Nathan Melenbrink

DESIGNING FOR UNSUPERVISED CONSTRUCTION

An Investigation of the Affordances of On-site Autonomy

RESEARCH REPORTS
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Edited by Professor Achim Menges

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Foreword

Ausgangspunkt der Dissertation von Nathan Melenbrink sind aktuelle Entwicklungen von Hardware- und Steuerungssystemen, die neue Ansätze für das robotische Bauen vor Ort ermöglichen und in ihrer Konsequenz auch Einfluss auf Entwurf, Planung und Konstruktion von baulichen Strukturen haben werden. Durch die Betrachtung der Wechselwirkungen von Bauprozess, Baumaschine, Bausystem und daraus entstehendem Bauwerken stellt die Arbeit bisherige Ansätze der Automatisierung von prädigitalem, schwerem Baugerät und den dazugehörigen Bauabläufe und Bauplanungsprozesse durch die Nutzung agilerer oder verteilter robotischer Systeme, den dazugehörigen Datenerfassungs- und Datenverarbeitungsmethoden sowie Sensor- und Aktorsystemen in Frage. Sie basiert auf einer überzeugenden Analyse des derzeitigen Stands der Forschung auf dem Gebiet der Vorort-Robotik im Bauwesen. Daraus leitet sie Ansätze für verteilter Baurobotersysteme und agilere, autonome Baumaschinen ab. Diese werden nicht nur konzeptualisiert und simuliert, sondern durch umfangreiche Experimentreihen auf beeindruckende Weise auch in Ihrer physischen Umsetzung getestet und evaluiert. Auf dem Weg zu einer neuen Art des Bauens leistet die Arbeit einen wichtigen Beitrag!

The starting point of Nathan Melenbrink's dissertation is current developments in hardware and control systems that will enable new approaches to robotic construction on site and, in their consequence, will also influence the design, planning and construction of building structures. By considering the interactions of the construction process, construction machine, construction system, and resulting building structures, this work challenges previous approaches to automating pre-digital heavy construction equipment and associated construction workflows and construction planning processes through the use of more agile or distributed robotic systems, associated data acquisition and processing methods, and sensor and actuator systems. It is based on a compelling analysis of the current state of research in the field of on-site robotics in construction. From this, it derives approaches for distributed construction robotics systems and more agile autonomous construction machines. These are not only conceptualized and simulated, but also impressively tested and evaluated in their physical implementation through extensive series of experiments. On the way to a new kind of construction, the dissertation makes an important contribution!

Professor Achim Menges

DESIGNING FOR UNSUPERVISED CONSTRUCTION

An Investigation of the Affordances of On-Site Autonomy

A dissertation approved
by the Faculty of Architecture and Urban Planning of the
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for the conferral of the title of
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Submitted by
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Professor Achim Menges

Committee member:
Dr. Justin Werfel

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Universität Stuttgart
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Nathan Melenbrink

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Abstract

Since the First Industrial Revolution, the construction and maintenance of buildings and infrastructure has been characterized by a reliance upon heavy equipment, which has shaped how designers and engineers conceive of their agency in the built environment. However, 21st century advances in hardware and control systems allow for distributed and autonomous hardware solutions, enabling a paradigm shift in the co-design of machines and the interventions they deliver. However, in order to overcome the inertia of the mature technologies developed around heavy equipment, an entirely new suite of sensors, actuators and algorithms needs to be developed.

This thesis will present an argument for small-scale distributed robotics for construction automation, and will demonstrate that this approach can utilize practical materials to build useful structures in unpredictable environments. This argument is supported by an extensive literature review focused on the technological requirements for unsupervised (fully autonomous) robotic construction, and identifies gaps between academic and industry research that remain unfilled. Among these overlooked areas are (1) the need for embedded sensing in construction materials, and for co-designing robot hardware in coordination with novel construction robots, and (2) the need for an autonomous solution to providing foundation support. These two needs are explored through the representative example tasks of truss assembly and pile driving, respectively. Each task is demonstrated in prototypical hardware, with an emphasis on realistic materials and scenarios not dependent on human preparation. Each task is explored in simulation as multi-agent deployments. Finally, a summarizing demonstration illustrates how these two research findings might be leveraged in coordination to advance autonomy in an example construction scenario.

Zusammenfassung

Seit der Ersten Industriellen Revolution ist der Bau sowie die spätere Instandhaltung von Gebäuden und gebauter Infrastruktur durch die Abhängigkeit von schwerem Gerät gekennzeichnet. Dies hat die Art und Weise, wie Entwerfer*innen und Ingenieur*innen die gebaute Umwelt konzipieren, nachhaltig geprägt.

Die Fortschritte des 21. Jahrhunderts, vor allem in der Entwicklung von Hardware und Steuerungssystemen, ermöglichen mittlerweile verteilte und autonome Hardware-Lösungen, welche einen grundlegenden Paradigmenwechsel hin zum Co-Design von Maschinen und den von ihnen durchgeführten Eingriffen ermöglichen. Um jedoch die Trägheit der vorwiegend für schweres Baugerät entwickelten und inzwischen etablierten Technologien zu überwinden, muss eine völlig neue Bandbreite an Sensoren, Aktoren und Algorithmen entwickelt werden.

Hierfür stellt diese Dissertation ein Konzept für verteilte, kleinmaßstäbliche Robotik in der Bauautomatisierung vor und zeigt auf, dass es mit diesem Ansatz möglich ist, praxistaugliche Baumaterialien für die Konstruktion nutzbarer Strukturen in nicht planbaren Umgebungen einzusetzen. Das vorgestellte Konzept baut auf einer umfangreichen Literaturübersicht auf, die sich auf die technologischen Anforderungen an unbeaufsichtigte (vollständig autonome) Bauprozesse mit verteilter Robotik konzentriert und bestehende Lücken zwischen akademischer und industrieller Forschung aufzeigt. Zu diesen bislang weitgehend unbeachteten Bereichen gehören (1) der Bedarf an eingebetteter Sensorik in Baumaterialien und an der Mitgestaltung von Roboterhardware in Koordination mit neuartigen Konstruktionsrobotern und (2) der Bedarf an einer autonomen Lösung für die Bereitstellung von Fundamentunterstützungen. Diese beiden Erfordernisse werden anhand repräsentativer Beispielaufgaben in der Montage von Tragwerken sowie der Spundwandrammung untersucht. Diese Aufgaben werden anhand prototypischer Hardware demonstriert, wobei der Schwerpunkt auf realistischen Materialien und Szenarien liegt, die nicht von menschlicher Vorarbeit abhängig sind. Jede Aufgabe wird zudem in Simulationen anhand von Multi-Agenten-Systemen erforscht. Abschließend wird in einer zusammenfassenden Demonstration veranschaulicht, wie diese beiden Forschungsergebnisse in einem Beispielszenario für mehr Autonomie in der Bauausführung genutzt werden könnten.

