the tension force might drag the rubber bands out from the ends. Therefore, it is also important to consider the temporal aspects and intermediate states for tensegrity assembly.

"Learning by doing" is important for understanding origami as well as tensegrities. My comprehension of rotational symmetry and assembly sequences significantly deepens through manual assembly compared to modeling the same structures on a computer screen.

12

Macro- and Micro-Level Optimization for the Compression Units in a Two-Element Tensegrity Structure

This section of the dissertation has been adapted from the following course paper:

Han IX. Macro- and Micro-Level Optimization for the Compression Units in a Two-Element Tensegrity Structure. MSE517/CEE517/MAE571 Rapid Prototyping for Structure Engineering Project Paper, Princeton University, Instructor: Prof. Glaucio H. Paulino. May, 2024.

12.1 Introduction

Buckminster Fuller introduced the term "Tensegrity," derived from "tensional integrity," to characterize structures that achieve spatial stability by combining compression and tension elements[285]. The tensegrity structure combines a visually striking "floating" appearance with benefits such as lightweight design, efficient material utilization, and robustness.

Researchers have explored various optimization approaches for tensegrity structures. In terms of topology optimization, Liu and Paulino conduct mixed integer linear programming (MILP) analysis on ground structures to derive optimal tensegrity designs[340]. With a known tensegrity typology, sizing and prestress optimization can be performed to maximum the lightweight quality of the structure[341]. Additionally, Pietroni et al. proposed geometric optimization techniques for element positioning to preserve the original design shapes[325].

However, most of the existing optimization methods treat the compression element as a cylinder-shaped strut with a constant radius along its length, leaving limited exploration of individual compression member topology within tensegrity structures. This project seeks to address this research gap by optimizing compression members in a simple two-element tensegrity structure.

12.2 Problem Statement

Conduct macro-level topology optimization and micro-level material optimization for an individual compression component within a two-element tensegrity structure, commonly found as commercial products like side tables or table lamps.

Validate the optimization outcomes by producing a scaled model using 3D printing and rubber bands.

12.3 Proposed Model

12.3.1 Macro-Level Topology Optimization

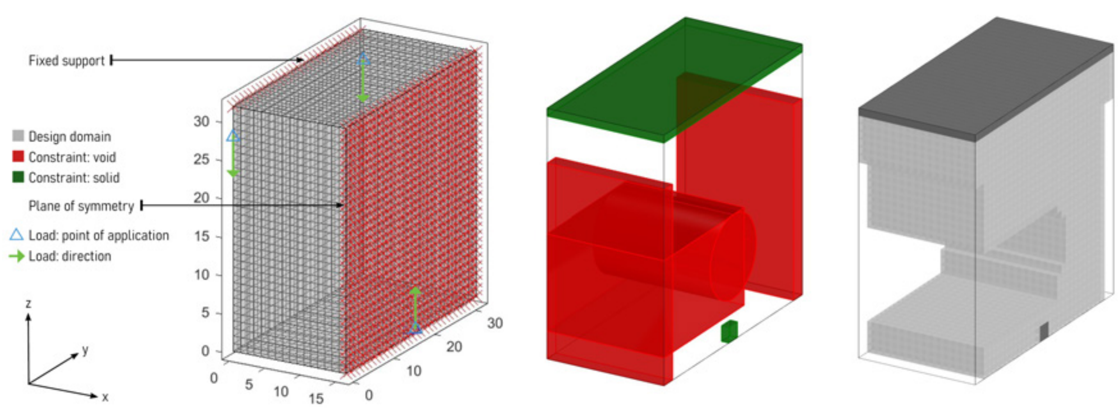
Mesh Computing

The upper component of the two-element tensegrity structure was selected for optimization. The Top3D code created by Liu and Tovar in 2013 [342] was employed, with modifications introduced by Tomas Zegard in 2014. Additional parameter adjustments and constraint conditions were implemented to define the specific tensegrity optimization problem in this project.

The specified parameters used in `Top3D_modZ` to achieve the final optimized model are outlined as follows:

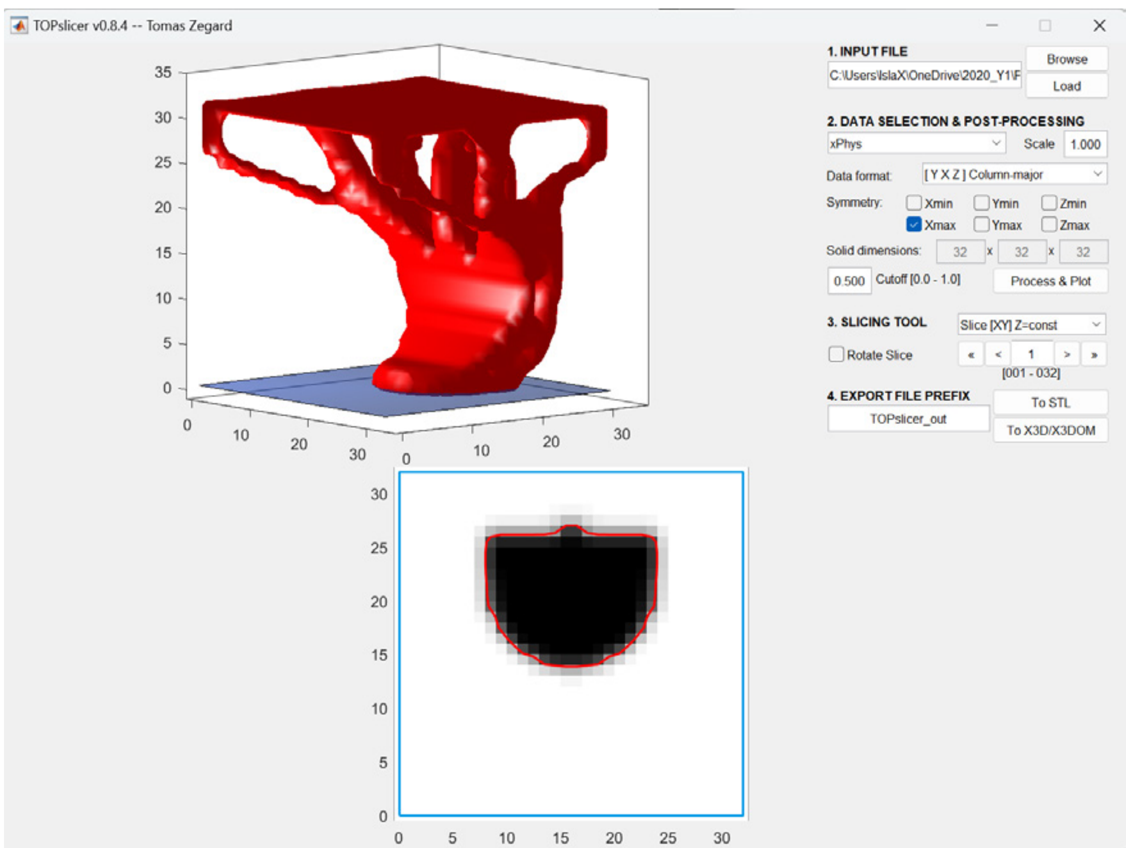
Domain discretization	nelx = 16, nely = 32, nelz = 32
Total number of elements	16,384
Volume fraction	10%
Maximum number of iterations	350
Initial penalization	1.0
Filter radius	2.5
Filter exponent	3
Numerical solver	Direct solver

Figure 12.1: Selected boundary conditions for topology optimization using *Top3D_modZ*



To preserve the symmetry of the overall geometry, a vertical symmetry plane is used to divide the geometry in half (Figure 12.1, left). Two passive solid zones (depicted in green in Figure 12.1, middle) are applied to create a flat top surface capable of supporting objects and to guarantee enough area to hook the central tension cord at the bottom. Additionally, four passive void zones (shown in red in Figure 12.1, middle) are incorporated to: 1) create space for interlocking two of such elements, thus achieving rotational symmetry, and 2) provide room for tension cords at both ends. The constrained design domain is illustrated in the diagram on the right-hand side of Figure 12.1.

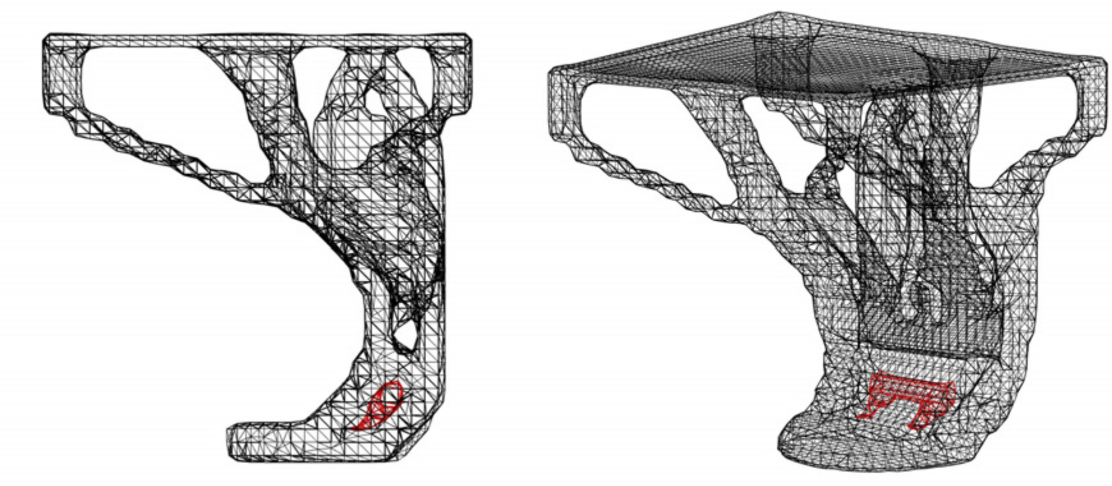
Figure 12.2: *TOPslicer* interface in *MATLAB*



The generated `.mat` file from `Top3D_modZ` is then imported into TOPslicer[343], which mirrors the model along the y-z plane to complete the full geometry (Figure 12.2) and export the model in `.stl` format.

The `.stl` file undergoes additional processing in two software applications to add utility features and achieve a smooth surface finish. However, before further processing, it is worth noticing that the orig-

Figure 12.3: The internal void mesh (red) and the outer shell mesh (black)



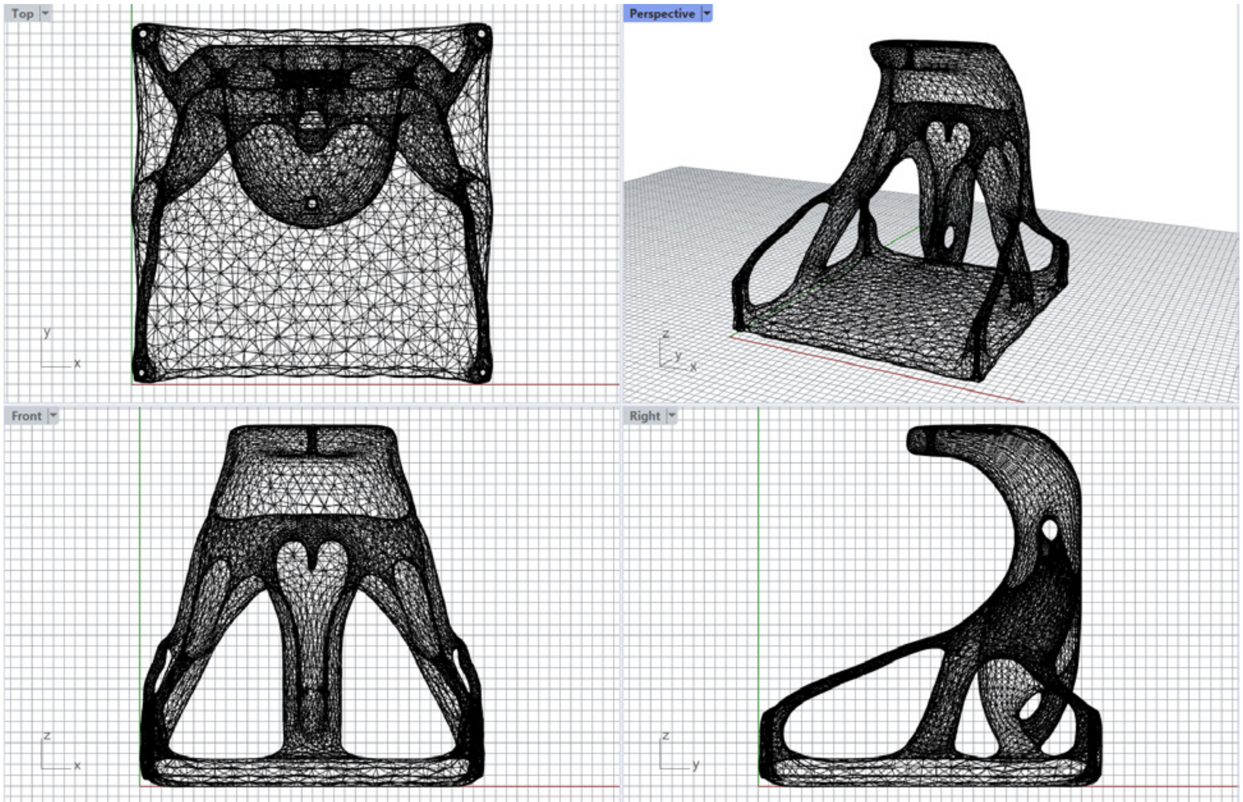
inal mesh has two independent mesh surfaces, one being the internal void of the other (void marked in red in Figure 12.3). For the ease of mesh processing and fabricating, only the outer shell is considered, and the internal void mesh is excluded from further steps.

In Rhinoceros 3D[344], the "table surface" is edited to be slightly thickened to prevent potential breakage when removing 3D-printing supports and to resist bending caused by shrinkage during the cooling process after printing. Furthermore, five cylindrical holes are incorporated into the existing mesh to accommodate the attachment of tension cables. Subsequently, MeshLab[345], an open-source mesh processing tool, is employed to smooth the mesh using the Taubin smoothing algorithm[346] with the following parameters:

λ	0.7
μ	-0.53
Smoothing steps	10

The resulting meshing (Figure 12.4) is a closed double precision polygon mesh with 12,558 vertices and 18,108 faces with normals, as compared to the original rough mesh with 11,387 vertices and 12,660 faces with normals.

Figure 12.4: Top, front, side, and perspective views of a smooth mesh in wireframe mode



Validation

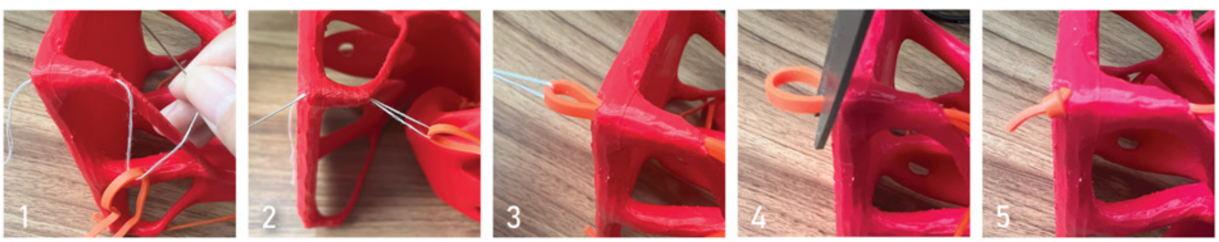
The final design is visualized and validated via rendering as well as a scaled model.

A 3D model of the complete two-element tensegrity structure is generated in Rhinoceros 3D by rotating the optimized mesh 180 degrees along the x-axis. Five thin cable geometries are modeled to represent the tension components. Subsequently, the finalized model is imported into Unreal Engine[347], where material textures and lighting effects are applied to achieve a studio-quality rendering.