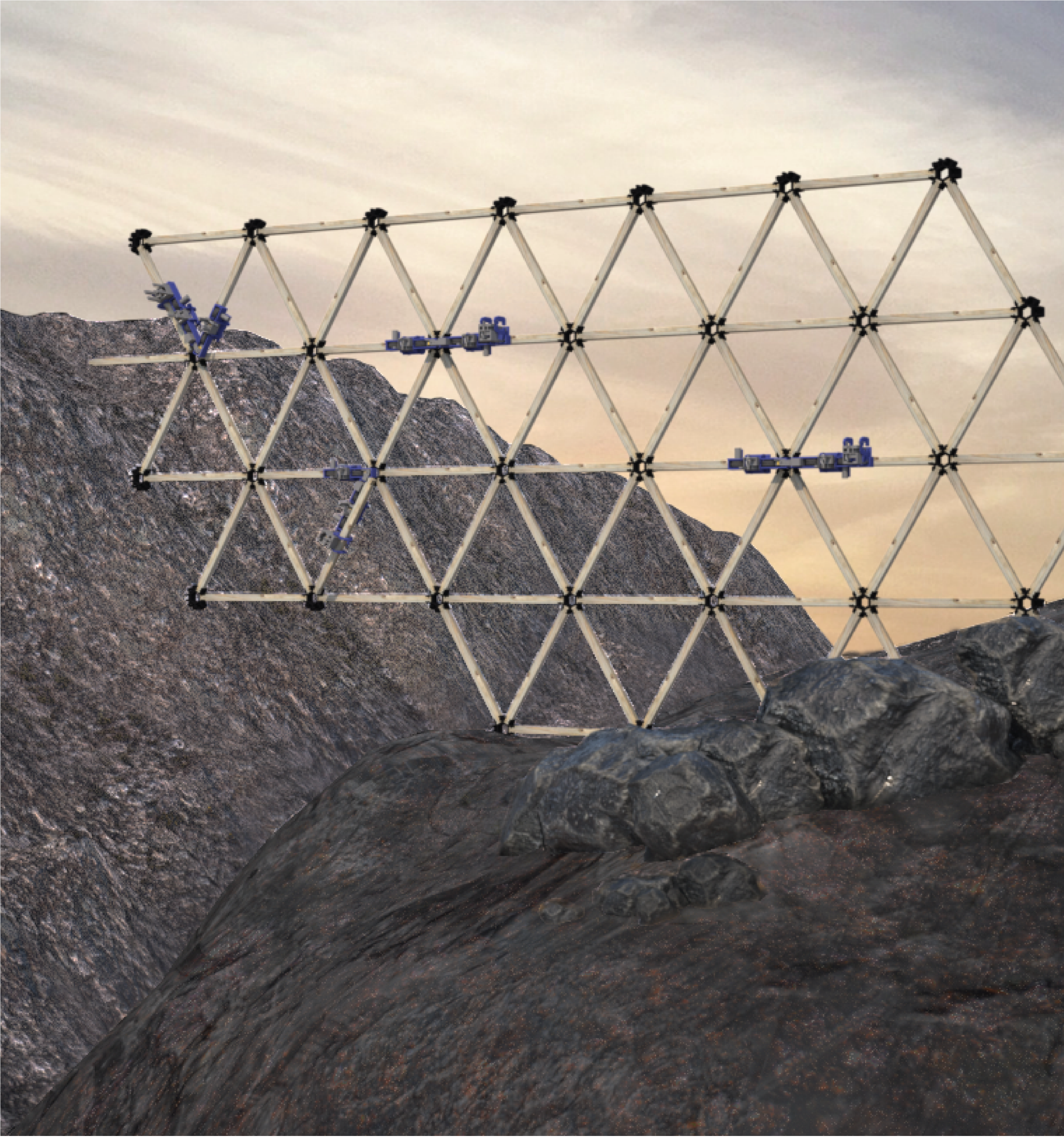

Figure 1.1: A hypothetical swarm of strut-climbing robots collectively builds a truss without human supervision using customized building materials instrumented specifically for robotic manipulation.

1

Introduction

Since the Industrial Revolution, technology has consistently moved at a pace regulated by the supply of human labor. Larger machines have meant greater productivity, and mechanization has been associated with increasingly larger scales of operation. However, with the advent of autonomous control systems and efficient electromechanical actuators, this association no longer holds true. Recent decades have seen the emergence of machines designed specifically for autonomously executing construction tasks. Without the need to support human operators or bulky diesel engines, these machines can embody a variety of scales, form factors and control schemes that would have been unthinkable in decades past. This new paradigm of emerging technologies for construction automation is fertile ground for designers and engineers who wish to re-conceptualize the role of automation in the construction and maintenance of the built environment. Rather than relying on legacy tools and techniques that were not designed for autonomous operation, taking full advantage of this opportunity requires the coordinated redesign of building components, robotic hardware, and on-site operations based on fundamental construction needs.

1.1 Dissertation aim

This thesis aims to **present an argument for the development of fully-autonomous construction systems**, capable of utilizing practical materials to build useful structures in unpredictable environments without human supervision. First, Article A articulates a motivation for pursuing the goal of unsupervised construction, which is carried through the whole of the Dissertation. Article A aims to **identify gaps where fundamental requirements toward this goal have gone unaddressed**, as well as to **provide a metric for evaluating on-site autonomy**, which could serve as the basis for evaluating future efforts.

Among the fundamental requirements for unsupervised construction that was identified in Article A is a system for distributed force sensing to ensure reliable robotic assembly, which is addressed in Article B. The objective of this article is to **determine whether force awareness improves the performance** of constrained robotic agents conducting discrete assembly tasks. Furthermore, this article aims to **uncover the affordances of building components instrumented with slim-profile force sensors**.

Article C presents a robotic method for autonomously anchoring structures to the ground, another requirement for unsupervised construction identified in Article A. This research aims to **determine whether a novel miniaturized morphology can effectively drive piles in natural environments**. While prior literature shows that costly simulant building materials such as 3D printed geared struts can improve robot performance, this article seeks to **investigate the utility of readily-available materials like rebar and T-posts**.

Finally, a motivating scenario of a hypothetical autonomous bridge construction is presented in Figure 1.3 with the aim of **providing an organizing goal for future developments**. As a preliminary step toward this goal, a custom anchoring node integrates both the pile-driving and force-sensing hardware contributions presented in this thesis. While this new hardware demonstration constitutes only a small part of the work that would be needed to realize a fully autonomous scenario, the conclusion to this Dissertation **highlights the remaining work that would be needed to achieve unsupervised construction**.