A scaled model is fabricated to validate the tensegrity structure using the MakerBot Replicator+ 3D printer with a build volume of 11.6" (length) x 7.5" (width) x 6.3" (height). The individual mesh model is resized to approximately 4 1/4" x 4 1/4" x 4 1/4". Two identical meshes are printed using red PLA filament, and tension is applied between the two prints using orange rubber bands as shown in Figure 12.6. Upon assembly with five tension members, the final model measures approximately 4 1/4" x 4 1/4" x 6 1/4" (Figure 12.7).

Figure 12.5: Rendering of the optimized topology design

Figure 12.6: Process of attaching rubber bands to 3D printed model



12.3.2 Micro-Level Material Optimization

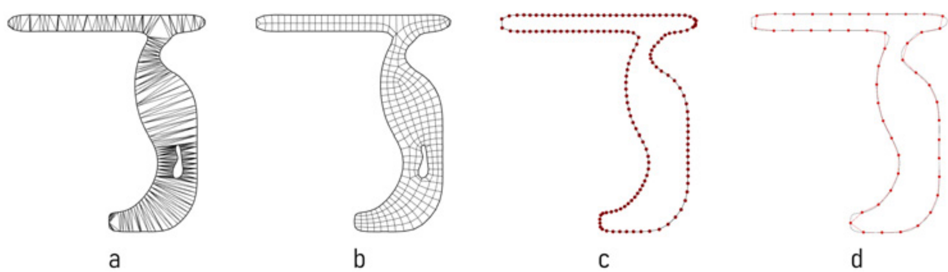
Mesh Generation

`Material TopOpt` is used to "...perform material topology optimization of a globally periodic, linear-elastic, bi-material microstructure in order to maximize the stiffness (i.e., minimize the compliance) ..."[348]. This project considers a simplified scenario where the material is optimized based on the 2D section on the y-z plane in the central location along the x-axis. Similar to Section 12.3.1, the void in a mesh surface in this case is being disregarded in future steps for simplicity of computation.

Figure 12.8 shows how the control points of the section cut mesh are extracted. Firstly, `Quad Remesh` is used in Rhinoceros 3D to simplify the existing section cut mesh (Figure 12.8, step b). Secondly, the

Figure 12.7: Photos of the 3D printed scaled model

Figure 12.8: Section cut to be optimized



control points outlining the mesh from step b are extracted and further simplified using the Grasshopper plugin (Figure 12.8, steps c and d; Figure 12.9).

The output from Grasshopper, which consists of a list of points represented by ordered pairs shown on the right-hand side of Figure 12.9, is stored and used in the `Tenbracket_mesh_IXH_notes.py` code as bounding points to generate a simple 3-node triangle mesh in `.inp` format (refer to Appendix B).

Material TopOpt

The predefined supports and loads are illustrated in Figure 12.10, where the top surface serves as fixed supports and an upward-pointing force is applied to the tip of the hook, representing the tension exerted by the central cord, all defined on the vertices of the triangular meshed generated from the previous step.

Figure 12.9: *Grasshopper* definition to refine and export bounding points from an existing edge curve

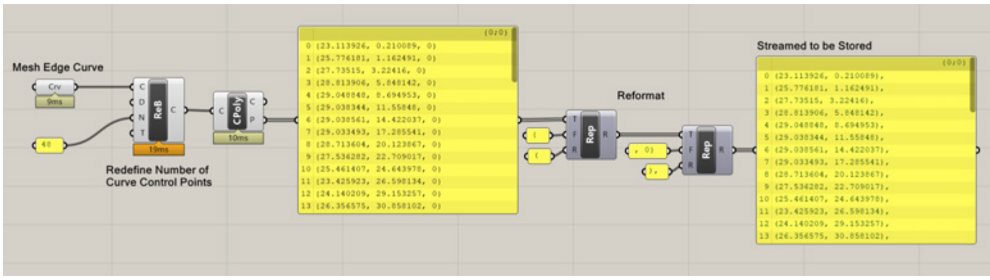
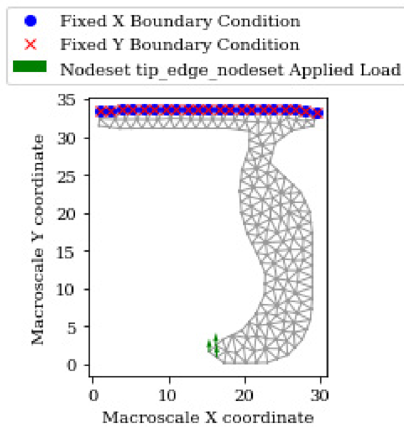


Figure 12.10: Supports and loads



The optimization problem is run in `SetupDesignProblemAdnRun_RP_IXH_notes.py` code (Appendix C). The resulting material topology after 250 iterations is displayed in Figure 12.11

Figure 12.11: Material optimization result

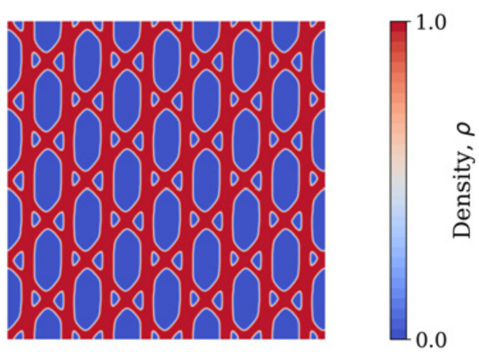
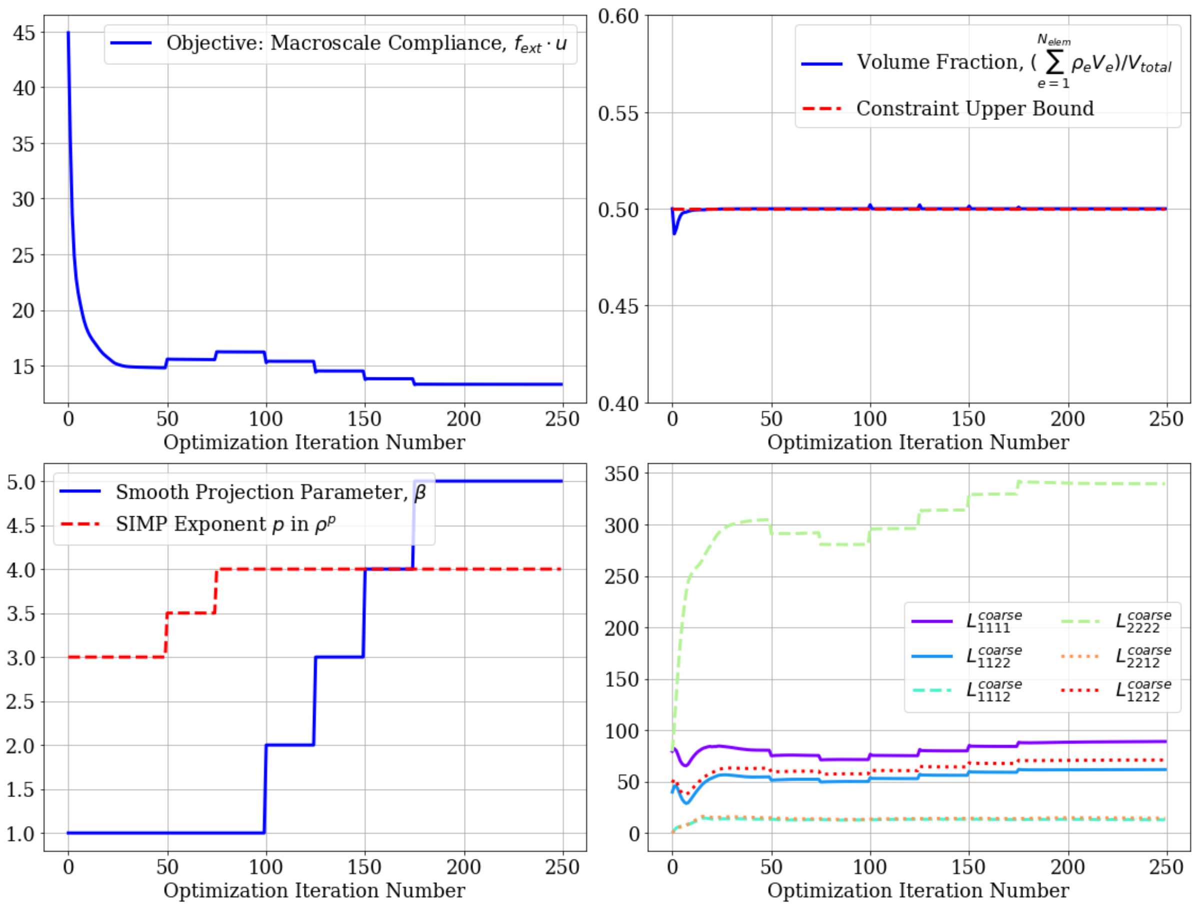


Figure 12.12: Material performance through iterations



12.4 Results and Discussions

This project optimizes both the macro- and micro-level topology of a two-element tensegrity structure. A scaled 3D-printed model is fabricated to validate the structural design (see Figure 12.7).

Drawing from the project's experiences and results, the following observations and comments can be made:

- Voids within meshes, whether in 3D (Figure 12.3) or 2D (Figure 12.8), are one of the main causes of inaccuracy in this project. Addressing this issue requires the development of algorithms capable of avoiding or efficiently processing such entrapped voids within geometries.

- The project leveraged a diverse range of software, platforms, and codes to capitalize on the unique strengths and capabilities of each tool. This underscores the importance of generating outputs in formats that facilitate seamless integration and collaboration across different software environments.

- In future iterations, additional consideration can be given to how tension cables attach to compression elements, potentially integrating this aspect into optimization processes.
- Optimized geometries often exhibit organic shapes that can present challenges during fabrication. While 3D printing is viable for small-scale models, scaling up for mass production introduces complexities related to manufacturing costs and time constraints associated with fabricating optimized designs.

Chapter VI Conclusion

This dissertation investigated the central research question: How can humans and machines better collaborate through a non-linear, integrated workflow—enabled by advances in human-robot interaction (HRI) and artificial intelligence (AI)—to unlock new modes of co-creativity and design space? This inquiry was explored through the development and implementation of an improvisational construction framework, tested iteratively through a series of construction prototypes. These prototypes spanned diverse material systems, robot platforms, and HRI interfaces—including visual sensing and natural language communication.

12.1 Collective Human-Robot Construction

The conceptual foundation for this dissertation lies in Collective Human-Robot Construction (CHRC), detailed in Section 2. CHRC addresses a unique intersection of disciplines: it departs from Collective Robotic Construction (CRC) by emphasizing human agency; from traditional HRI by prioritizing collectiveness; and from human-robot teams through its focused application in construction and space making. The dual axes of *autonomy–collaboration* and *design–fabrication*, as mapped in Figure 2.1, were used to contextualize CHRC and position it within the broader research landscape.

Section 2's review established four core topics and identified eight future research directions for CHRC, influencing this dissertation's methodology and inspiring subsequent scholarly work. Topics such as social and physical HRI, human-swarm collaboration, extended reality (VR/AR/XR), and task coordination became critical to the experimental efforts described in the following chapters.

12.2 Improvisational Construction Framework

Situated in the CHRC framework, this dissertation introduced a novel improvisational construction framework to challenge the conventional linear pipeline of design–engineer–fabrication. Drawing from theories of improvisation in theater, music, and organizational management, the proposed framework was deployed at multiple scales and across various material systems.

Section 6, *Block Play*, presented the initial exploration of an improvisational construction framework, where a human and a robot took turns to contribute to the same stacking structure. The design space was constrained to an 11" wide, 18" high, and 1.5" thick wooden frame, with pre-fabricated, commercially available toy blocks that are 1" thick with a central color film as the basic building blocks. The experiment used a UR5 robotic arm combined with a webcam and color sensor. The robot initiated "spatial prompts," allowing human collaborators to respond with creative placements that diverged from what either party might achieve independently. The experiment highlighted the significance of agency distribution and the interplay of human and robotic "preferences" in determining the final form.

Section 7, *Improv-Structure*, extended this concept to the architectural scale. Here, interwoven bamboo rods (4' in length and 3/8" in diameter) formed a flexible, spatially expansive material system, secured by zip ties and informed by 3D LiDAR scanning. We further structured the improvisational construction workflow into discrete design-construction "action units," between which the existing structure was re-scanned using a 3D LiDAR sensor to update the digital model in Rhino/Grasshopper. This updated model then informed the robots' design proposal and guiding rods' placements in the subsequent "action unit." Within each "action unit," two ABB IRB 4600-255/40 robotic arms, mounted on linear tracks, positioned new building rods in mid-air at a distance of approximately 0.65–0.85 times the length of a bamboo rod from the existing structure. This spatial prompt invited the human collaborator to devise a design solution that completed or responded to the robotic placement. The two robotic arms alternated roles between placing new elements and providing temporary structural support, enabling the construction of spanning and cantilevered forms. The resulting prototype measured approximately 7' × 14' × 7' and was completed over five days. It comprised around 500 bamboo rods, with approximately 30 rods acting as guiding elements placed by the robots. The construction process unfolded across five "action units," two of which involved significant revisions based on the human collaborators' real-time assessment of the built form. These shifts underscore the flexibility of the improvisational workflow and highlight the value of enabling human designers to engage with the structure at full scale and in real materials, while retaining the ability to make design decisions dynamically.

Section 8, *Spontaneous Tensegrity*, further expanded the possibilities of collaborative structures enabled by the improvisational design framework by applying it to the design and fabrication of tensegrity systems. Departing from the slower cycle of re-scanning at the start of each "action unit" as demonstrated in Section 7, Spontaneous Tensegrity accelerated the process by leveraging visual-servoing, allowing the robots to make real-time decisions and movements based on immediate visual input. A custom-designed end-effector was developed, featuring an L-shaped aluminum profile equipped with two perpendicularly mounted SCHUNK JGP 100-I grippers for handling tensegrity modules, and a compact camera for 2D visual feedback. The system was implemented using two stationary ABB IRB 2600 robotic arms.

Two experiments were conducted in Section 8: the first explored stigmergic construction of an X-Module tensegrity structure; the second built a linked series of T3-Prism tensegrity, influenced by multiple layers of design inputs, with the resulting structure measuring 2.5m × 1.6m × 2.5m. The integration of visual-servoing significantly reduced the robots' response time, enabling decisions based primarily on spatial sensing of the evolving structure. This real-time interaction between human, robot, and structure gave rise to novel collaborative scenarios, such as a "hand-over" function, where a human could position a module in space and the robot, upon recognizing the module's location, would grasp it directly from the human's hand for placement.

12.3 Human Robot Interaction and the Roles of Robotic Agents

The shift toward real-time, physical HRI, particularly in *Spontaneous Tensegrity*, revealed robots' potentials not only as a design guide by placing spatial prompts, but also as a collaborative assistant capable of working closely with humans in material handling. This evolution continued in Section 9, where the integration of large language models (LLMs) enabled verbal communication between human designers and robots.

By leveraging GPT-3.5-Turbo LLM, users could issue natural language commands that were translated into robotic motion through prompt engineering using techniques such as step-by-step instructions and few-shot examples, achieving an average accuracy rate of 92.31% for text-to-code updates. Several challenges emerged during implementation, including decreased audio-to-text transcription accuracy due to construction site noises, an added response time of 0.6–0.7 seconds per AI query, and variability in accuracy depending on task complexity. To address safety concerns, the system included AI reiteration steps that prompted human confirmation via a physical button before executing any task in real life. Despite these limitations, the LLM-enabled workflow presented several advantages: it freed up one of the human operator's hands, lowered technical entry barriers, supported task customization, and offered greater precision than traditional pendant-based controls.

Section 10, *Rhythm Bots*, further expanded the role of robots beyond that of collaborators or assistants—reimagining them as the environment itself. In this Section, robots shaped the spatial experiences dynamically through movements that responded to human presence. The work presented the physical embodiment of the Nonlinear Opinion Dynamics (NOD)[22] model through a custom-designed swarm robotic art installation, where coordinated motion became a medium of spatial expression. Rather than constructing static forms, the robots acted as kinetic architectural elements, forming an immersive and responsive environment where space was continuously reshaped by their rhythmic movement.