1.2 Toward unsupervised construction

A great deal of research (past, present and future) is conducted from the standpoint of incrementally introducing autonomy to the construction industry, such as adding semi-autonomous operator-assist controls to heavy machinery [20] or developing robots to assist human workers with repetitive tasks such as bricklaying [8]. While these innovations around mature technologies may confer benefits to the construction industry in the short term, they don't necessarily advance the goal of unsupervised construction. Rather, progress toward this goal seems best advanced by emerging technologies that are designed specifically for autonomous operation. To date, these emerging technologies have been largely developed as narrow, ad-hoc point solutions that aren't intended to advance a broader goal such as an unsupervised multi-task construction project. The disconnected nature of university departments has further hampered efforts at meaningful progress across disciplines. The primary contribution of Article A was to provide a unifying framework and metric for contextualizing recent developments toward this goal.

A fully autonomous (i.e., unsupervised) construction system would be particularly attractive because it would enable construction in settings where it is currently not feasible, including disaster relief scenarios, extraterrestrial construction, decommissioning nuclear power plants or maintaining remote infrastructures.

1.2.1 Biological inspiration and the swarm approach

Unsupervised construction has already been achieved using simulant building materials in controlled laboratory environments. The state of the art in this regard has been set by the TERMES project (Figure 1.2A), in which a collective of independent robots stack foam blocks to build structures larger than themselves [41]. While other researchers have demonstrated multi-agent construction sequences with simulant building materials [36; 22; 42; 14], only TERMES demonstrates full autonomy with multiple agents. The TERMES robots are able to achieve full autonomy for their construction routines because agents act completely independently and without preplanning, taking after their biological role model of termites collectively manipulating passive matter. Each agent is programmed with a blueprint of the final desired state of the structure as well as a ”structpath”, which is essentially a roadmap laid over the 3D grid of blocks that enumerates all possible movements for a robot at a particular location. This was crucial for preventing deadlocks or the stacking of blocks to create un-climbable conditions.

The TERMES project highlights the advantages of the swarm approach to construction. Cooperative building facilitates the construction of large and resilient structures through parallel execution of simple tasks and exists at many scales of nature, from social weaver birds and termites to the assembly of cytoskeletal proteins into regular grid-like structures. Like their biological role models, TERMES robots are robust to unexpected perturbations in the construction sequence. The swarm can accelerate the pace of construction through parallelism (i.e., increasing the number of agents), and can continue building even if some of the agents fail.

However, extending these achievements from laboratory settings to challenging real-world environments where they would be most needed is extremely difficult. First and foremost, TERMES robots are designed to perform a construction task of stacking foam blocks, which is ideal for indoor demonstrations but does not correspond to any known real-world tasks employed in the construction of the built environment. Even performing the same building task in a challenging environment may be impossible for the TERMES robots, which are not designed to operate in unstructured environments.

While advancing the swarm approach in on-site automation is not the primary motivation for this thesis, biological role models serve as inspiration for the multi-agent deployments that are studied in simulation (Articles B and C). The control advantages of parallelism and robustness to failure (such as is demonstrated in the TERMES project) are attractive for increasing on-site autonomy.

However, it was determined that producing further hardware demonstrations using simulant building materials in controlled laboratory settings would have diminishing returns toward the goal of deploying a fully autonomous construction system in the real world. Rather, what seems to be missing are key developments in hardware fundamentals (specifically distributed force sensing and autonomous anchoring). The design and characterization of possible solutions to these fundamental requirements constitute the hardware components of this work.

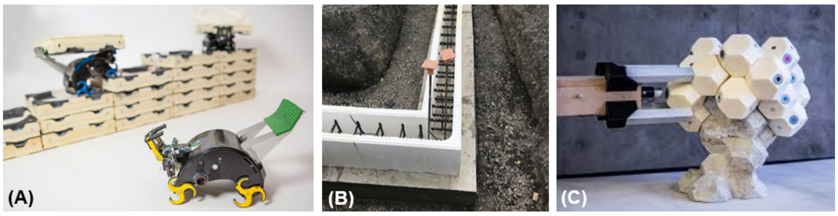

Figure 1.2: (A) TERMES robots climb atop the structures they build using custom foam blocks. (B) Insulated Concrete Forms are a real-world construction task that may be conducive to robotic automation. (C) The VoxelCrete project explored formwork as a practical application of robotically assembled digital materials.

1.2.2 Motivating scenarios

Achieving unsupervised on-site construction is a lofty goal. While semi-autonomy may already be tremendously valuable in the construction industry, full autonomy would be required for applications that are too remote or too dangerous for conventional construction to take place. Examples may include disaster preparedness and recovery, building remote research outposts in challenging environments like the Arctic, deserts or extraterrestrial settings, or installing, maintaining and protecting critical infrastructure like dams, roadways or utilities.

Systems like TERMES are not designed to be directly applied to any of these challenges, and the tools with which these challenges are currently addressed are not designed for autonomous operation. This thesis is specifically concerned with the fundamental design challenge of applying a fully autonomous distributed approach to a realistic construction project. To date there are no examples of such unsupervised on-site construction. A primary objective of this work is to evaluate which previous developments in the literature might help address this challenge, and what gaps remain unsolved. **Article A** has identified construction tasks that may be appropriate first steps toward this goal. For example, the building element perhaps most similar to the foam blocks used by TERMES are the foam blocks used for Insulated Concrete Forms (ICFs, Figure 1.2B), modular units typically made of rigid thermal insulation that lock together to make formwork that stays in place after concrete is cast inside the cavity they form. Modular formwork assembly is suitable for autonomous operation because it uses easily manipulated lightweight components that are designed to facilitate self-alignment (i.e., digital materials), yet still plays an important auxiliary role in the building of concrete structures.

The topic of robotically assembled modular formwork was introduced in a workshop led by the author for ITECH students at the University of Stuttgart in 2017. Students Ramon Weber and Samuel Leder developed a modular formwork concept called VoxelCrete (Figure 1.2C) where formwork is composed of interlocking cellular solids held together with magnets, which can be reconfigured after concrete cures [40]. This demonstration was conducted with an industrial robot and a prepared base to which the blocks could attach. Performing this task with fully autonomous robots on a construction site would first require a means of anchoring the formwork to the ground, which is often achieved with rebar stakes. Addressing this requirement for an autonomous solution to anchoring is the primary contribution of **Article C**. Furthermore, building formworks that span or cantilever would benefit from force awareness, so that robots could verify throughout the construction sequence that joints are not in danger of breaking. **Article B** describes a concept for distributed force sensing that would allow for simple construction robots to make these structural assessments in real-time.