12.4 Co-Creativity and Extending Craft through Human-Robot Collaboration

At the heart of this research lies a sustained inquiry into co-creativity—a shared authorship between human and robotic agents. The experiments presented in this dissertation interrogated various HRI setups to discover how robots and humans could collectively enhance both design thinking and material assembly.

Robot "preferences" were explored based on a range of inputs—spatial proximity, structural orientation, color, stylistic continuity, and human prompts—first tested in isolation (e.g., *Block Play*) and later integrated in architectural-scale demonstrators (Sections 7, 8, 10). These preferences informed both local and global structural interventions, demonstrating the potential for expressive, responsive robotic agencies.

On the human side, a spectrum of material systems was introduced: from vertical block stacking to interlocking bamboo lattices to intricate tensegrity configurations. The depth of craft required for each system varied, highlighting the importance of material knowledge and tacit expertise in the collaborative design processes. Chapter V contributed further by advancing computational tools for understanding tensegrity logics and selecting optimal unit topologies for improvisational construction workflows.

12.5 Future work

This dissertation opens several promising avenues for future inquiry:

- Design Knowledge Databases: Establishing datasets of spatial structures could enable machine learning models to develop more nuanced "design instincts" based on diverse structural archetypes and spatial configurations.

- Safety and Proxemics: As human-robot collaboration becomes more physically integrated, future work must develop robust strategies for safe, legible, and proxemic interaction during live construction.

- Robots as Environment: This work encourages a redefinition of architecture as dynamic and responsive. Robots, embedded within environments, could continuously adapt and reconstruct space in response to human activity.

- Craft Augmentation: Robots may serve not only as assistants, but also as learners and teachers, capable of adapting to human craft techniques and potentially passing on learned behavior to future collaborators.

- Improvisational Design-Construction Frameworks at Scale: Broader applications of the improvisational construction framework extend beyond exploring novel formal expressions; they can also serve as a more effective approach for integrating and managing robotic applications on construction sites, enabling greater flexibility and adaptability in the construction process.

References

[1] Mary N Woods. *From craft to profession: The practice of architecture in nineteenth-century America*. Univ of California Press, 2023.

[2] Lauren Vasey and Achim Menges. Potentials of cyber-physical systems in architecture and construction. In *Construction 4.0*, pages 90–112. Routledge, 2020.

[3] Salman Azhar. Building information modeling (bim): Trends, benefits, risks, and challenges for the aec industry. *Leadership and management in engineering*, 11(3):241–252, 2011.

[4] Howard W Ashcraft. Building information modeling: A framework for collaboration. *Constr. Law.*, 28:5, 2008.

[5] Saurabh Vaidya, Prashant Ambad, and Santosh Bhosle. Industry 4.0–a glimpse. *Procedia manufacturing*, 20:233–238, 2018.

[6] Klaus Schwab. *The Fourth Industrial Revolution*. Crown Currency, New York, first u.s. edition edition, 2016.

[7] Klaus Schwab. The fourth industrial revolution: what it means, how to respond1. In *Handbook of research on strategic leadership in the Fourth Industrial Revolution*, pages 29–34. Edward Elgar Publishing, 2024.

[8] Ercan Oztemel and Samet Gursev. Literature review of industry 4.0 and related technologies. *Journal of intelligent manufacturing*, 31(1):127–182, 2020.

[9] Rinat Galin and Roman Meshcheryakov. Automation and robotics in the context of industry 4.0: the shift to collaborative robots. In *IOP Conference Series: Materials Science and Engineering*, volume 537, page 032073. IOP Publishing, 2019.

[10] Bo Xiao, Chen Chen, and Xianfei Yin. Recent advancements of robotics in construction. *Automation in Construction*, 144:104591, 2022.

[11] Gantenbein vineyard facade, fläsch, switzerl and, 2006 non-standardised brick façade. `https://gramaziokohler.arch.ethz.ch/web/e/forschung/52.html`. Accessed: 2021-12-22.

[12] Luka Piškorec, David Jenny, Stefana Parascho, Hannes Mayer, Fabio Gramazio, and Matthias Kohler. The brick labyrinth. In *Robotic Fabrication in Architecture, Art and Design 2018: Foreword by Sigrid Brell-Çokcan and Johannes Braumann, Association for Robots in Architecture*, pages 489–500. Springer International Publishing, 2019.

[13] Yi Zhou, Bowen Huang, Boge Dong, Yi Wen, and Molong Duan. Dynamic robotic bricklaying force-position control considering mortar dynamics for enhanced consistency. *Automation in Construction*, 174:106090, 2025.

[14] Philipp Eversmann, Fabio Gramazio, and Matthias Kohler. Robotic prefabrication of timber structures: towards automated large-scale spatial assembly. *Construction Robotics*, 1(1):49–60, 2017.

[15] Stephen Mulligan, Geoff Melton, Ari Lylynoja, and Keith Herman. Autonomous welding of large steel fabrications. *Industrial Robot: An International Journal*, 32(4):346–349, 2005.

[16] Tom Shaked, Karen Lee Bar-Sinai, and Aaron Sprecher. Adaptive robotic stone carving: Method, tools, and experiments. *Automation in Construction*, 129:103809, 2021.

[17] Matthias Leschok, Ina Cheibas, Valeria Piccioni, Bharath Seshadri, Arno Schlüter, Fabio Gramazio, Matthias Kohler, and Benjamin Dillenburger. 3d printing facades: Design, fabrication, and assessment methods. *Automation in construction*, 152:104918, 2023.

[18] Yomna K Abdallah and Alberto T Estévez. 3d-printed biodigital clay bricks. *Biomimetics*, 6(4):59, 2021.

[19] Gido Dielemans, David Briels, Fabian Jaugstetter, Klaudius Henke, and Kathrin Dörfler. Additive manufacturing of thermally enhanced lightweight concrete wall elements with closed cellular structures. *Journal of Facade Design and Engineering*, 9(1):59–72, 2021.

[20] Stefana Parascho, Isla Xi Han, Samantha Walker, Alessandro Beghini, Edvard PG Bruun, and Sigrid Adriaenssens. Robotic vault: a cooperative robotic assembly method for brick vault construction. *Construction Robotics*, 4(3):117–126, 2020.

[21] Stefana Parascho. Construction robotics: from automation to collaboration. *Annual Review of Control, Robotics, and Autonomous Systems*, 6(1):183–204, 2023.

[22] Naomi Ehrich Leonard, Anastasia Bizyaeva, and Alessio Franci. Fast and flexible multiagent decision-making. *Annual Review of Control, Robotics, and Autonomous Systems*, 7, 2024.

[23] Jan Willmann, Philippe Block, Marco Hutter, Kendra Byrne, and Tim Schork. *Robotic fabrication in architecture, art and design 2018: foreword by Sigrid Brell-Cokcan and Johannes Braumann, association for robots in architecture*. Springer, 2018.

[24] Kirstin H Petersen, Nils Napp, Robert Stuart-Smith, Daniela Rus, and Mirko Kovac. A review of collective robotic construction. *Science Robotics*, 4(28):eaau8479, 2019.

[25] Benjamin Felbrich, Nikolas Frueh, Marshall Prado, Saman Saffarian, James Solly, Lauren Vasey, Jan Knippers, and Achim Menges. Multi-machine fabrication: an integrative design process utilising an autonomous uav and industrial robots for the fabrication of long-span composite structures. In *Acadia 2017 Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, pages 248–259, 2017.

[26] Stefana Parascho, Augusto Gandia, Ammar Mirjan, Fabio Gramazio, and Matthias Kohler. Cooperative fabrication of spatial metal structures. *Fabricate 2017*, pages 24–29, 2017.

[27] Romana Rust, David Jenny, Fabio Gramazio, and Matthias Kohler. Spatial wire cutting: Cooperative robotic cutting of non-ruled surface geometries for bespoke building components. In *Proceedings of the 21st international conference on computer-aided architectural design research in Asia: living systems and micro-utopias: towards continuous designing (CAADRIA 2016)*, pages 529–538. CAADRIA, 2016.

[28] Hans Jakob Wagner, Martin Alvarez, Abel Groenewolt, and Achim Menges. Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the buga wood pavilion. *Construction Robotics*, 4(3):187–204, 2020.

[29] Y Uny Cao, Andrew B Kahng, and Alex S Fukunaga. Cooperative mobile robotics: Antecedents and directions. *Robot colonies*, pages 7–27, 1997.

[30] Terrence Fong, Charles Thorpe, and Charles Baur. Collaboration, dialogue, human-robot interaction. In *Robotics research: The tenth international symposium*, pages 255–266. Springer, 2003.

[31] Michael A Goodrich, Alan C Schultz, et al. Human–robot interaction: a survey. *Foundations and Trends® in Human–Computer Interaction*, 1(3):203–275, 2008.

[32] Aaron Steinfeld, Terrence Fong, David Kaber, Michael Lewis, Jean Scholtz, Alan Schultz, and Michael Goodrich. Common metrics for human-robot interaction. In *Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*, pages 33–40, 2006.

[33] Sebastian Thrun. Toward a framework for human-robot interaction. *Human–Computer Interaction*, 19(1-2):9–24, 2004.

[34] Kamel S Saidi, Thomas Bock, and Christos Georgoulas. Robotics in construction. In *Springer handbook of robotics*, pages 1493–1520. Springer, 2016.

[35] Justin Werfel, Kirstin Petersen, and Radhika Nagpal. Designing collective behavior in a termite-inspired robot construction team. *Science*, 343(6172):754–758, 2014.

[36] Adam Braithwaite, Talib Alhinai, Maximilian Haas-Heger, Edward McFarlane, and Mirko Kovač. Tensile web construction and perching with nano aerial vehicles. *Robotics Research: Volume 1*, pages 71–88, 2018.

[37] Allen Hsu, Annjoe Wong-Foy, Brian McCoy, Cregg Cowan, John Marlow, Bryan Chavez, Takao Kobayashi, Don Shockey, and Ron Pelrine. Application of micro-robots for building carbon fiber trusses. In *2016 international conference on manipulation, automation and robotics at small scales (MARSS)*, pages 1–6. IEEE, 2016.

[38] Thomas B Sheridan. Human–robot interaction: status and challenges. *Human factors*, 58(4):525–532, 2016.

[39] Jacques Ferber and Gerhard Weiss. *Multi-agent systems: an introduction to distributed artificial intelligence*, volume 1. Addison-wesley Reading, 1999.

[40] David Andréen, Petra Jenning, Nils Napp, and Kirstin Petersen. Emergent structures assembled by large swarms of simple robots. In *Acadia*, pages 54–61, 2016.

[41] Van Du Nguyen and Ngoc Thanh Nguyen. Intelligent collectives: Theory, applications, and research challenges. *Cybernetics and Systems*, 49(5-6):261–279, 2018.

[42] Keith Sawyer. Improvisational creativity: An analysis of jazz performance. *Creativity research journal*, 5(3):253–263, 1992.

[43] R Keith Sawyer. *Group creativity: Music, theater, collaboration*. Psychology Press, 2014.

[44] Tudor Rickards, Mark A Runco, and Susan Moger. *The Routledge companion to creativity*, volume 400. Routledge London, 2009.

[45] Gil Weinberg, Brian Blosser, Trishul Mallikarjuna, and Aparna Raman. The creation of a multi-human, multi-robot interactive jam session. In *NIME*, pages 70–73, 2009.

[46] Richard Savery. Machine learning driven musical improvisation for mechanomorphic human-robot interaction. In *Companion of the 2021 ACM/IEEE international conference on human-robot interaction*, pages 559–561, 2021.

[47] Claire Mikalauskas, Tiffany Wun, Kevin Ta, Joshua Horacsek, and Lora Oehlberg. Improvising with an audience-controlled robot performer. In *Proceedings of the 2018 designing interactive systems conference*, pages 657–666, 2018.

[48] Hélène Landemore and Jon Elster. *Collective wisdom: Principles and mechanisms*. Cambridge University Press, 2012.

[49] Michael A Peters and Richard Heraud. Toward a political theory of social innovation: collective intelligence and the co-creation of social goods. *Journal of Self-Governance & Management Economics*, 3(3), 2015.

[50] Michael Wooldridge. *An introduction to multiagent systems*. John wiley & sons, 2009.

[51] Sankar Virdhagriswaran, Damian Osisek, and Pat O'Connor. Standardizing agent technology. *StandardView*, 3(3):96–101, 1995.

[52] T Bock. „robot oriented design ", architectural product engineering, seko, 1988.

[53] Jeffrey M Bradshaw, Stuart Dutfield, Pete Benoit, and John D Woolley. Kaos: Toward an industrial-strength open agent architecture. *Software agents*, 13:375–418, 1997.

[54] Autodesk. What is bim: Building information modeling. `https://www.autodesk.com/solutions/bim`. Accessed 15 Dec 2020.

[55] Thomas Bock and Thomas Linner. *Robot oriented design*. Cambridge university press, 2015.

[56] T Bock and TL Linner. Integration along the value chain in construction through robot oriented management. *Architectural Management in the Digital Arena*, page 21, 2011.

[57] Amos Tversky and Daniel Kahneman. Judgment under uncertainty: Heuristics and biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *science*, 185(4157):1124–1131, 1974.

[58] Holly A Yanco and Jill Drury. Classifying human-robot interaction: an updated taxonomy. In *2004 IEEE international conference on systems, man and cybernetics (IEEE Cat. No. 04CH37583)*, volume 3, pages 2841–2846. IEEE, 2004.

[59] Jean Scholtz. Theory and evaluation of human robot interactions. In *36th Annual Hawaii International Conference on System Sciences, 2003. Proceedings of the*, pages 10–pp. IEEE, 2003.

[60] Helge Huttenrauch and Kerstin Severinson Eklundh. Investigating socially interactive robots that give the right cues and make their presence felt. In *Proceedings of the CHI 2004 workshop on shaping human-robot interaction*, pages 17–20, 2004.

[61] Lidia Atanasova, Daniela Mitterberger, Timothy Sandy, Fabio Gramazio, Matthias Kohler, and Kathrin Dorfler. Prototype as artefact-design tool for open-ended collaborative assembly processes. In *40th Annual Conference of the Association for Computer Aided Design in Architecture: Distributed Proximities, ACADIA 2020*, pages 350–359. ACADIA, 2020.

[62] Lauren Vasey, Tovi Grossman, Heather Kerrick, and Danil Nagy. The hive: a human and robot collaborative building process. In *ACM SIGGRAPH 2016 Talks*, SIGGRAPH '16, New York, NY, USA, 2016. Association for Computing Machinery.

[63] Madeline Gannon. *Human-centered Interfaces for autonomous fabrication machines*. PhD thesis, Carnegie Mellon University Pittsburgh, PA, 2018.

[64] Chris Harrison, Desney Tan, and Dan Morris. Skinput: appropriating the body as an input surface. In *Proceedings of the SIGCHI conference on human factors in computing systems*, pages 453–462, 2010.

[65] U. I. Abe, K. Hotta, A. Hotta, Y. Takami, H. Ikeda, and Y. Ikeda. Digital construction - demonstration of interactive assembly using smart discrete papers with rfid and ar codes. In P. Janssen, P. Loh, A. Raonic, and M. A. Schnabel, editors, *Protocols, Flows, and Glitches - Proceedings of the 22nd CAADRIA Conference*, pages 75–84, Xi'an Jiaotong-Liverpool University, Suzhou, China, 2017. CUMINCAD.

[66] Gwyllim Jahn, Cameron Newnham, Nick Van Den Berg, and Matthew Beanland. Making in mixed reality: Holographic design, fabrication, assembly and analysis of woven steel structures. In *ACADIA 2018: Recalibration. On Imprecision and Infidelity. Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture*, pages 88–97. ACADIA, 2018.