A hypothetical motivating scenario might be a research outpost that must be constructed in a remote location where it is difficult to transport workers and conventional machinery, making

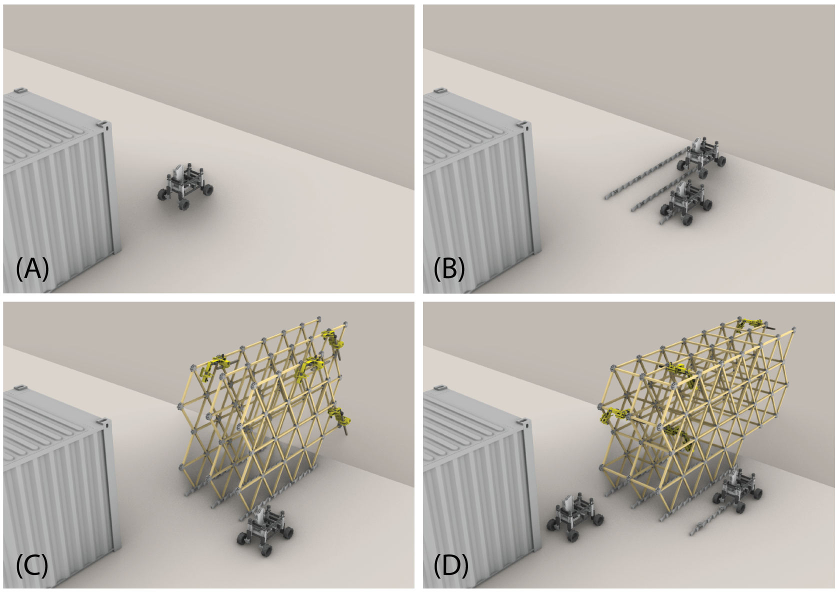

Figure 1.3: The sequence by which multiple task-specific robots might co-operatively build a bridge without human supervision. (A) A sheet pile driving robot identifies a suitable location to begin establishing anchoring for a bridge structure. (B) Multiple pile driving robots work together to place anchoring support for the structure. Certain piles feature a special node to which struts can be attached (Figure 2.3). (C) Strut-climbing robots arrange nodes and struts to form vertical cantilevering truss structures, paying attention for internal forces as they go in order to guide building activity. (D) Robots connect vertical trusses with horizontal struts (this step would require a robot with more DOFs than the one presented in Article B).

unsupervised construction an attractive option. The first phase of construction might be site preparation, including leveling and digging foundation trenches. Autonomous execution of these tasks has already been demonstrated by researchers at ETH [13; 17]. The next phase of construction might require robotic placement of formwork (as described above) as well as reinforcement, for which considerable progress toward autonomy has already been made [10]. More work is required for fully automated concrete placement [29], which could then be used to pour a foundation.

A different scenario might require building a bridge across a chasm to help evacuate people from the site of a natural disaster (Figure 1.3). Assuming the robots and materials are only accessible from one side of the chasm, this task might first require establishing anchoring to support a cantilevering bridge. This could be achieved using either discrete posts or interlocking sheet piles, as described in **Article C**. Following the construction of a foundation, a bridge could be built from either struts or blocks, extending a cantilever outward yet using distributed force sensing to verify the structural integrity of the structure at each step of the construction sequence (this concept is presented in **Article B**). Installing force sensors at the joints between different building components (e.g., between sheet piles and struts) is a large topic for future work, but a preliminary illustrative example is provided in Chapter 2, and early results are presented in Chapter 3.

1.3 Current state of the art

The current state of the art in on-site construction automation is characterized by two distinct paradigms of mature technologies and emerging technologies. As illustrated in Figure 1.4, automating mature technologies typically preserves a stark contrast between simple conventional building materials and sophisticated robots needed to manipulate them [8; 7], while emerging technologies offer the possibility of blurring the boundaries between "robot" and "building material" in order to yield a more performative system [43; 36]. While increasing automation in mature technologies may yield cost-saving benefits in the short term (e.g., adding operator-assist functionality to excavators) they provide limited capacity for innovation as they are locked in to industry standard tools and practices. On the other hand, emerging technologies require considerable resources to develop, and in the near term may not offer a competitive advantage over using industry standard mature technologies. Professor Thomas Bock suggests over time, it becomes increasingly more expensive to make even marginal improvements to mature technologies. Unable to evolve to meet contemporary challenges, on a long enough time scale they will eventually be replaced by emerging technologies [6]. **Article A** provides an overview of the individual research projects that illustrate these trends, and argues that the limitations of mature technologies may be prohibitive for achieving the goal of full autonomy. The state of the art is summarized below with a concise discussion of both mature and emerging technologies used for on-site automation. Then, specific attention is given to related work that considers force awareness and autonomous anchoring, respectively.

1.3.1 Mature technologies

The current state of construction automation in industry is dominated by mature technologies, especially with large machines designed for human operation. The first backhoes, tractors, bulldozers and excavators all emerged around 100 years ago (Figure 1.5), which could be considered the dawn of the “Heavy Equip-

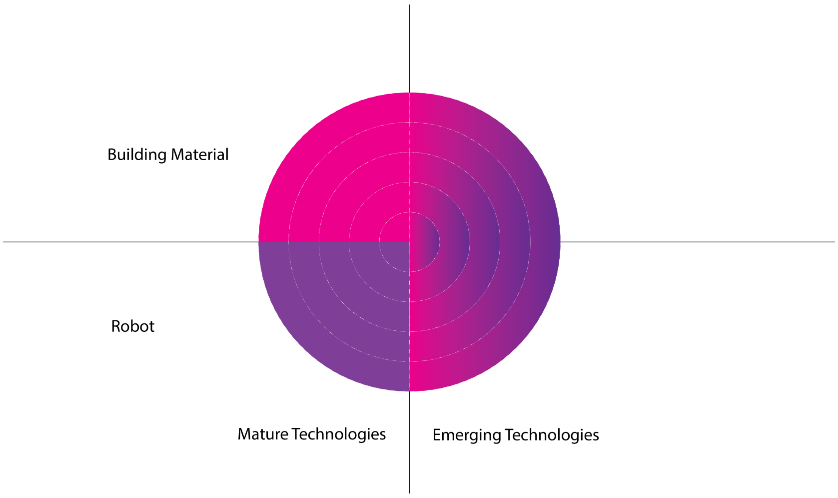

Figure 1.4: The conventional approach consists of a stark contrast between robot and building material. Instead, emerging technologies afford the possibility of blurring the boundaries between the two.

ment Age". The morphologies of these machines are characterized by a dedicated space for a human operator and for a single diesel engine, from which all other degrees of freedom are powered. However, this archetype grows increasingly less applicable in the age of autonomy, as centralized diesel engines can be replaced by more efficient distributed electromechanical actuators, and human operators can be replaced by onboard processors.

Although unsupervised construction equipment is now more feasible than ever, there are very few machines that have been designed for autonomous operation. Conventional construction equipment has seen little evolution for the past hundred years. Instead, these machines have followed a trajectory of "mechanical gigantism", simply getting larger over time without experiencing any fundamental shifts to the machine's morphology or mode of operation. This trend persisted because industries that rely on heavy equipment (not only construction, but also agriculture, mining and land management) were always limited by labor supply.