[67] Daniela Mitterberger, Kathrin Dörfler, Timothy Sandy, Foteini Salveridou, Marco Hutter, Fabio Gramazio, and Matthias Kohler. Augmented bricklaying. *Construction Robotics*, 4(3):151–161, 2020.

[68] George M Whitesides and Bartosz Grzybowski. Self-assembly at all scales. *Science*, 295(5564):2418–2421, 2002.

[69] Scott Camazine, Jean-Louis Deneubourg, Nigel R Franks, James Sneyd, Guy Theraula, and Eric Bonabeau. Self-organization in biological systems. In *Self-Organization in Biological Systems*. Princeton university press, 2020.

[70] Peter Anthony Lawrence. *The making of a fly: the genetics of animal design.* Wiley-Blackwell, 1992.

[71] Carl Anderson, Guy Theraulaz, and J-L Deneubourg. Self-assemblages in insect societies. *Insectes sociaux*, 49:99–110, 2002.

[72] Anastasia Bizyaeva, Alessio Franci, and Naomi Ehrich Leonard. A general model of opinion dynamics with tunable sensitivity. *arXiv preprint arXiv:2009.04332*, 2020.

[73] Michael A Goodrich, Brian Pendleton, PB Sujit, and José Pinto. Toward human interaction with bio-inspired robot teams. In *2011 IEEE International Conference on Systems, Man, and Cybernetics*, pages 2859–2864. IEEE, 2011.

[74] Michael A. Goodrich, Brian Pendleton, Sean Kerman, and P. B. Sujit. What types of interactions do bio-inspired robot swarms and flocks afford a human? In *Robotics: Science and Systems VIII*. The MIT Press, 07 2013.

[75] Shin-Young Jung and Michael A Goodrich. Multi-robot perimeter-shaping through mediator-based swarm control. In *2013 16th International Conference on Advanced Robotics (ICAR)*, pages 1–6. IEEE, 2013.

[76] Daniel S Brown, Shin-Young Jung, and Michael A Goodrich. Balancing human and inter-agent influences for shared control of bio-inspired collectives. In *2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 4123–4128. IEEE, 2014.

[77] Musad Haque, Electa Baker, Christopher Ren, Douglas Kirkpatrick, and Julie A Adams. Analysis of biologically inspired swarm communication models. *Advances in Hybridization of Intelligent Methods: Models, Systems and Applications*, pages 17–38, 2018.

[78] Robert Ambrose, R Askew, W Bluethmann, MA Diftler, SM Goza, D Magruder, and F Rehnmark. The development of the robonaut system for space operations. *Proceedings of ICAR, Invited Session on Space Robotics*, 2001.

[79] Terrence Fong and Illah Nourbakhsh. Interaction challenges in human-robot space exploration. *interactions*, 12(2):42–45, 2005.

[80] Lloyd S Shapley and Martin Shubik. The assignment game i: The core. *International Journal of game theory*, 1(1):111–130, 1971.

[81] Dimitri P Bertsekas. The auction algorithm for assignment and other network flow problems: A tutorial. *Interfaces*, 20(4):133–149, 1990.

[82] R Preston McAfee and John McMillan. Auctions and bidding. *Journal of economic literature*, 25(2):699–738, 1987.

[83] Brian Paul Gerkey. *On multi-robot task allocation*. PhD thesis, University of Southern California, 2003.

[84] Steven M LaValle and Seth Hutchinson. Game theory as a unifying structure for a variety of robot tasks. In *Proceedings of 8th IEEE International Symposium on Intelligent Control*, pages 429–434. IEEE, 1993.

[85] Yan Meng. Multi-robot searching using game-theory based approach. *International Journal of Advanced Robotic Systems*, 5(4):44, 2008.

[86] Kang Woo Lee and Jeong-Hoon Hwang. Human–robot interaction as a cooperative game. *Trends in Intelligent Systems and Computer Engineering*, pages 91–103, 2008.

[87] Dylan Hadfield-Menell, Stuart J Russell, Pieter Abbeel, and Anca Dragan. Cooperative inverse reinforcement learning. *Advances in neural information processing systems*, 29, 2016.

[88] Erin Paeng, Jane Wu, and James Boerkoel. Human-robot trust and cooperation through a game theoretic framework. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 30, 2016.

[89] Jane Wu, Erin Paeng, Kari Linder, Piercarlo Valdesolo, and James C Boerkoel. Trust and cooperation in human-robot decision making. In *2016 aaai fall symposium series*, 2016.

[90] Vladimir Lefebvre. *Lectures on the Reflexive Games Theory*. Lulu. com, 2010.

[91] Sergey Tarasenko. The inverse task of the reflexive game theory: Theoretical matters, practical applications and relationship with other issues. *arXiv preprint arXiv:1011.3397*, 2010.

[92] Todd Wareham. Designing robot teams for distributed construction, repair, and maintenance. *ACM Transactions on Autonomous and Adaptive Systems (TAAS)*, 14(1):1–29, 2019.

[93] Jenay M Beer, Arthur D Fisk, and Wendy A Rogers. Toward a framework for levels of robot autonomy in human-robot interaction. *Journal of human-robot interaction*, 3(2):74, 2014.

[94] Hui-Min Huang, Elena Messina, Robert Wade, Ralph English, Brian Novak, and James Albus. Autonomy measures for robots. In *ASME International Mechanical Engineering Congress and Exposition*, volume 47063, pages 1241–1247, 2004.

[95] Hui-Min Huang, Kerry Pavek, James Albus, and Elena Messina. Autonomy levels for unmanned systems (alfus) framework: An update. In *Unmanned Ground Vehicle Technology VII*, volume 5804, pages 439–448. SPIE, 2005.

[96] Hui-Min Huang, Kerry Pavek, Brian Novak, James Albus, and E Messin. A framework for autonomy levels for unmanned systems (alfus). *Proceedings of the AUVSI's unmanned systems North America*, pages 849–863, 2005.

[97] Hui-Min Huang, Kerry Pavek, Mark Ragon, Jeffry Jones, Elena Messina, and James Albus. Characterizing unmanned system autonomy: Contextual autonomous capability and level of autonomy analyses. In *Unmanned Systems Technology IX*, volume 6561, pages 509–517. SPIE, 2007.

[98] Michael A Goodrich and Dan R Olsen. Seven principles of efficient human robot interaction. In *SMC'03 Conference Proceedings. 2003 IEEE International Conference on Systems, Man and Cybernetics. Conference Theme-System Security and Assurance (Cat. No. 03CH37483)*, volume 4, pages 3942–3948. IEEE, 2003.

[99] Dan R Olsen and Michael A Goodrich. Metrics for evaluating human-robot interactions. In *Proceedings of PERMIS*, volume 2003, page 4. Citeseer, 2003.

[100] David Feil-Seifer, Kristine Skinner, and Maja J Matarić. Benchmarks for evaluating socially assistive robotics. *Interaction Studies*, 8(3):423–439, 2007.

[101] Guy Hoffman and Cynthia Breazeal. Collaboration in human-robot teams. In *AIAA 1st intelligent systems technical conference*, page 6434, 2004.

[102] Terrence Fong, Charles Thorpe, and Charles Baur. Robot, asker of questions. *Robotics and Autonomous systems*, 42(3-4):235–243, 2003.

[103] Michael Baker and Holly A Yanco. Autonomy mode suggestions for improving human-robot interaction. In *2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No. 04CH37583)*, volume 3, pages 2948–2953. IEEE, 2004.

[104] David J Bruemmer, Donald D Dudenhoeffer, and Julie L Marble. Dynamic-autonomy for urban search and rescue. In *AAAI mobile robot competition*, pages 33–37. Menlo Park, CA, 2002.

[105] David J Bruemmer and M Walton. Collaborative tools for mixed teams of humans and robots. In *Proceedings of the Workshop on Multi-Robot Systems*, pages 219–229. Citeseer, 2003.

[106] Amos Freedy, Ewart DeVisser, Gershon Weltman, and Nicole Coeyman. Measurement of trust in human-robot collaboration. In *2007 International symposium on collaborative technologies and systems*, pages 106–114. IEEE, 2007.

[107] Ning Wang, David V Pynadath, and Susan G Hill. Trust calibration within a human-robot team: Comparing automatically generated explanations. In *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pages 109–116. IEEE, 2016.

[108] John Lee and Neville Moray. Trust, control strategies and allocation of function in human-machine systems. *Ergonomics*, 35(10):1243–1270, 1992.

[109] Guy Hoffman. Evaluating fluency in human–robot collaboration. *IEEE Transactions on Human-Machine Systems*, 49(3):209–218, 2019.

[110] Guy Hoffman and Cynthia Breazeal. Effects of anticipatory perceptual simulation on practiced human-robot tasks. *Autonomous Robots*, 28:403–423, 2010.

[111] Jeffrey P Bigham, Michael S Bernstein, and Eytan Adar. Human-computer interaction and collective intelligence. *Handbook of collective intelligence*, 57(4), 2015.

[112] Nikolaos Mavridis, Thirimachos Bourlai, and Dimitri Ognibene. The human-robot cloud: Situated collective intelligence on demand. In *2012 IEEE international conference on cyber technology in automation, control, and intelligent systems (CYBER)*, pages 360–365. IEEE, 2012.

[113] Sami Haddadin and Elizabeth Croft. Physical human–robot interaction. *Springer handbook of robotics*, pages 1835–1874, 2016.

[114] Dongqing Shi, Emmanuel G Collins Jr, Brian Goldiez, Arturo Donate, Xiuwen Liu, and Damion Dunlap. Human-aware robot motion planning with velocity constraints. In *2008 International symposium on collaborative technologies and systems*, pages 490–497. IEEE, 2008.

[115] Jim Mainprice, E Akin Sisbot, Léonard Jaillet, Juan Cortés, Rachid Alami, and Thierry Siméon. Planning human-aware motions using a sampling-based costmap planner. In *2011 IEEE International Conference on Robotics and Automation*, pages 5012–5017. IEEE, 2011.

[116] Matteo Saveriano, Fabian Hirt, and Dongheui Lee. Human-aware motion reshaping using dynamical systems. *Pattern Recognition Letters*, 99:96–104, 2017.

[117] Kynan Eng, Matti Mintz, and Paul FMJ Verschure. Collective human behavior in interactive spaces. In *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, pages 2057–2062. IEEE, 2005.

[118] Axel Kilian. The flexing room architectural robot: an actuated active-bending robotic structure using human feedback. In *Recalibration: On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture*, pages 232–141. Assoc. Comput. Aided Des. Archit. Dover, DE, 2018.

[119] Nikolaos Mavridis. A review of verbal and non-verbal human–robot interactive communication. *Robotics and Autonomous Systems*, 63:22–35, 2015.

[120] Nikolaos Mavridis and Deb Roy. Grounded situation models for robots: Where words and percepts meet. In *2006 IEEE/RSJ international conference on intelligent robots and systems*, pages 4690–4697. IEEE, 2006.

[121] John R Searle. A taxonomy of illocutionary acts. 1975.

[122] Rainer Stiefelhagen, Hazim Kemal Ekenel, Christian Fugen, Petra Gieselmann, Hartwig Holzapfel, Florian Kraft, Kai Nickel, Michael Voit, and Alex Waibel. Enabling multimodal human–robot interaction for the karlsruhe humanoid robot. *IEEE Transactions on Robotics*, 23(5):840–851, 2007.

[123] Britta Wrede, Stephan Buschkaemper, Claudia Muhl, and Katharina J Rohlfing. Analyses of feedback in hri. *How People Talk to Computers, Robots, and Other Artificial Communication Partners*, page 38, 2006.

[124] Joseph Weizenbaum. Eliza—a computer program for the study of natural language communication between man and machine. *Communications of the ACM*, 9(1):36–45, 1966.

[125] Michael L Mauldin. Chatterbots, tinymuds, and the turing test: Entering the loebner prize competition. In *AAAI*, volume 94, pages 16–21, 1994.

[126] Christian Wallraven, Michael Schultze, Betty Mohler, Argiro Vatakis, and Katerina Pastra. The poeticon enacted scenario corpus—a tool for human and computational experiments on action understanding. In *2011 IEEE International Conference on Automatic Face & Gesture Recognition (FG)*, pages 484–491. IEEE, 2011.

[127] Cynthia Breazeal and Juan Velásquez. Toward teaching a robot 'infant'using emotive communication acts. In *Proceedings of the 1998 simulated adaptive behavior workshop on socially situated intelligence*, pages 25–40. Citeseer, 1998.

[128] Kazunori Komatani, Ryosuke Ito, Tatsuya Kawahara, and Hiroshi G Okuno. Recognition of emotional states in spoken dialogue with a robot. In *Innovations in Applied Artificial Intelligence: 17th International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems, IEA/AIE 2004, Ottawa, Canada, May 17-20, 2004. Proceedings 17*, pages 413–423. Springer, 2004.

[129] Susan E Brennan, Xin Chen, Christopher A Dickinson, Mark B Neider, and Gregory J Zelinsky. Coordinating cognition: The costs and benefits of shared gaze during collaborative search. *Cognition*, 106(3):1465–1477, 2008.

[130] Susan R Fussell, Robert E Kraut, and Jane Siegel. Coordination of communication: Effects of shared visual context on collaborative work. In *Proceedings of the 2000 ACM conference on Computer supported cooperative work*, pages 21–30, 2000.

[131] Stefan Waldherr, Roseli Romero, and Sebastian Thrun. A gesture based interface for human-robot interaction. *Autonomous Robots*, 9:151–173, 2000.

[132] Volker Klingspor, John Demiris, and Michael Kaiser. Human-robot communication and machine learning. *Applied Artificial Intelligence*, 11(7):719–746, 1997.

[133] Nick DePalma, Sonia Chernova, and Cynthia Breazeal. Leveraging online virtual agents to crowdsource human-robot interaction. In *Proceedings of CHI Workshop on Crowdsourcing and Human Computation*. Citeseer, 2011.

[134] M. Waibel, M. Beetz, J. Civera, R. D'Andrea, J. Elfring, D. Gálvez-López, K. Häussermann, R.J.M. Janssen, J.M.M. Montiel, A. Perzylo, B. Schiessle, M. Tenorth, O. Zweigle, and M.J.G. Molengraft, van de. Roboearth. *IEEE Robotics and Automation Magazine*, 18(2):69–82, 2011.

[135] Dominique Hunziker, Mohanarajah Gajamohan, Markus Waibel, and Raffaello D'Andrea. Rapyuta: The roboearth cloud engine. In *2013 IEEE international conference on robotics and automation*, pages 438–444. IEEE, 2013.

[136] Yosuke Matsusaka, Shinya Fujie, and Tetsunori Kobayashi. Modeling of conversational strategy for the robot participating in the group conversation. In *Seventh European conference on speech communication and technology*, 2001.

[137] Hartwig Holzapfel. Towards development of multilingual spoken dialogue systems. In *Proceedings of the 2nd Language and Technology Conference*, 2005.

[138] Roland Snooks and Gwyllim Jahn. Closeness: on the relationship of multi-agent algorithms and robotic fabrication. *Robotic fabrication in architecture, art and design 2016*, pages 218–229, 2016.

[139] Jenny Preece, Yvonne Rogers, Helen Sharp, David Benyon, Simon Holland, and Tom Carey. *Human-computer interaction*. Addison-Wesley Longman Ltd., 1994.

[140] Maria Yablonina and Achim Menges. Distributed fabrication: cooperative making with larger groups of smaller machines. *Architectural design*, 89(2):62–69, 2019.

[141] Malte F Jung, Dominic DiFranzo, Brett Stoll, Solace Shen, Austin Lawrence, and Houston Claure. Robot assisted tower construction-a resource distribution task to study human-robot collaboration and interaction with groups of people. *arXiv preprint arXiv:1812.09548*, 2018.

[142] Andrea Bauer, Dirk Wollherr, and Martin Buss. Human–robot collaboration: a survey. *International Journal of Humanoid Robotics*, 5(01):47–66, 2008.

[143] Samuel Leder, Ramon Weber, Dylan Wood, Oliver Bucklin, and Achim Menges. Distributed robotic timber construction. *Proceedings of the 39th ACADIA*, 2019.

[144] Kirstin Petersen, Radhika Nagpal, Justin Werfel, et al. Termes: An autonomous robotic system for three-dimensional collective construction. In *Robotics: science and systems*, volume 7, pages 257–264. Los Angeles, CA, USA, 2011.

[145] Justin Werfel and Radhika Nagpal. Extended stigmergy in collective construction. *IEEE Intelligent Systems*, 21(2):20–28, 2006.

[146] Isla Xi Han, Edvard PG Bruun, Stuart Marsh, Matteo Tavano, Sigrid Adriaenssens, and Stefana Parascho. From concept to construction-a transferable design and robotic fabrication method for a building-scale vault. In *Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture: Distributed Proximities, Acadia 2020*, 2020.

[147] Steven J Keating, Julian C Leland, Levi Cai, and Neri Oxman. Toward site-specific and self-sufficient robotic fabrication on architectural scales. *Science robotics*, 2(5):eaam8986, 2017.

[148] Paul Kassabian, Simpson Gumpertz, Heger Achim Menges, and Justin Werfel. Towards force-aware robot collectives for on-site construction. In *Proc. of the 37th ACADIA Conf*, 2017.

[149] Michael Allwright, Navneet Bhalla, Haitham El-faham, Anthony Antoun, Carlo Pinciroli, and Marco Dorigo. Srocs: Leveraging stigmergy on a multi-robot construction platform for unknown environments. In *Swarm Intelligence: 9th International Conference, ANTS 2014, Brussels, Belgium, September 10-12, 2014. Proceedings 9*, pages 158–169. Springer, 2014.

[150] Plerre-P Grassé. La reconstruction du nid et les coordinations interindividuelles chezbellicositermes natalensis etcubitermes sp. la théorie de la stigmergie: Essai d'interprétation du comportement des termites constructeurs. *Insectes sociaux*, 6(1):41–80, 1959.

[151] Erin S Gloag, Lynne Turnbull, and Cynthia B Whitchurch. Bacterial stigmergy: an organising principle of multicellular collective behaviours of bacteria. *Scientifica*, 2015, 2015.

[152] Leslie Marsh and Christian Onof. Stigmergic epistemology, stigmergic cognition. *Cognitive Systems Research*, 9(1-2):136–149, 2008.

[153] E Wilson. The insect societies belknap press of harvard university press. *Cambridge, MA*, 1971.

[154] Edward O Wilson. Sociobiology: The new synthesis, cambridge, ma: Harvard u, 1975.

[155] Edmund R Hunt, Simon Jones, and Sabine Hauert. Testing the limits of pheromone stigmergy in high-density robot swarms. *Royal Society open science*, 6(11):190225, 2019.

[156] Yan Meng and Jing Gan. Livs: Local interaction via virtual stigmergy coordination in distributed search and collective cleanup. In *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1371–1376. IEEE, 2007.

[157] Andrew P Smith. An investigation of the mechanisms underlying nest construction in the mud wasp paralastor sp.(hymenoptera: Eumenidae). *Animal Behaviour*, 26:232–240, 1978.

[158] William Homan Thorpe. Learning and instinct in animals. 1956.

[159] Holly A Downing and Robert L Jeanne. Nest construction by the paper wasp, polistes: a test of stigmergy theory. *Animal behaviour*, 36(6):1729–1739, 1988.

[160] István Karsai and Zsolt Pénzes. Comb building in social wasps: self-organization and stigmergic script. *Journal of theoretical biology*, 161(4):505–525, 1993.

[161] Guy Theraulaz and Eric Bonabeau. A brief history of stigmergy. *Artificial life*, 5(2):97–116, 1999.

[162] Guy Theraulaz, Eric Bonabeau, and Jean-Louis Deneubourg. The mechanisms and rules of coordinated building in social insects. In *Information processing in social insects*, pages 309–330. Springer, 1999.

[163] Holly A Downing and Robert L Jeanne. The regulation of complex building behaviour in the paper wasp, polistes fuscatus (insecta, hymenoptera, vespidae). *Animal Behaviour*, 39(1):105–124, 1990.

[164] Guy Theraulaz and Eric Bonabeau. Modelling the collective building of complex architectures in social insects with lattice swarms. *Journal of theoretical biology*, 177(4):381–400, 1995.

[165] Chris Jones and Maja J Mataric. Automatic synthesis of communication-based coordinated multi-robot systems. In *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)(IEEE Cat. No. 04CH37566)*, volume 1, pages 381–387. IEEE, 2004.

[166] Justin Werfel, Yaneer Bar-Yam, and Radhika Nagpal. Construction by robot swarms using extended stigmergy. 2005.

[167] Ken Sugawara and Yohei Doi. Collective construction of dynamic structure initiated by semi-active blocks. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 428–433. IEEE, 2015.

[168] Ken Sugawara and Yohei Doi. Collective construction by cooperation of simple robots and intelligent blocks. In *International Conference on Intelligent Robotics and Applications*, pages 452–461. Springer, 2016.

[169] Michael Allwright, Navneet Bhalla, and Marco Dorigo. Structure and markings as stimuli for autonomous construction. In *2017 18th International Conference on Advanced Robotics (ICAR)*, pages 296–302. IEEE, 2017.

[170] Hadi Ardiny, Stefan John Witwicki, and Francesco Mondada. Autonomous construction of separated artifacts by mobile robots using slam and stigmergy. In *Proceedings of the 2015 Conference on Autonomous and Robotic Construction of Infrastructure, Ames, Iowa.© 2015*, number CONF, 2015.

[171] István Karsai and John W Wenzel. Productivity, individual-level and colony-level flexibility, and organization of work as consequences of colony size. *Proceedings of the National Academy of Sciences*, 95(15):8665–8669, 1998.

[172] Teshan Liyanage and Subha Fernando. Optimizing robotic swarm based construction tasks. *arXiv preprint arXiv:2106.09749*, 2021.

[173] Fritz Vollrath and Thiemo Krink. Spider webs inspiring soft robotics. *Journal of the Royal Society Interface*, 17(172):20200569, 2020.

[174] Jasmine Nguyen-Duc, Mehmet Mutlu, Simon Hauser, Alexandre Barnerdino, and Auke Ijspeert. Cooperative bridge building by self-reconfigurable modular robotsbased on ants' stigmergic behaviour. In *9th International Symposium on Adaptive Motion of Animals and Machines (AMAM 2019)*, number CONF, 2019.

[175] Oncay Yasa, Yasunori Toshimitsu, Mike Y Michelis, Lewis S Jones, Miriam Filippi, Thomas Buchner, and Robert K Katzschmann. An overview of soft robotics. *Annual Review of Control, Robotics, and Autonomous Systems*, 6:1–29, 2023.

[176] Daniela Rus and Michael T Tolley. Design, fabrication and control of soft robots. *Nature*, 521(7553):467–475, 2015.

[177] Francesco Stella and Josie Hughes. The science of soft robot design: A review of motivations, methods and enabling technologies. *Frontiers in Robotics and AI*, 9:1059026, 2023.

[178] Robert K Katzschmann, Joseph DelPreto, Robert MacCurdy, and Daniela Rus. Exploration of underwater life with an acoustically controlled soft robotic fish. *Science Robotics*, 3(16):eaar3449, 2018.

[179] Jahan Zeb Gul, Young Jin Yang, Kim Young Su, and Kyung Hyun Choi. Omni directional multimaterial soft cylindrical actuator and its application as a steerable catheter. *Soft robotics*, 4(3):224–240, 2017.

[180] Jun Shintake, Vito Cacucciolo, Dario Floreano, and Herbert Shea. Soft robotic grippers. *Advanced materials*, 30(29):1707035, 2018.

[181] Jiaqing Xiong, Jian Chen, and Pooi See Lee. Functional fibers and fabrics for soft robotics, wearables, and human–robot interface. *Advanced Materials*, 33(19):2002640, 2021.

[182] Hao Zhang, Zhaohua Lin, Yong Hu, Suqian Ma, Yunhong Liang, Lei Ren, and Luquan Ren. Low-voltage driven ionic polymer-metal composite actuators: Structures, materials, and applications. *Advanced Science*, 10(10):2206135, 2023.

[183] George M Whitesides. Soft robotics. *Angewandte Chemie International Edition*, 57(16):4258–4273, 2018.

[184] Aleksey V Maksimkin, Tarek Dayyoub, Dmitry V Telyshev, and Alexander Yu Gerasimenko. Electroactive polymer-based composites for artificial muscle-like actuators: A review. *Nanomaterials*, 12(13):2272, 2022.

[185] Creative Commons. Attribution 4.0 international (cc by 4.0), 2013. Accessed: 2025-04-17.

[186] Muyu Hao, Yanjie Wang, Zicai Zhu, Qingsong He, Denglin Zhu, and Minzhou Luo. A compact review of ipmc as soft actuator and sensor: current trends, challenges, and potential solutions from our recent work. *Frontiers in Robotics and AI*, 6:129, 2019.

[187] Jiale Wang, Yanjie Wang, Zicai Zhu, Jiahui Wang, Qingsong He, and Minzhou Luo. The effects of dimensions on the deformation sensing performance of ionic polymer-metal composites. *Sensors*, 19(9):2104, 2019.

[188] Tomoya Higashihara, Kazuya Matsumoto, and Mitsuru Ueda. Sulfonated aromatic hydrocarbon polymers as proton exchange membranes for fuel cells. *Polymer*, 50(23):5341–5357, 2009.

[189] Creative Commons. Attribution-noncommercial-noderivs 3.0 unported (cc by-nc-nd 3.0), 2007. Accessed: 2025-04-17.

[190] Matthew Damon Bennett and DJ Leo. Manufacture and characterization of ionic polymer transducers employing non-precious metal electrodes. *Smart Materials and Structures*, 12(3):424, 2003.

[191] Wei Liang, Hao Liu, Kunyang Wang, Zhihui Qian, Luquan Ren, and Lei Ren. Comparative study of robotic artificial actuators and biological muscle. *Advances in Mechanical Engineering*, 12(6):1687814020933409, 2020.

[192] Liang Yang, Hong Wang, and Xining Zhang. Recent progress in preparation process of ionic polymer-metal composites. *Results in Physics*, 29:104800, 2021.

[193] Longfei Chang, Yanfa Liu, Qian Yang, Linfeng Yu, Jiaqin Liu, Zicai Zhu, Pin Lu, Yucheng Wu, and Ying Hu. Ionic electroactive polymers used in bionic robots: a review. *Journal of Bionic Engineering*, 15:765–782, 2018.

[194] Mohsen Annabestani and Nadia Naghavi. Nonlinear identification of ipmc actuators based on anfis–narx paradigm. *Sensors and Actuators A: Physical*, 209:140–148, 2014.

[195] Hojat Zamyad, Nadia Naghavi, and Hasan Barmaki. A combined fuzzy logic and artificial neural network approach for non-linear identification of ipmc actuators with hysteresis modification. *Expert Systems*, 35(4):e12283, 2018.

[196] Yanjie Wang, Jiayu Liu, Yetao Zhu, Denglin Zhu, and Hualing Chen. Formation and characterization of dendritic interfacial electrodes inside an ionomer. *ACS applied materials & interfaces*, 9(36):30258–30262, 2017.

[197] Naoko Fujiwara, Kinji Asaka, Yasuo Nishimura, Keisuke Oguro, and Eiichi Torikai. Preparation of gold- solid polymer electrolyte composites as electric stimuli-responsive materials. *Chemistry of materials*, 12(6):1750–1754, 2000.

[198] Barbar Akle, Saila Nawshin, and Donald Leo. Reliability of high strain ionomeric polymer transducers fabricated using the direct assembly process. *Smart materials and structures*, 16(2):S256, 2007.

[199] Ozgun Cem Yılmaz, Ibrahim Sen, Baris Oguz Gurses, Okan Ozdemir, Levent Cetin, Mehmet Sarıkanat, Yoldas Seki, Kutlay Sever, and Emine Altinkaya. The effect of gold electrode thicknesses on electromechanical performance of nafion-based ionic polymer metal composite actuators. *Composites Part B: Engineering*, 165:747–753, 2019.

[200] Qingsong He, Min Yu, Linlin Song, Haitao Ding, Xiaoqing Zhang, and Zhendong Dai. Experimental study and model analysis of the performance of ipmc membranes with various thickness. *Journal of Bionic Engineering*, 8(1):77–85, 2011.

[201] Jie Ru, Yanjie Wang, Longfei Chang, Hualing Chen, and Dichen Li. Preparation and characterization of water-soluble carbon nanotube reinforced nafion membranes and so-based ionic polymer metal composite actuators. *Smart Materials and Structures*, 25(9):095006, 2016.

[202] Maxwell J Fleming, Kwang J Kim, and Kam K Leang. Mitigating ipmc back relaxation through feedforward and feedback control of patterned electrodes. *Smart materials and structures*, 21(8):085002, 2012.

[203] João Barramba, João Silva, and PJ Costa Branco. Evaluation of dielectric gel coating for encapsulation of ionic polymer–metal composite (ipmc) actuators. *Sensors and Actuators A: Physical*, 140(2):232–238, 2007.

[204] Yanjie Wang, Hualing Chen, Yongquan Wang, Zicai Zhu, and Dichen Li. Effect of dehydration on the mechanical and physicochemical properties of gold-and palladium-ionomeric polymer-metal composite (ipmc) actuators. *Electrochimica Acta*, 129:450–458, 2014.

[205] Matthew D Bennett and Donald J Leo. Ionic liquids as stable solvents for ionic polymer transducers. *Sensors and Actuators A: Physical*, 115(1):79–90, 2004.

[206] Frédéric Vidal, Cédric Plesse, Dominique Teyssié, and Claude Chevrot. Long-life air working conducting semi-ipn/ionic liquid based actuator. *Synthetic metals*, 142(1-3):287–291, 2004.

[207] Viljar Palmre, Joel J Hubbard, Maxwell Fleming, David Pugal, Sungjun Kim, Kwang J Kim, and Kam K Leang. An ipmc-enabled bio-inspired bending/twisting fin for underwater applications. *Smart Materials and Structures*, 22(1):014003, 2012.

[208] Joel J Hubbard, Maxwell Fleming, Viljar Palmre, David Pugal, Kwang J Kim, and Kam K Leang. Monolithic ipmc fins for propulsion and maneuvering in bioinspired underwater robotics. *IEEE Journal of Oceanic Engineering*, 39(3):540–551, 2013.

[209] Mehran Mojarrad and Mohsen Shahinpoor. Biomimetic robotic propulsion using polymeric artificial muscles. In *Proceedings of International Conference on Robotics and Automation*, volume 3, pages 2152–2157. IEEE, 1997.

[210] International Federation of Robotics. World robotics report. https://ifr.org/ifr-press-releases/news/global-industrial-robot-sales-doubled-over-the-past-five-years, 2018. Accessed: 2025-05-08.

[211] Lara Davis, Matthias Rippmann, Tom Pawlofsky, and Philippe Block. Innovative funicular tile vaulting: A prototype vault in switzerland. *Structural Engineer*, 90(11):46–55, 2012.

[212] Tomás Méndez Echenagucia, DA Pigram, Andrew Liew, Tom Van Mele, and Philippe Block. Full-scale prototype of a cable-net and fabric formed concrete thin-shell roof. *International Association for Shell and Spatial Structures*, 2018.

[213] Diederik Veenendaal and Philippe Block. Design process for prototype concrete shells using a hybrid cable-net and fabric formwork. *Engineering structures*, 75:39–50, 2014.

[214] Edvard PG Bruun, Ian Ting, Sigrid Adriaenssens, and Stefana Parascho. Human–robot collaboration: a fabrication framework for the sequential design and construction of unplanned spatial structures. *Digital Creativity*, 31(4):320–336, 2020.