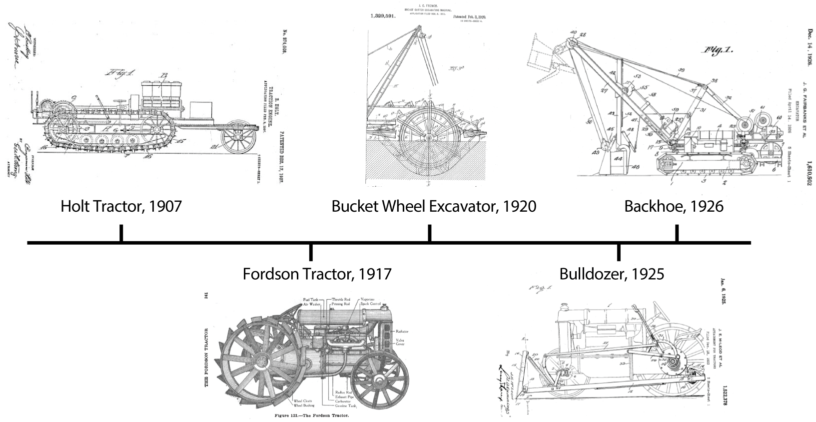

Figure 1.5: "Heavy Equipment" machine designs emerged around 100 years ago, and are characterized by their reliance upon human operators and diesel engines.

For example, a construction worker with a larger bulldozer is able to move more earth in a shorter time, and a farmer with a larger plow can cover more acres. However, these economic incentives toward mechanical gigantism also do not apply in an age of autonomy where a collective of smaller machines is just as easily operated as a single large machine.

Introducing autonomy and semi-autonomy to conventional heavy equipment has been met with some success, however. Researchers at ETH have demonstrated autonomous trenching with the HEAP walking excavator [16; 17]. However, there are considerable limitations to focusing research efforts on incremental improvements of mature technologies, as is illustrated through research efforts to retrofit a conventional shotcrete pumping machine to be fully autonomous [29]. The researchers discovered that one degree of freedom was not equipped with proportional control and had to be operated in on/off mode, which resulted in bouncing and jerking and introduced errors of up to 50mm. Furthermore, the retrofitted machine did not supply enough hydraulic power to operate all of the manipulator's joints simultaneously, which further affected the smoothness of the trajectories. The researchers concluded that unexpected difficulties and performance limitations are likely to arise when attempting to automate machines that were not expressly designed for autonomous operation.

1.3.2 Emerging technologies

In the emerging technologies paradigm of construction automation, examples can be found of researchers designing custom-purpose machines to address the fundamental challenges of construction tasks. Many examples in the realm of earthmoving and site preparation have been developed for extraterrestrial applications, such as the design of an autonomous bucket-wheel excavator [34]. It was found that mounting the bucket such that its rotation is perpendicular to the forward locomotion of the robot allows for a higher payload ratio when compared to conventional heavy equipment. While this machine was not specifically designed for operation as part of a collective, it illustrates a case in which smaller, more responsive machines are more conducive to efficient autonomous control than conventional heavy equipment. Furthermore, the successful demonstration of these emerging technologies underscores their ability to enable construction projects in settings where using conventional equipment is not feasible (such as in outer space).

One way to categorize emerging technologies in autonomous multi-robot construction systems is by locomotion strategies for mobile robots. While stationary robots have been used in on-site construction [1; 19], the workspace limitations they impose make them unsuitable for a great many construction tasks. Mobile construction robots avoid this limitation with either aerial, climbing, or terrestrial locomotion.

Researchers have demonstrated centrally-controlled construction systems in which aerial robots build structures with blocks [42; 2] or struts [21; 22]. However, these systems rely on laboratory-based localization systems that cannot be easily generalized to on-site applications. More recent work has demonstrated outdoor building with an aerial robot, though the localization system still requires human intervention to be calibrated in advance [43]. The building sequences in these examples are pre-planned, and therefore not able to adapt on-the-fly to unexpected changes on-site.

The primary advantage of aerial robots is their large workspace, while their primary disadvantage is their high power consumption. Compared to aerial robots, climbing robots may offer a more power-efficient way to achieve a larger viable workspace (compared to stationary or terrestrial robots). Examples of climbing construction robots in the literature include the previously described TERMES project (Figure 1.2) [41] as well as the AMAS system [36]. While these systems are able to build structures of theoretically boundless workspaces, they are unable to build cantilevers or span unsupported distances.

Climbing robots have also been used to build with nodes and struts as opposed to blocks. Researchers have developed a strut-climbing robot that relies upon costly 3D-printed and instrumented struts to provide robot odometry [44; 30]. While they achieved a successful demonstration of a material-robot system, its reliance on highly customized and expensive hardware as well as its inability to diagonally reinforce trusses draws into question whether this approach is suitable outside of a laboratory environment.

There are far fewer examples of mobile robots being used for construction on-site. Most of these outdoor examples are terrestrial robots, which often consist of an arm mounted to a wheeled chassis [35; 33; 11]. Notable accomplishments in this regard include the Digital Construction Platform, which consists of two robotic arms mounted in series atop a mobile platform [18] as well as the Minibuilders team of 3 specialized robots (two climbing robots and one terrestrial robot) capable of building large structures through continuous material deposition [15]. However, all of these projects assume that structural stability is guaranteed throughout the building process. They do not consider how structures could be anchored to the ground, nor how construction robots might measure and react to forces acting on the structure they are building.

1.3.3 Force awareness

Force awareness is an easily overlooked requirement for assembly robots to guarantee the structural integrity of the structure they assemble. Unlike conventional structural engineering methods that typically only require analyzing the structure in its completed state, assembly robots must be able to continuously monitor building state (at least locally), confirming structural strength and stability at each step of construction. Though largely neglected in construction automation literature, force feedback has been used in robotics research to coordinate cooperative transport [39].

A considerable amount of the published work on force sensing in the built environment is related to experimental modal analysis, a type of structural health monitoring that involves the comparison of an on-site frequency response to a known finite element model. This field of research is valuable for the evaluation of completed structures where the global topology is known in advance, but does not afford techniques that could be employed during the construction process, all the more so if the final structural layout is not predetermined. Also of note is a considerable amount of research from the fields of architectural design, structural design and building construction. Much of this work previews construction in the sense that finite element or physics simulations are used to facilitate agent-based optimization of force-aware building elements within the design process [31; 3; 4; 37]. However, it is important to differentiate work that deals with a force-aware design process from work that deals with a force-aware construction process. While a force-aware design process can optimize material usage for a static structural state, it does not consider forces that change dynamically during construction, and therefore does not allow for real-time adaptation of the building sequence.