[215] John Thomson. Brick-laying machine. https://patents.google.com/patent/US772191A/en, 1904. Filed May 9, 1904; issued October 11, 1904.

[216] British Pathé. Mechanical bricklayer (1967). https://www.youtube.com/watch?v=4MWald1Goqk, 2014. Shenfield, Essex. Accessed: 2025-05-08.

[217] Thomas Bock. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in construction*, 59:113–121, 2015.

[218] Daniel W Halpin and Roozbeh Kangari. Robotics feasibility in the construction industry. 1985.

[219] Kazutaka Yokota, Tsuyoshi Suzuki, Hajime Asama, Akihiro Matsumoto, and Isao Endo. A human interface system for the multi-agent robotic system. In *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, pages 1039–1044. IEEE, 1994.

[220] Stefana Parascho, Isla Xi Han, Alessandro Beghini, Masaaki Miki, Samantha Walker, Edvard PG Bruun, and Sigrid Adriaenssens. Lightvault: a design and robotic fabrication method for complex masonry structures. *Advances in Architectural Geometry*, page 25, 2021.

[221] Tobias Bonwetsch, Daniel Kobel, Fabio Gramazio, and Matthias Kohler. The informed wall: applying additive digital fabrication techniques on architecture. In *Proceedings of the 25th annual conference of the association for computer-aided design in architecture*, pages 489–495, 2006.

[222] Tobias Bonwetsch, Fabio Gramazio, and Matthias Kohler. Digitally fabricating non-standardised brick walls. In *ManuBuild, 1st international conference, Rotterdam*, pages 191–196, 2007.

[223] Gustave Falconnier. Glass building-block. https://www.glassian.org/Prism/Patent/402073/page1.html, 1886. Issued November 11, 1886.

[224] Philippe Block, Tom Van Mele, Andrew Liew, Matthew DeJong, David Escobedo, and John A Ochsendorf. Structural design, fabrication and construction of the armadillo vault. *The Structural Engineer: Journal of the Institution of Structural Engineer*, 96(5):10–20, 2018.

[225] Matthias Rippmann, Tom Van Mele, Mariana Popescu, Edyta Augustynowicz, Tomás Méndez Echenagucia, Cristian Javier Calvo Barentin, Ursula Frick, and Philippe Block. The armadillo vault: Computational design and digital fabrication of a freeform stone shell. In *Advances in architectural geometry 2016*, pages 344–363. vdf Hochschulverlag AG, 2016.

[226] Sébastien Goessens, Caitlin Mueller, and Pierre Latteur. Feasibility study for drone-based masonry construction of real-scale structures. *Automation in Construction*, 94:458–480, 2018.

[227] Kathrin Dörfler, Timothy Sandy, Markus Giftthaler, Fabio Gramazio, Matthias Kohler, and Jonas Buchli. Mobile robotic brickwork: automation of a discrete robotic fabrication process using an autonomous mobile robot. *Robotic fabrication in architecture, art and design 2016*, pages 204–217, 2016.

[228] Sherif Morad Abdelmohsen, Khaled Aly Tarabieh, Islam Ibrahim Salem, Yomna Saad El-Ghazi, Rana Bahaa El-Dabaa, and Asmaa Gamal Hassan. Coupling parametric design and robotic assembly simulation to generate thermally responsive brick walls. In *Building Simulation 2019*, volume 16, pages 3006–3013. IBPSA, 2019.

[229] Stefana Parascho, Jan Knippers, Moritz Dörstelmann, Marshall Prado, and Achim Menges. Modular fibrous morphologies: computational design, simulation and fabrication of differentiated fibre composite building components. In *Advances in architectural geometry 2014*, pages 29–45. Springer, 2015.

[230] Isla Xi Han, Forrest Meggers, and Stefana Parascho. Bridging the collectives: A review of collective human–robot construction. *International Journal of Architectural Computing*, 19(4):512–531, 2021.

[231] Karl E Weick. The collapse of sensemaking in organizations: The mann gulch disaster. *Administrative science quarterly*, pages 628–652, 1993.

[232] Gary A Kreps and Susan Lovegren Bosworth. Disaster, organizing, and role enactment: A structural approach. *American Journal of Sociology*, 99(2):428–463, 1993.

[233] David J Mendonca and William Al Wallace. A cognitive model of improvisation in emergency management. *IEEE Transactions on systems, man, and cybernetics-Part A: Systems and humans*, 37(4):547–561, 2007.

[234] Guy Hoffman and Gil Weinberg. Gesture-based human-robot jazz improvisation. In *2010 IEEE international conference on robotics and automation*, pages 582–587. IEEE, 2010.

[235] Guy Hoffman and Gil Weinberg. Interactive improvisation with a robotic marimba player. *Autonomous Robots*, 31(2):133–153, 2011.

[236] Mary M Crossan. Improvisation in action. *Organization Science*, 9(5):593–599, 1998.

[237] Keith Johnstone and Irving Wardle. *Impro: Improvisation and the theatre*. Routledge, 1979.

[238] Graham Wallas. *The art of thought.* J. Cape: London, 1926.

[239] Robert Keith Sawyer. *Creativity in performance*. Praeger, 1997.

[240] R Keith Sawyer. *Group creativity: Music, theater, collaboration*, chapter 6. Collective Ideation: Creativity, Teamwork, and Collaboration, pages 262–304. Psychology Press, 2014.

[241] R Keith Sawyer. *Group creativity: Music, theater, collaboration*, chapter 1. The characteristics of Group Creativity, pages 21–33. Psychology Press, 2014.

[242] Farook R Hamzeh, Hasnaa Alhussein, and Farah Faek. Investigating the practice of improvisation in construction. *Journal of Management in Engineering*, 34(6):04018039, 2018.

[243] Vanessa Ratten and Josh Hodge. So much theory, so little practice: a literature review of workplace improvisation training. *Industrial and Commercial Training*, 2016.

[244] Dusya Vera and Mary Crossan. Improvisation and innovative performance in teams. *Organization science*, 16(3):203–224, 2005.

[245] Philip A Ringstrom. "yes, and..."—how improvisation is the essence of good psychoanalytic dialogue: Reply to commentaries. *Psychoanalytic Dialogues*, 11(5):797–806, 2001.

[246] Bridget Erica Elam. " yes and": Exploring and heightening the positive psychology in improvisation. 2020.

[247] Dusya Vera and Mary Crossan. Theatrical improvisation: Lessons for organizations. *Organization Studies*, 25(5):727–749, 2004.

[248] Christopher D Azzara. An aural approach to improvisation: Music educators can teach improvisation even if they have not had extensive exposure to it themselves. here are some basic strategies. *Music Educators Journal*, 86(3):21–25, 1999.

[249] Rogério Costa. Free musical improvisation and the philosophy of gilles deleuze. *Perspectives of new music*, 49(1):127–142, 2011.

[250] Ed Sarath. A new look at improvisation. *Journal of music theory*, 40(1):1–38, 1996.

[251] Stephen A Leybourne. Managing change by abandoning planning and embracing improvisation. *Journal of General Management*, 31(3):11–29, 2006.

[252] Elizabeth Jochum and Jeroen Derks. Tonight we improvise! real-time tracking for human-robot improvisational dance. In *Proceedings of the 6th International Conference on Movement and Computing*, pages 1–11, 2019.

[253] Oscar Thörn, Peter Knudsen, and Alessandro Saffiotti. Human-robot artistic co-creation: a study in improvised robot dance. In *2020 29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, pages 845–850. IEEE, 2020.

[254] Kory Mathewson and Piotr Mirowski. Improvised theatre alongside artificial intelligences. In *Proceedings of the AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment*, volume 13, 2017.

[255] Isla Xi Han, Edvard PG Bruun, Stuart Marsh, Matteo Tavano, Sigrid Adriaenssens, and Stefana Parascho. Robotic vault: a cooperative robotic assembly method for brick vault construction. *ACADIA 2020 Conference Proceedings*, 2021.

[256] Mary Ellen Foster, Tomas By, Markus Rickert, and Alois Knoll. Human-robot dialogue for joint construction tasks. In *Proceedings of the 8th international conference on Multimodal interfaces*, pages 68–71, 2006.

[257] Hank Jones and Stephen Rock. Dialogue-based human-robot interaction for space construction teams. In *Proceedings, IEEE Aerospace Conference*, volume 7, pages 7–7. IEEE, 2002.

[258] Sangseok You, Jeong-Hwan Kim, SangHyun Lee, Vineet Kamat, and Lionel P Robert Jr. Enhancing perceived safety in human–robot collaborative construction using immersive virtual environments. *Automation in Construction*, 96:161–170, 2018.

[259] Seong-Whan Lee. Automatic gesture recognition for intelligent human-robot interaction. In *7th International Conference on Automatic Face and Gesture Recognition (FGR06)*, pages 645–650. IEEE, 2006.

[260] Selma Sabanovic, Marek P Michalowski, and Reid Simmons. Robots in the wild: Observing human-robot social interaction outside the lab. In *9th IEEE International Workshop on Advanced Motion Control, 2006.*, pages 596–601. IEEE, 2006.

[261] Yizhi Liu, Mahmoud Habibnezhad, and Houtan Jebelli. Brainwave-driven human-robot collaboration in construction. *Automation in Construction*, 124:103556, 2021.

[262] Onur Soysal and Erol Sahin. Probabilistic aggregation strategies in swarm robotic systems. In *Proceedings 2005 IEEE Swarm Intelligence Symposium, 2005. SIS 2005.*, pages 325–332. IEEE, 2005.

[263] Manuele Brambilla, Eliseo Ferrante, Mauro Birattari, and Marco Dorigo. Swarm robotics: a review from the swarm engineering perspective. *Swarm Intelligence*, 7(1):1–41, 2013.

[264] Bruce W Tuckman. Developmental sequence in small groups. *Psychological bulletin*, 63(6):384, 1965.

[265] Bailey Derek. Improvisation: its nature and practice in music. *The British Library National Sound Archive*, 1992.

[266] intersubjectivity. Oxford Reference.

[267] Universal Robots. Ur5 collaborative robot arm: Flexible and lightweight robotic arm.

[268] lady ada, Dan Halbert, Anne Barela, Kattni Rembor, and John Park. Adafruit circuit playground express. Adafruit. First published on Oct 12, 2017; last updated on May 05, 2021.

[269] Jonas Buchli, Markus Giftthaler, Nitish Kumar, Manuel Lussi, Timothy Sandy, Kathrin Dörfler, and Norman Hack. Digital in situ fabrication-challenges and opportunities for robotic in situ fabrication in architecture, construction, and beyond. *Cement and Concrete Research*, 112:66–75, 2018.

[270] Aleksandra Anna Apolinarska, Matteo Pacher, Hui Li, Nicholas Cote, Rafael Pastrana, Fabio Gramazio, and Matthias Kohler. Robotic assembly of timber joints using reinforcement learning. *Automation in Construction*, 125:103569, 2021.

[271] Charles M Eastman, Chuck Eastman, Paul Teicholz, Rafael Sacks, and Kathleen Liston. *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons, 2011.

[272] Jeff Pressing. Improvisation: methods and models. *John A. Sloboda (Hg.): Generative processes in music, Oxford*, pages 129–178, 1988.

[273] Andrew Saint. *Architect and engineer: a study in sibling rivalry*. Yale University Press New Haven, CT, 2007.

[274] Daniel Paes, Javier Irizarry, and Diego Pujoni. An evidence of cognitive benefits from immersive design review: Comparing three-dimensional perception and presence between immersive and non-immersive virtual environments. *Automation in Construction*, 130:103849, 2021.

[275] Patrick Baudisch, Stefanie Mueller, et al. Personal fabrication. *Foundations and Trends® in Human–Computer Interaction*, 10(3–4):165–293, 2017.

[276] Aluna Everitt. Enabling digital fabrication approaches for the design and prototyping of robotic artifacts.

[277] David Rutten. Grasshopper [computer software]. `https://www.grasshopper3d.com/`, 2021.

[278] Jesse Rond, Alan Sanchez, Jaden Berger, and Heather Knight. Improv with robots: creativity, inspiration, co-performance. In *2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, pages 1–8. IEEE, 2019.

[279] Iremnur Tokac, Benay Gursoy, Herman Bruyninckx, and Andrew Vande Moere. Craft-inspired digital fabrication: A study of interactive robotic clay carving. In *Proceedings of the 7th Annual ACM Symposium on Computational Fabrication*, pages 1–14, 2022.

[280] Isla Xi Han and Stefana Parascho. Improv-structure: exploring improvisation in collective human-robot construction. In *International Conference on Trends on Construction in the Post-Digital Era*, pages 233–243. Springer, 2022.

[281] Daniela Mitterberger, Lidia Atanasova, Kathrin Dörfler, Fabio Gramazio, and Matthias Kohler. Tie a knot: human–robot cooperative workflow for assembling wooden structures using rope joints. *Construction Robotics*, 6(3):277–292, 2022.

[282] Irene Alcubilla Troughton, Kim Baraka, Koen Hindriks, and Maaike Bleeker. Robotic improvisers: Rule-based improvisation and emergent behaviour in hri. In *2022 17th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pages 561–569. IEEE, 2022.

[283] Sonia Moore. *Training an actor: the stanislavski system in class*. Harmondsworth; New York: Penguin Books, 1979.

[284] Guy Hoffman. On stage: robots as performers. In *RSS 2011 Workshop on Human-Robot Interaction: Perspectives and Contributions to Robotics from the Human Sciences. Los Angeles, CA*, volume 1, page 21, 2011.

[285] Anthony Pugh. *An introduction to tensegrity*. Univ of California Press, 1976.

[286] Kenneth Snelson. Snelson on the tensegrity invention. *International Journal of Space Structures*, 11(1-2):43–48, 1996.

[287] Kenneth Snelson. The art of tensegrity. *International journal of space structures*, 27(2-3):71–80, 2012.

[288] Reg Connelly and Maria Terrell. Globally rigid symmetric tensegrities. *Structural Topology 1995 núm 21*, 1995.

[289] Kenneth Duane Snelson. Continuous tension, discontinuous compression structures, U.S. Patent 3,169,611; Filed Mar. 14, 1960; Granted Feb. 16, 1965.

[290] KHUSHKARSTUDIO. Case study: Moom pavilion, 2017. Accessed: 2017-04-25.

[291] Mark Cohen. Kenneth snelson: the lyricism of structure. *Sculpture*, 1999.

[292] Lauren Vasey, Long Nguyen, Tovi Grossman, Heather Kerrick, Tobias Schwinn, David Benjamin, Maurice Conti, and Achim Menges. Human and robot collaboration enabling the fabrication and assembly of a filament-wound structure. In *ACADIA//2016: Posthuman Frontiers: Data, Designers, and Cognitive Machines, Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*, pages 184–195, 2016.

[293] Benjamin Lafreniere, Tovi Grossman, Fraser Anderson, Justin Matejka, Heather Kerrick, Danil Nagy, Lauren Vasey, Evan Atherton, Nicholas Beirne, Marcelo H Coelho, et al. Crowdsourced fabrication. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 15–28, 2016.

[294] Birzhan Nurimbetov, Margulan Issa, and Huseyin Atakan Varol. Robotic assembly planning of tensegrity structures. In *2019 IEEE/SICE International Symposium on System Integration (SII)*, pages 73–78. IEEE, 2019.

[295] Gary Bradski. The opencv library. *Dr. Dobb's Journal: Software Tools for the Professional Programmer*, 25(11):120–123, 2000.

[296] Tom Van Mele, Andrew Liew, Tomas Mendez, Matthias Rippmann, et al. Compas: A framework for computational research in architecture and structures. *ETHZ: Block Researc h Group*, 2017.

[297] Daniela Mitterberger and Kathrin Dörfler. Rethinking digital construction: A collaborative future of humans, machines and craft. *Architectural Design*, 94(5):108–117, 2024.

[298] Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N Gomez, Łukasz Kaiser, and Illia Polosukhin. Attention is all you need. *Advances in neural information processing systems*, 30, 2017.

[299] Isla Xi Han and Stefana Parascho. Spontaneous tensegrity: Exploring improvisational design and robotic fabrication in tensegrity structures. *ROB|ARCH 2024 Beyond Optimization conference*, 2024.

[300] Alex Wang, Yada Pruksachatkun, Nikita Nangia, Amanpreet Singh, Julian Michael, Felix Hill, Omer Levy, and Samuel Bowman. Superglue: A stickier benchmark for general-purpose language understanding systems. *Advances in neural information processing systems*, 32, 2019.

[301] JINMIN LI, YILU LUO, SHUAI LU, JINGYUN ZHANG, J Wang, RIZEN GUO, and SHAOMING WANG. Chatdesign: bootstrapping generative floor plan design with pre-trained large language models. In *Proceedings of the 29th International Conference of the Association for Computer Aided Architectural Design Research in Asia (CAADRIA) 2024*, volume 1, pages 99–108, 2024.

[302] Kyungki Kim, Mykhailo Ivashchenko, Prashnna Ghimire, and Pei-Chi Huang. Context-aware and adaptive task planning for autonomous construction robots through llm-robot communication. *Available at SSRN 4827728*, 2024.

[303] Junwen Zheng and Martin Fischer. Dynamic prompt-based virtual assistant framework for bim information search. *Automation in Construction*, 155:105067, 2023.

[304] Nikos Dimitropoulos, Pantelis Papalexis, George Michalos, and Sotiris Makris. Advancing human-robot interaction using ai–a large language model (llm) approach. In *European Symposium on Artificial Intelligence in Manufacturing*, pages 116–125. Springer, 2023.

[305] OpenAI. Openai api. version 1.35.15. gpt-3.5-turbo [large language model]. https://platform.openai.com, 2024. Accessed: 2024.

[306] Taylor Marks. Playsound [computer software]. https://github.com/TaylorSMarks/playsound, 2021. GitHub. Retrieved November 8, 2024.

[307] Microsoft. Use voice typing to talk instead of type on your pc. https://support.microsoft.com/en-us/windows/use-voice-typing-to-talk-instead-of-type-on-your-pc-fec94565-c4bd-329d-e59a-af033fa5689f, n.d. Microsoft Support. Retrieved November 8, 2024.

[308] Ggaliwango Marvin, Nakayiza Hellen, Daudi Jjingo, and Joyce Nakatumba-Nabende. Prompt engineering in large language models. In *International conference on data intelligence and cognitive informatics*, pages 387–402. Springer, 2023.

[309] Jiawei Liu, Chunqiu Steven Xia, Yuyao Wang, and Lingming Zhang. Is your code generated by chatgpt really correct? rigorous evaluation of large language models for code generation. *Advances in Neural Information Processing Systems*, 36:21558–21572, 2023.

[310] Philippe Fleischmann, Gonzalo Casas, and Michael Lyrenmann. COMPAS RRC: Online control for abb robots over a simple-to-use python interface., 7 2020. https://compas-rrc.github.io/compas$_r$*rc*.

[311] Isla Xi Han. Llm-enabled hri. https://github.com/islaxihan/HRI$_L$*LM.git*, 2024.*Accessed : Date*.

[312] Creative X Project. Rhythm Bots, 2025. Accessed: 2025-03-23.

[313] Susan Marshall Company. Rhythm Bath, 2023. Accessed: 2025-03-23.

[314] Naomi Ehrich Leonard, Jane Cox, Dan Trueman, María Santos, Kathryn Wantlin, Isla Xi Han, Sarah Witzman, and Tess James. Rhythm bots (2024): A sensitive improvisational environment. In *Conference on Neural Information Processing Systems, NeurIPS, Creative-AI Track*, 2024.

[315] Mahsoo Salimi. *Swarm Systems in Art and Architecture: State of the Art*. Springer Nature, 2021.

[316] Studio Drift. I Am Storm, n.d. Accessed: March 11, 2025.

[317] Vedant Vyas, Martin Schuck, Dinushka O Dahanaggamaarachchi, Siqi Zhou, and Angela P Schoellig. Swarmgpt-primitive: A language-driven choreographer for drone swarms using safe motion primitive composition. *arXiv preprint arXiv:2412.08428*, 2024.

[318] NCPA China. 2047 Apologue by Director ZHANG Yimou - NCPA China, n.d. [Accessed: 14-Dec-2019].

[319] ZKM | Center for Art and Media Karlsruhe. Resonate: An Interactive Light and Sound Installation, 2012. Accessed: 2025-03-18.

[320] Benjamin Knichel and Holger Reckter. Resonate: an interactive light-and sound-installation using a spatial tangible interface. In *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology*, pages 1–4, 2014.

[321] TUNDRA. THE DAY WE LEFT FIELD, 2023. Accessed: 2025-03-18.

[322] Creative Commons. Attribution-noncommercial-noderivatives 4.0 international (cc by-nc-nd 4.0), 2013. Accessed: 2025-04-17.

[323] TUNDRA. THE DAY WE LEFT FIELD, 2019. Accessed: 2025-03-18.

[324] J Paulo Davim, VC Clemente, and Sérgio Silva. Surface roughness aspects in milling mdf (medium density fibreboard). *The International Journal of Advanced Manufacturing Technology*, 40:49–55, 2009.

[325] Nico Pietroni, Marco Tarini, Amir Vaxman, Daniele Panozzo, and Paolo Cignoni. Position-based tensegrity design. *ACM Transactions on Graphics*, 36(6), 2017.

[326] Yuta Shimoda, Kai Suto, Sei Hayashi, Tomoyuki Gondo, and Tomohiro Tachi. Developable membrane tensegrity structures based on origami tessellations. *Advances in Architectural Geometry 2023*, page 303, 2023.

[327] Sachin Sean Gupta, Ying Yi Tan, Pei Zhi Chia, Christyasto P Pambudi, Yu Han Quek, Christine Yogiaman, and Kenneth J Tracy. Prototyping knit tensegrity shells: a design-to-fabrication workflow. *SN Applied Sciences*, 2:1–13, 2020.

[328] Yohei Nagano and Takuo Nagai. Form-finding and structural modeling of membrane-tensegrity composite structures with proposal for highly feasible model. *Proceedings of the IASS 2024 Symposium: Redefining the Art of Structural Design*, 2024.

[329] Richard Buckminster Fuller. Tensile-integrity structures, U.S. Patent 3,063,521; Filed Aug. 31, 1959; Granted Nov. 13, 1962.

[330] David Georges Emmerich. Construction de réseaux autotendants, French Patent 1.377.290; Filed Apr. 10, 1963; Granted Nov. 06, 1964.

[331] Katherine Liapi and Jinman Kim. Tensegrity structures of helical shape: A parametric approach. In *Proceedings of the eCAADe 2009 Conference on Computation: The New Realm of Architectural Design, Istanbul*, pages 53–58, 2009.

[332] Katherine A. Liapi. Enneper tensegrity pavilion - form & force international exhibition of innovative structures crown plaza - fira center, barcelona, 2019, 2019. Accessed: 2025-04-05.

[333] Katherine A. Liapi. Let me fly high, in context of the 16th venice biennale. time space existence exhibition., 2018. Accessed: 2025-04-05.

[334] Kröller-Müller Museum. Needle tower, 1968 by kenneth snelson, n.d. Accessed: 2025-04-05.

[335] JY Zhang, SD Guest, and M Ohsaki. Symmetric prismatic tensegrity structures: Part i. configuration and stability. *International Journal of Solids and Structures*, 46(1):1–14, 2009.

[336] Daniel Piker. Kangaroo physics, 2025. Accessed: 2025-04-05.

[337] Karamba3D. Karamba3d, 2025. Accessed: 2025-04-05.

[338] Li-Yuan Zhang, Yue Li, Yan-Ping Cao, Xi-Qiao Feng, and Huajian Gao. Self-equilibrium and super-stability of truncated regular polyhedral tensegrity structures: a unified analytical solution. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 468(2147):3323–3347, 2012.

[339] Ke Liu, Tomás Zegard, Phanisri P Pratapa, and Glaucio H Paulino. Unraveling tensegrity tessellations for metamaterials with tunable stiffness and bandgaps. *Journal of the Mechanics and Physics of Solids*, 131:147–166, 2019.

[340] Ke Liu and Glaucio H Paulino. Tensegrity topology optimization by force maximization on arbitrary ground structures. *Structural and Multidisciplinary Optimization*, 59:2041–2062, 2019.

[341] Kaan Yildiz and George A Lesieutre. Sizing and prestress optimization of class-2 tensegrity structures for space boom applications. *Engineering with Computers*, 38(2):1451–1464, 2022.

[342] Kai Liu and Andrés Tovar. An efficient 3d topology optimization code written in matlab. *Structural and multidisciplinary optimization*, 50:1175–1196, 2014.

[343] Tomás Zegard and Glaucio H Paulino. Bridging topology optimization and additive manufacturing. *Structural and Multidisciplinary Optimization*, 53:175–192, 2016.

[344] Robert McNeel et al. Rhinoceros 3d, version 7.0. *Robert McNeel & Associates, Seattle, WA*, 2020.

[345] Paolo Cignoni, Marco Callieri, Massimiliano Corsini, Matteo Dellepiane, Fabio Ganovelli, Guido Ranzuglia, et al. Meshlab: an open-source mesh processing tool. In *Eurographics Italian chapter conference*, volume 2008, pages 129–136. Salerno, Italy, 2008.

[346] Gabriel Taubin. A signal processing approach to fair surface design. In *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 351–358, 1995.

[347] Epic Games, Version 5.3.2. Unreal engine. `https://www.unrealengine.com`, 2023.

[348] Jonathan Russ. Material topopt. `https://github.com/jr3737/material_topopt`, 2023.

List of Figures

A
Top3D_modZ MATLAB Code

```
 1 % A 169 LINE 3D TOPOLOGY OPITMIZATION CODE BY LIU AND TOVAR (JUL 2013)
 2 % --- MODIFIED BY TOMAS ZEGARD (JAN 2014)
 3 %
 4 % --- MODIFIED BY ISLA XI HAN for tensegrity optimization RP (APR 2024)
 5 % domain: half of the base element of a 2-element tensegrity
 6 %          (the result needs to be mirrored along x-axis for
 7 %           a complete piece)
 8 nelx = 16;
 9 nely = 32; % need to be even number for this program
10 nelz = 32;
11 volfrac = 0.1;
12 penal = 1.0;                 % Initial penalization (see lines 127-135 for continuation)
13 rmin = 2.5;                  % Filter radius
14 Q = 3;                       % Filter exponent
15
16 % USER-DEFINED LOOP PARAMETERS
17 maxloop = 350;               % Maximum number of iterations
18 tolx = 0.00;                 % Termination criterion (disabled for continuation - default: 0.01)
19 displayflag = true;          % Display structure flag
20 plotcutoff = 0.50;           % Display density cutoff
21 storefileprefix = 'output'; % Filename prefix for storage
22 storeiters = false;          % Store data for each iteration
23 storefinal = true;           % Store final result
24
25 % USER-DEFINED MATERIAL PROPERTIES
26 E0 = 1;             % Young's modulus of solid material
27 Emin = 1e-9;        % Young's modulus of void-like material
28 nu = 0.3;           % Poisson's ratio
29 % USER-DEFINED LOAD DOFs
30 % loads (1 down; 2 up)
31 loadnid = [(nelx+1)*(nely+1)*2-nely/2 ...
32             (nelx+1)*(nely+1)*(nelz-4)+1 ...
33             (nelx+1)*(nely+1)*(nelz-4)+nely+1];
34 loaddof = 3*loadnid(:) % DOFs notes # -1 -> y ; -2 -> x
35 loadval = [1.5 ...
36            -1 ...
37            -1];
38
39 % USER-DEFINED SUPPORT FIXED DOFs
40 % fixednid1 are fixed in all directions
41 % fixednid2 are fixed only along x axis, creating the plane where the
42 % geometry will be mirrored
43
44 fixednid1 = (nelx+1)*(nely+1)*(nelz+1)-(nelx+1)*(nely+1)+1:(nelx+1)*(nely+1)*(nelz+1)-(nelx+1)*(nely+1)+nely;                          % Node IDs
45
46 [Jf,Kf] = meshgrid(1:nely+1,1:nelz+1);                    % Coordinates
47 fixednid2 = nelx*(nely+1)+(Kf-1)*(nelx+1)*(nely+1)+Jf;  % Node IDs
```

```
fixeddof = [3*fixednid1(:); 3*fixednid1(:)-1; 3*fixednid1(:)-2; ...
            3*fixednid2(:)-2];        % DOFs


% PREPARE FINITE ELEMENT ANALYSIS
nele = nelx*nely*nelz;
ndof = 3*(nelx+1)*(nely+1)*(nelz+1);
F = sparse(loaddof,1,loadval,ndof,1);
U = zeros(ndof,1);
freedofs = setdiff(1:ndof,fixeddof);
KE = lk_H8(nu);
nodegrd = reshape(1:(nely+1)*(nelx+1),nely+1,nelx+1);
nodeids = reshape(nodegrd(1:end-1,1:end-1),nely*nelx,1);
nodeidz = 0:(nely+1)*(nelx+1):(nelz-1)*(nely+1)*(nelx+1);
nodeids = repmat(nodeids,size(nodeidz))+repmat(nodeidz,size(nodeids));
edofVec = 3*nodeids(:)+1;
edofMat = repmat(edofVec,1,24)+ ...
    repmat([0 1 2 3*nely + [3 4 5 0 1 2] -3 -2 -1 ...
    3*(nely+1)*(nelx+1)+[0 1 2 3*nely + [3 4 5 0 1 2] -3 -2 -1]],nele,1);
iK = kron(edofMat,ones(24,1))';
jK = kron(edofMat,ones(1,24))';
% HOUSEKEEPING
clear If Jf Kf Fl Il Jl fixednid1 fixednid2 fixednid3 nodegrd nodeidz nodeids
% PREPARE FILTER
step = ceil(rmin)-1;
iH = zeros(nele*(2*step+1)^3,1);
jH = zeros(size(iH)); vH = zeros(size(iH));
n = 0;
for el=1:nele
    [i,j,k] = ind2sub([nely,nelx,nelz],el);
    [ispan,jspan,kspan] = meshgrid(max(1,i-step):min(nely,i+step),max(1,j-step):min(nelx,j+step),max(1,k-step):min(nelz,k+step));
    dist = max(0,rmin-sqrt((ispan-i).^2 + (jspan-j).^2 + (kspan-k).^2)).^Q;
    vH(n+(1:numel(dist))) = dist(:);
    iH(n+(1:numel(dist))) = el;
    jH(n+(1:numel(dist))) = sub2ind([nely nelx nelz],ispan,jspan,kspan);
    n = n + numel(dist);
end
iH(n+1:end)=[]; jH(n+1:end)=[]; vH(n+1:end)=[];
H = sparse(iH,jH,vH);
Hs = sum(H,2);
% HOUSEKEEPING
clear iH jH vH ispan jspan kspan dist

% DEFINE PASSIVE-SOLID ZONES
% The top plane, which will be the table surface, must be solid
% Additionally, the bottom center where the cable will be attached is also
% solid.

pass_solid = false(nelx*nely*nelz,1);
```

```matlab
pass_solid(nelx*nely*nelz-1*nelx*nely+1:nelx*nely*nelz) = true;
pass_solid(nelx*nely-nely/2:nelx*nely-nely/2+1) = true;
pass_solid(2*nelx*nely-nely/2:2*nelx*nely-nely/2+1) = true;

df_solid = sum(sum(sum(pass_solid)))/(nelx*nely*nelz);
volfrac = volfrac+df_solid; % Adjust the volume fraction to consider passive
% HOUSEKEEPING

% APPLY PASSIVE ZONES
% Several areas are carved out.
% A sphere above the bottom center is carved out due to the rotational
% symetry requirement of the geometry to hange the cable.
% More over, the area along one side of the sphere is taken out to push for
% a hook-like shape, also for rotational symetry.
% Finally, the area right below the hanging point on the table surface is
% taken out to leave space for the cable.
passive = false(1,nely,nelz);
for ely=1:nely
    for elz=1:nelz
        if sqrt(((ely + ely-1)/2-nely/2.)^2+((elz + elz-1)/2-nelz/3.)^2)<nelz/4
            passive(1,ely,elz)=1;
        else
            passive(1,ely,elz)=0;
        end
        if (rem(ely,nely) <= nely*0.58) && (rem(elz,nelz) <= nelz/2) && (rem(elz,nelz) >= nelz/9)
            passive(1,ely,elz)=1;
        end
        if (rem(ely,nely) <= 2) && (rem(elz,nelz) <= nelz-6)
            passive(1,ely,elz)=1;
        end
        if ((rem(ely,nely) >= nely-1)||(rem(ely,nely) == 0)) && (rem(elz,nelz) <=nelz-6)
            passive(1,ely,elz)=1;
        end
    end
end
passive=repmat(passive,[1,nelx,1]);
x = repmat(volfrac,[nely,nelx,nelz]);
x(pass_solid) = 1;
x(find(passive))=0;

% PLOT DOMAIN AND BCS
plotDomainBCs(nelx,nely,nelz,loaddof,fixeddof,loadval) % Plot the domain and BCs

% INITIALIZE ITERATION
xPhys = x;
loop = 0;
change = 1;
```

```
if displayflag, figure('Color','w'), end
fprintf('=== ITERATIONS BEGIN... ===\n')
% START ITERATION
while change > tolx && loop < maxloop
    if storeiters
        filename = sprintf('%s%03.0f.mat',storefileprefix,loop);
        save(filename,'xPhys','change','c','penal');
    end
    loop = loop+1;
    % FE-ANALYSIS
    sK = KE(:)*(Emin+xPhys(:)'.^penal*(E0-Emin));
    K = sparse(iK(:),jK(:),sK(:)); K = (K+K')/2;

    % OPTION 1: Direct solver (original)
    U(freedofs,:) = K(freedofs,freedofs)\F(freedofs,:);
    % OPTION 2: Jacobi PCG (suggested by Liu & Tovar for large problems)
    % M = diag(diag(K(freedofs,freedofs)));
    % U(freedofs,:) = pcg(K(freedofs,freedofs),F(freedofs,:),1e-8,1000,M);
    % OPTION 3: Incomplete Cholesky PCG [fast but might fail]
    % L = ichol(K(freedofs,freedofs));
    % U(freedofs,:) = pcg(K(freedofs,freedofs),F(freedofs,:),1e-8,2000,L,L');

    % OBJECTIVE FUNCTION AND SENSITIVITY ANALYSIS
    ce = reshape(sum((U(edofMat)*KE).*U(edofMat),2),[nely,nelx,nelz]);
    c = sum(sum(sum((Emin+xPhys.^penal*(E0-Emin)).*ce)));
    dc = -penal*(E0-Emin)*xPhys.^(penal-1).*ce;
    dv = ones(nely,nelx,nelz);
    % FILTERING AND MODIFICATION OF SENSITIVITIES
    dc(:) = H*(dc(:)./Hs);
    dv(:) = H*(dv(:)./Hs);
    % OPTIMALITY CRITERIA UPDATE
    if loop<round(maxloop/6),          l1 = 0.0;      l2 = 1e9;      move = 0.15;
    elseif loop<round(maxloop/3),      l1 = 0.0;      l2 = 1e9;      move = 0.15; penal = 1.5;
    elseif loop<round(maxloop/2),      l1 = 0.0;      l2 = 1e9;      move = 0.15; penal = 2.0;
    elseif loop<round(maxloop*2/3),    l1 = lmid/1.1; l2 = lmid*1.1; move = 0.15; penal = 2.5;
    elseif loop<round(maxloop*3/4),    l1 = lmid/1.1; l2 = lmid*1.1; move = 0.12; penal = 3.0;
    elseif loop<round(maxloop*5/6),    l1 = lmid/1.1; l2 = lmid*1.1; move = 0.10; penal = 3.5;
    elseif loop<round(maxloop*11/12),  l1 = lmid/1.1; l2 = lmid*1.1; move = 0.08; penal = 4.0;
    else,                              l1 = lmid/1.1; l2 = lmid*1.1; move = 0.04; penal = 4.25;
    end
    while (l2-l1)/(l1+l2) > 1e-3
        lmid = 0.5*(l2+l1);
        xnew = max(0,max(x-move,min(1,min(x+move,x.*sqrt(-dc./dv/lmid)))));
```

```
        xnew(pass_solid) = 1;
        xPhys(:) = (H*xnew(:))./Hs;
        if sum(xPhys(:)) > volfrac*nele, l1 = lmid; else l2 = lmid; end
    end
    change = max(abs(xnew(:)-x(:)));
    x = xnew;
    % PRINT RESULTS
    fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f ch.:%7.3f\n',loop,c,mean(xPhys(:)),change);
    % PLOT DENSITIES
    if displayflag
        plotTOP3D(xPhys,plotcutoff);
        s = sprintf('Iteration = %03.0f      Penal = %.2f',loop,penal);
        title(s), drawnow
    end
end
if storefinal
    filename = sprintf('%s%03.0f.mat',storefileprefix,loop);
    save(filename,'xPhys','change','c','penal');
end
```