The issue of considering forces at each stage of the construction sequence has been addressed with a path planning algorithm for assembly sequences that promotes stability by selecting the most stable option at each time step in the construction process (based on a centralized evaluation of the entire structure) [23]. However, force measurements were simulated (not measured from a physical prorotype) and it was assumed that the truss was anchored to a flat surface, so that the overall stability of the structure (i.e., preventing toppling) was not a consideration. In general there is little research on using structural forces to inform a construction process because conventional building practices do not require considering such issues. Unsupervised construction is a research goal that requires new methods for sensing and reacting to forces throughout the building sequence.

1.3.4 Autonomous anchoring

As a rule, useful terrestrial structures require foundations. Foundations perform essential functions, including anchoring against natural forces like wind, frost, floods, erosion and seismic activity, transferring the load of the structure to the ground and distributing it to prevent overloading or unequal settlement, and providing a level platform for subsequent building operations. While foundation building is a critical component of nearly every construction project, it has been largely overlooked as an area of research.

While conventional foundation construction requires a great deal of planning and coordination of heavy-duty machinery, not all anchoring tasks are necessarily so complex. Though typically less permanent and robust, anchoring can be established through more rudimentary processes like pile or post driving. Such techniques are commonly used to anchor temporary structures, and may be applicable to many situations where fully autonomous or unsupervised construction is desirable, such as building temporary shelters for disaster relief or for extraterrestrial construction.

To date, no examples of autonomous solutions have been presented, but the variety of commercially available pile-driving tools suggest a broad demand for such automation at a range of scales.

Although foundations are essential to almost all construction projects, confounding factors such as unpredictable soil mechanics and regional variations further complicate the notion of conducting academic research in this domain, which may explain why it has seen so few efforts at advancing autonomy. The few relevant examples that do exist, such as the TunConstruct semi-automated concrete pump [29], highlight the limitations of automating equipment that was designed for human operators, and suggest that progress toward the goal of unsupervised construction may benefit more from hardware that is custom-designed for autonomous operation.

1.4 Thesis overview

This thesis is initially concerned with literature review and problem identification, in order to identify the opportunities and challenges of pursuing an unsupervised construction system. This work is addressed in **Article A**. This effort towards understanding the research landscape in the realm of construction automation revealed considerable gaps between academic and industry research. It was concluded that **distributed force sensing** and **autonomous anchoring** are two areas of research that would likely be applicable to almost any fully autonomous construction project, yet have been largely overlooked in the literature to date. These two areas are then each explored in turn, consisting of multi-agent computer simulations as well as demonstrations with prototypical hardware. A final demonstration shows one possible way in which these two contributions could be stitched together in a fully autonomous construction scenario (Figure 2.4).

1.4.1 Problem identification

Article A is a review that presents a broad range of advancements in construction automation research with an emphasis on the fundamental needs of achieving unsupervised on-site robotic construction. It finds that construction in unstructured environments will require considerably more development in all three groups of tasks that characterize nearly all real-world construction projects: site preparation (earthmoving, leveling), anchoring (foundations), and superstructure (load-bearing elements, facade, plumbing, wiring, etc.). Furthermore, it finds that there are considerable limitations to adding autonomy to equipment designed for human operators and suggests that the achievement of unsupervised construction will almost certainly require new task-specific material-robot systems to be designed and developed.

While laboratory-based projects such as TERMES have already demonstrated unsupervised construction, they do not consider the challenges of realistic environments where full autonomy would be most needed. On the other hand, the machines that have been developed over time for operation in challenging environments have mechanical and control limitations that make them poorly suited to autonomous operation. **Article A** suggests that this gap could be bridged by new hardware contributions that focus on the fundamental requirements of specific construction tasks.

1.4.2 Distributed force sensing

Among the recommendations provided in **Article A** is an emphasis on the development of distributed passive sensing systems to be embedded into building materials in order to facilitate robotic assembly. This topic was explored in **Article B**, in which a hypothetical collective of strut-climbing robots extend the trusses they climb, using force sensors embedded in the load paths of the truss elements to inform their building activity.

While prior work on robotic truss assembly generally neglected to consider forces acting on the structure, this information would be necessary to guarantee against failure during construction. **Article B** presents a climbing robot capable of limited locomotion along wooden struts, but its more significant contribution to the field is the development of passive low-cost embedded force sensors that can be parsed by a robot as it traverses and assembles a truss. Importantly, these sensors are characterized in physical hardware, and their properties are modeled in a computer simulation environment. These simulations allow for efficient testing of various behavioral algorithms that determine how collectives of distributed climbing robots can use local force measurements to assess aspects of global structural state. Furthermore, this article shows how these simple force sensors can be configured and installed on other building materials such as blocks or voxels, suggesting that this is could be a broadly generalizable solution that could aid in a wide range of autonomous construction scenarios.

1.4.3 Autonomous anchoring

Another finding from the literature review conducted in **Article A** is that advances in construction automation have been almost exclusively concerned with either automating earthmoving equipment or assembling superstructure elements, leaving the critical task of anchoring introduced material into soil almost entirely neglected.

Article C proposes methods by which autonomous robots could address anchoring, and discusses real-world applications. A design and prototype for a novel sheet pile driving robot named Romu is presented for driving small-scale piles. The robot is designed to carry a payload of materials (either interlocking sheet piles or discrete posts) into a target setting and drive them into the ground in sequence. Among other applications, this could serve to provide anchoring for subsequent construction tasks. The robot uses a combination of a vibratory hammer and its own weight to help drive piles to greater depths, unlike conventional processes which require transporting a dedicated bias mass for this purpose.

At its current scale, Romu is capable of shallow anchoring tasks that require driving material ~20–30cm into soil, such as conducting geological surveys, securing formwork for foundations, light fencing, staking temporary structures, and land management tasks such as anchoring coir logs for erosion control. Automating these processes is important because they would likely be constituent tasks in many of the scenarios where unsupervised construction would be desirable.

Custom-built computer simulations based on real-world environments are employed to evaluate the potential impact of a collective of such robots when tasked with a simple construction objective like building check dams for erosion control. In hardware, the effects of mechanical parameters on the depth and extraction force of driven piles were characterized, and operation was demonstrated in both controlled and natural environments.

1.4.4 Relevance to architecture

In its formulation of ”Designing for unsupervised construction”, this dissertation takes a broad interpretation of the role of design in architectural practice, referring not only to the design of completed buildings and finished spaces, but also to the materials and methods used to build and maintain them. Designing for unsupervised robotic construction requires consideration not only of the morphologies of construction robots, but also of the materials they handle, and how those materials can both facilitate robotic manipulation and also deliver the structural and other performance requirements expected of a serious construction project. Unsupervised construction requires designing the interactions between robotic agents and building components imbued with an added dimension of embodied intelligence, which should facilitate reliable assembly without human intervention.

It may be tempting to view the development of novel construction robots and corresponding instrumented building materials as the domain of robotics, computer science, or mechanical engineering. Indeed, these fields have so far contributed the bulk of the relevant literature on the topic. Research projects originating in these fields have already executed complete demonstrations of unsupervised construction, though only in structured laboratory environments and with simulant building materials [41; 14]. However, university departments are notoriously compartmentalized, and departments of Computer Science or Mechanical Engineering will likely not be sufficiently incentivized to consider meaningful applications to building construction. While it is understandable that researchers in these departments would lack knowledge of building construction, it seems so far they have made few efforts to seek it out. Without the involvement of architects, they seem largely satisfied to avoid the challenges of field deployments and realistic building materials in favor of more easily controlled experiments. Accordingly, these carefully controlled experiments may have hit a ceiling in terms of their relevance to industry. What seems to be missing is an emphasis on translating lab-based accomplishments to the chaotic environments typical of construction sites, a formidable challenge that would be well met by increased cross-disciplinary participation from architects.

It is clear that robotic automation will have a tremendous impact on the construction, maintenance and occupancy of the built environment. What remains to be seen is whether the field of architecture will assert its agency in this domain, or will be satisfied to follow the lead of technologists and engineers. Engaging architects in the discourse around autonomous construction doesn't require their technological mastery, but it does require an interrogative desire to understand a nascent technology well enough to translate it into built form. The interest in initiatives such as the NCCR DFab and IntCDC is fueled by an increasing demand to lead these translational efforts from within the framework of architectural design.

On the other hand, a whole host of questions could go unaddressed should architects choose not to become active participants in translating robotic technology to building construction applications. The result could be developments that cling to inefficient legacy machines and protocols, and a failure to realize building systems that could enable new construction scenarios. Rather than default to an engineer's vision of robot-enabled construction, architects can contribute to the ongoing discourse by posing and investigating important questions, such as: what building materials are robots inherently well-equipped to manipulate? Can some materials be modified to facilitate robot manipulation, or should they be avoided entirely? Correspondingly, what type of robots are best-equipped to autonomously execute construction tasks? More specific to the goal of unsupervised building, what new modes of construction might this new paradigm enable? What impact might there be on our conception of the built environment if construction projects could be executed entirely without human intervention? Would unsupervised construction obviate the need for conventional construction phasing, such that a building could be conceived of as an assemblage of matter being constantly reorganized to suit the requirements of its occupants?

While computer science and engineering departments could provide essential resources and collaborators needed to address these kinds of questions, they are not likely to pose them on their own accord. Cross-disciplinary endeavors such as the work presented in this dissertation are best initiated from within an Architectural framework, because the aim of the investigation is not to optimize the performance of some particular combination of hardware and algorithms, but rather to demonstrate methods of increasing on-site automation in ways that could lead to new modes of resilient and energy efficient construction in settings where it is currently not feasible.

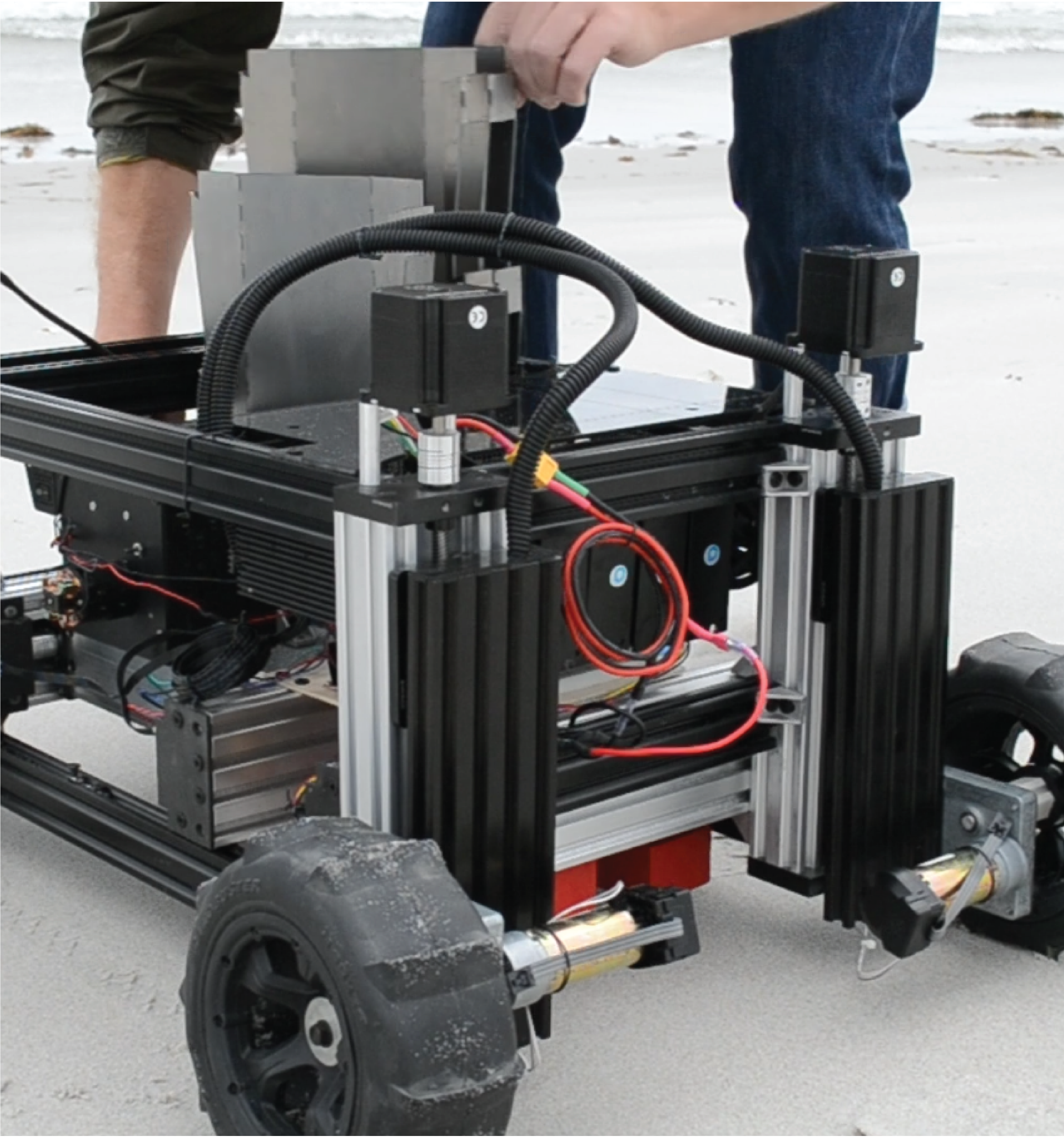

Figure 2.1: Measurements being taken during a field trial, as Romu demonstrates autonomous driving of sheet piles into soil. The methods used in this thesis rely heavily on on-site field testing.

2

Methods

Advances in construction automation can be achieved either by incremental improvements to mature technologies, or by the development of emerging technologies based on fundamentals of a given construction task. It is not obvious what the fundamental needs of an emerging paradigm of unsupervised construction might be. Chapter 1 identified distributed force sensing and automated anchoring as areas in which a fundamental approach has so far been lacking. This chapter presents the methods by which these needs are investigated.