B
Mesh .inp Format Generation Python Code

IslaRP\Tenbracket_mesh_IXH_notes.py

```
'''Script to create a simple 3-node triangle mesh of a general polygon.
Modified by Isla Xi Han on 2024/04/27 for
MSE517-CEE517-MAE571_S2024 Structural and Material Optimization
RP final project
'''
import numpy as np
import trimesh_utilities

mesh_filename = "Tenbracket.inp"
average_finite_element_size = 1.8
# Create a list of tuples representing the bounding (x, y) points of the polygon
#   Note: This list must start and end with the same (x, y) point
## The points are exported from Grasshopper/Rhino
my_bounding_points = [(23.113926, 0.210089),
                        (25.776181, 1.162491),
                        (27.73515, 3.22416),
                        (28.813906, 5.848142),
                        (29.048848, 8.694953),
                        (29.038344, 11.55848),
                        (29.038561, 14.422037),
                        (29.033493, 17.285541),
                        (28.713604, 20.123867),
                        (27.536282, 22.709017),
                        (25.461407, 24.643978),
                        (23.425923, 26.598134),
                        (24.140209, 29.153257),
                        (26.356575, 30.858102),
                        (29.147508, 31.438196),
                        (29.569618, 33.324191),
                        (26.756805, 33.666228),
                        (23.893428, 33.637586),
                        (21.029854, 33.63827),
                        (18.166279, 33.638291),
                        (15.302704, 33.638285),
                        (12.43913, 33.638326),
                        (9.575555, 33.637969),
                        (6.711983, 33.638524),
                        (3.848609, 33.670579),
                        (1.019095, 33.396817),
                        (0.823684, 31.466673),
                        (3.636498, 31.106535),
                        (6.499873, 31.138535),
                        (9.363446, 31.138419),
                        (12.22702, 31.138286),
                        (15.090595, 31.138149),
                        (17.954167, 31.136168),
                        (20.747547, 30.76922),
                        (20.687296, 28.357552),
                        (19.745133, 25.660443),
                        (19.444248, 22.819505),
                        (19.684321, 19.97042),
                        (20.436169, 17.212687),
                        (21.726179, 14.659852),
```

```python
                        (22.818353, 12.029199),
                        (22.750733, 9.194814),
                        (21.603214, 6.586244),
                        (19.7253, 4.437728),
                        (17.179185, 3.213097),
                        (15.418399, 1.610727),
                        (17.388972, 0.159627),
                        (20.252194, 0.134092),
                        (23.113926, 0.210089)]

nodal_coordinates, element_connectivity = trimesh_utilities.get_nodal_coordinates_and_element_connectivity(
        my_bounding_points,
        average_finite_element_size
    )

nodal_x_coordinates = nodal_coordinates[:, 0].ravel()
nodal_y_coordinates = nodal_coordinates[:, 1].ravel()

geometric_tolerance = average_finite_element_size / 100.0

# Create the index sets of nodes to specify boundary conditions later
indices_of_nodes_on_the_top_edge   = np.argwhere(np.abs(nodal_y_coordinates) > 33)
mask = (np.abs(nodal_y_coordinates) < 4) & (np.abs(nodal_y_coordinates) >0) & (np.abs(nodal_x_coordinates) <17)
indices_of_nodes_on_the_tip_edge  = np.argwhere(mask)

# nodesets is a dictionary which maps the nodeset name as a string to a numpy array
#   of integers representing the indices of the nodes in the nodeset
nodesets = {"top_edge_nodeset":   indices_of_nodes_on_the_top_edge,
            "tip_edge_nodeset": indices_of_nodes_on_the_tip_edge}

# Write the meshfile to the current directory
trimesh_utilities.write_the_mesh_to_file(mesh_filename, nodal_coordinates, element_connectivity, nodesets)

# Plot the mesh and the nodesets just as a quick visual check
trimesh_utilities.plot_mesh_and_nodesets(nodal_coordinates, element_connectivity, nodesets)

```

C
MaterialTopOpt Python Code

SetupDesignProblemAndRun_RP_IXH_notes.py

```python
"""The main file for problem setup and execution.

User parameters are specified for the macroscale problem, the representative
volume element problem, and for the optimizer. Subsequently, the optimization
problem is executed in the "main" function at the end of the file.

Modified by Isla Xi Han on 2024/04/27 for
MSE517-CEE517-MAE571_S2024 Structural and Material Optimization
RP final project
"""
import os
import logging
import numpy as np

import src.material_topopt.utilities as utils
from src.material_topopt.optimizer import MaterialOptimizer

logging_level = logging.INFO
utils.setup_logging(logging_level, logfile_path='') # Specify a logfile_path for console output to go into a file


########################################################################################################################
########################################################################################################################
def simp_exponent_continuation_function(iteration_number: int) -> float:
    """Computes the SIMP exponent.

    Using the optimization iteration number, the user should return a float
    corresponding to the SIMP exponent used in the elastic modulus interpolation
    within the representative volume element. The returned value must be greater
    than or equal to 1.0 and less than 5.

    Args:
        iteration_number: An integer containing the current optimization iteration number.

    Returns:
        A positive float for the SIMP exponent satisfying, 1 <= p < 5
    """
    if iteration_number < 50:
        return 3.0
    elif iteration_number < 75:
        return 3.5
    return 4.0


########################################################################################################################
########################################################################################################################
def smooth_heaviside_projection_continuation_function(iteration_number: int) -> float:
    """Computes the smooth Heaviside projection parameter.

    Using the optimization iteration number, the user should return a float
    corresponding to the smooth Heaviside projection parameter, \\beta in the function below.

    .. math::
        \\rho(\\hat{\\rho}) = \\frac{\\tanh{\\beta \\eta} + \\tanh{\\beta \\left( \\hat{\\rho} - \\eta \\right)}}
            {\\tanh{\\beta \\eta} + \\tanh{\\beta \\left( 1 - \\eta \\right)}}

    Args:
        iteration_number: An integer containing the current optimization iteration number.

    Returns:
        A smooth Heaviside projection parameter, beta, that is a positive float.
    """
    if iteration_number < 100:
        return 1.0
    elif iteration_number < 125:
        return 2.0
    elif iteration_number < 150:
```

```
        return 3.0
    elif iteration_number < 175:
        return 4.0
    return 5.0


##################################################################################################################
##################################################################################################################
def design_variable_initialization_function(nodal_x_coordinates: np.ndarray,
                                            nodal_y_coordinates: np.ndarray) -> np.ndarray:
    """Computes the initial design variables for the representative volume element.

    Given the X and Y coordinates of the nodes, this function should return an initial value
    for the design variable at each node using any method they wish. The design variables
    must all be between 0 and 1. Note that the X and Y nodal coordinates always range from 0 to 1.

    Args:
        nodal_x_coordinates: A numpy array containing the x coordinates of the RVE nodes.
        nodal_y_coordinates: A numpy array containing the y coordinates of the RVE nodes.

    Returns:
        A numpy array containing the initial design variables for each RVE node.
    """
    candidate_initial_design_variables = (0.5 + 0.5 * np.cos(2.0*np.pi * nodal_x_coordinates)) * \
                                         (0.5 + 0.5 * np.cos(2.0*np.pi * nodal_y_coordinates)) + \
                                         (0.5 + 0.5 * np.cos(2.0*np.pi * (nodal_x_coordinates - 0.5))) * \
                                         (0.5 + 0.5 * np.cos(2.0*np.pi * (nodal_y_coordinates - 0.5)))
    # Ensure design variables are between 0 and 1
    candidate_design_variable_min = np.amin(candidate_initial_design_variables)
    candidate_design_variable_extent = np.amax(candidate_initial_design_variables) - candidate_design_variable_min
    initial_design_variables = \
        (candidate_initial_design_variables - candidate_design_variable_min) / candidate_design_variable_extent
    return initial_design_variables


##################################################################################################################
##################################################################################################################
# User Defined Parameters

# The path to the directory in which the output files (e.g., VTK files, CSV files, figures, etc.) will be written.
output_directory_path = os.path.join(os.getcwd(), "outputRP_F5")

# The number of elements along each edge of the square RVE (must be a positive integer)
number_of_elements_along_each_edge = 100

# The radius of the design variable filter in units of the number of elements (must be a positive number > 1)
filter_radius_number_of_elements = 6

representative_volume_element_parameters = \
    {
        "number of elements along each edge": number_of_elements_along_each_edge,
        "stiff material elastic modulus": 1.0e3,
        "soft material elastic modulus": 1.0,
        "poissons ratio": 0.3,
        "SIMP exponent continuation function": simp_exponent_continuation_function,
        "smooth Heaviside projection continuation function": smooth_heaviside_projection_continuation_function,
        "design variable initialization function": design_variable_initialization_function,
        "density filter radius": float(filter_radius_number_of_elements) / float(number_of_elements_along_each_edge),
        "output directory path": output_directory_path,
        "enable vtk output": True,
        "enable matplotlib output": True
    }

# Letter G
fixed_boundary_nodesets = {"Fixed X Displacement Nodesets": ["top_edge_nodeset"],
                           "Fixed Y Displacement Nodesets": ["top_edge_nodeset"]}
applied_load_1 = {"Nodeset": "tip_edge_nodeset", "Load in X direction": 0.0, "Load in Y direction": 1.0}
applied_loads = [applied_load_1]
macroscale_problem_parameters = \
    {
```

```
        "macroscale finite element mesh filepath": "Tenbracket.inp",
        "fixed boundary condition nodesets": fixed_boundary_nodesets,
        "applied loads": applied_loads,
        "output directory path": output_directory_path
    }

optimization_problem_parameters = \
    {
        "maximum number of iterations": 250,
        "volume fraction constraint upper bound": 0.5,
        "restart iteration number": 0,
        "restart file write frequency": 500,
        "MMA move limit": 0.1,
        "optimization history output filepath": os.path.join(output_directory_path, "MaterialTopOptData.csv")
    }


########################################################################################################################
########################################################################################################################
if __name__ == "__main__":
    import matplotlib.pyplot as plt
    material_optimizer = \
        MaterialOptimizer(optimization_problem_parameters = optimization_problem_parameters,
                          macroscale_problem_parameters = macroscale_problem_parameters,
                          representative_volume_element_parameters = representative_volume_element_parameters)
    material_optimizer.macroscale_problem.plot_mesh()
    material_optimizer.macroscale_problem.representative_volume_element.plot_mesh()
    material_optimizer.run()
    material_optimizer.plot_history()
    plt.show()
```