2.1 Distributed force sensing

In conventional construction it is not necessary to measure forces between discrete building elements, as they are typically assembled by human workers who are constantly adjusting orientations and rely on intuition and proprioception to verify that building elements are correctly installed. Building components are assembled according to blueprints, the dimensions and material properties of which have been verified in advance by architects and structural engineers. These certainties would be difficult to guarantee during unsupervised construction in an unpredictable environment (such as that described in Figure 1.3).

Instead, robots would need some verification of their assembly sequence in real-time. This could be accomplished by installing expensive off-the-shelf strain gauges and radio protocols that allow each building element to communicate with a central controller. However, this approach would be constrained by the computational limitations of the central controller, and strain gauges won't necessarily predict all failure modes for a complete unsupervised construction project. Instead this thesis proposes a novel method of instrumenting passive building components with capacitive force sensing, which provides useful feedback for unsupervised construction in a way that is low in cost, power consumption and complexity.

2.1.1 Sensor design and characterization

Using force-sensitive sheet materials to measure applied loads with a resistance-based circuit (Figure 2.2A) is common in wearables, prosthetics and soft robotics [12]. Therefore, resistance-based circuits were selected for initial experiments. In wearable applications these sensors typically are constantly powered on, streaming force measurements to a microcontroller. However, a useful modification for building construction applications that is not readily apparent from the literature is that these sensors do not need to be persistently connected to their power sources. Therefore, a robot such as that proposed in Article B could apply a voltage to a passive sensor installed on any given building material. The voltage drop that is measured across the sensor can be used to calculate the force acting on it, given that the relationship between resistance and applied force is known for a given force-sensitive

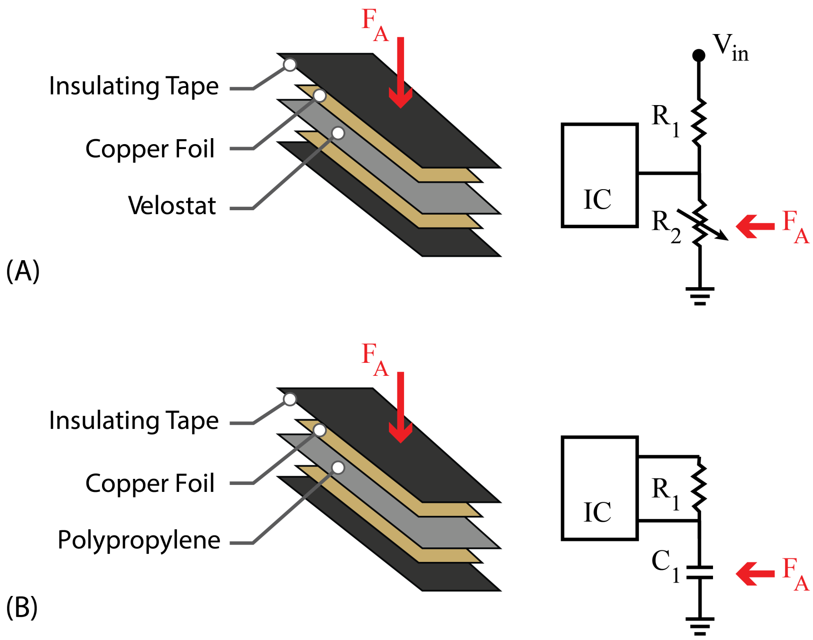

Figure 2.2: (A) Initial development employed a resistance-based circuit that relied on a force-sensitive polymer (Velostat) sandwiched between two copper foil plates. This sensor acts as a variable resistor (R_2) that changes value based on applied force (F_A). (B) Later developments instead used a capacitance-based circuit, consisting of the same layup, but replacing the force-sensitive polymer with a thin polypropylene elastomer. In this arrangement, applied force yields a difference in capacitance.

material. For example, in the case of the 100µm-thick Velostat material used for initial experiments, the relationship between the applied force F_A and the measured Voltage V_{OUT} was found to be:

$$F_A = \frac{V_{OUT}}{0.6} - 208 \tag{2.1}$$

The resistance-based circuit (Figure 2.2A) comprises a voltage divider, where the voltage measured by the microcontroller V_{OUT} is given by:

$$V_{OUT} = \frac{R_2}{R_1 + R_2} * V_{IN} \tag{2.2}$$

The range of values that can be measured using this method can be calibrated to some degree by using different fixed-value resistors (R_1). The nominal range of resistance for this thickness of Velostat is ~1kΩ–4kΩ; forces on the order of those found in building construction will fall on the lower end of this range. Therefore, using a fixed-value resistor (R_1) in the range of ~1kΩ would provide the most sensitivity to this range of forces. However, sensing larger loads would require using a different force-sensitive sheet material, which are produced in only a limited set of polymers and dimensions. Films of greater thickness could introduce undesirable compliance in the joint. Furthermore, most force-sensitive polymers are subject to degradation over time as well as other errors due to temperature fluctuation or installation inconsistencies.

The limitations of the resistance-based method inspired a search for an alternative. Capacitance-based sensors are used in a broad range of applications in consumer electronics (especially touch screens), but are not typically associated with forces on the orders of magnitude as typically observed on construction sites. While the resistance-based circuit depends on the conductivity of a semi-conducting polymer, the capacitance-based method is dependent on the permittivity of a dielectric, which is a more durable material property. Permittivity is a measure of the electric polarizability of a given dielectric material. Materials with a high permittivity are able to store more energy because they polarize more in response to an applied electric field. For designing capacitors, higher permittivity corresponds to greater capacitance. Permittivity is typically expressed as the unit-less relative permittivity ε_r, or ratio of a material's permittivity to vacuum permittivity. The relative permittivity of polypropylene is 2.3; other common materials include printer paper (1.4), polyethylene (2.2), silicone (3.5), rubber (7), and water (80).

The capacitance of a capacitor is a property that does not change when it charges and discharges. The formula for capacitance C (ability to store an electrical charge) in a parallel plate capacitor is a function of the relative permittivity of the dielectric ε_r, the area of the sensor A, and the distance between the two plates d:

$$C = \varepsilon_r \frac{A}{d} \tag{2.3}$$

Applying force to this sensor compresses the dielectric, thereby reducing the value of d. Even though this change is on the order of microns, the difference in the capacitance it yields should be reliably measurable by an integrated circuit (IC) on an assembler robot.

Two pins of an IC are designated respectively as send and receive pins, connected with a fixed-value resistor (Figure 2.2B). The assembler robot's IC triggers a state change to the send pin, which will eventually change the state of the receive pin. The time it takes for the receive pin to reflect the change of the send pin is a function of the RC time constant, where R is the value of the resistor and C is the capacitance (ability to store electrical charge)

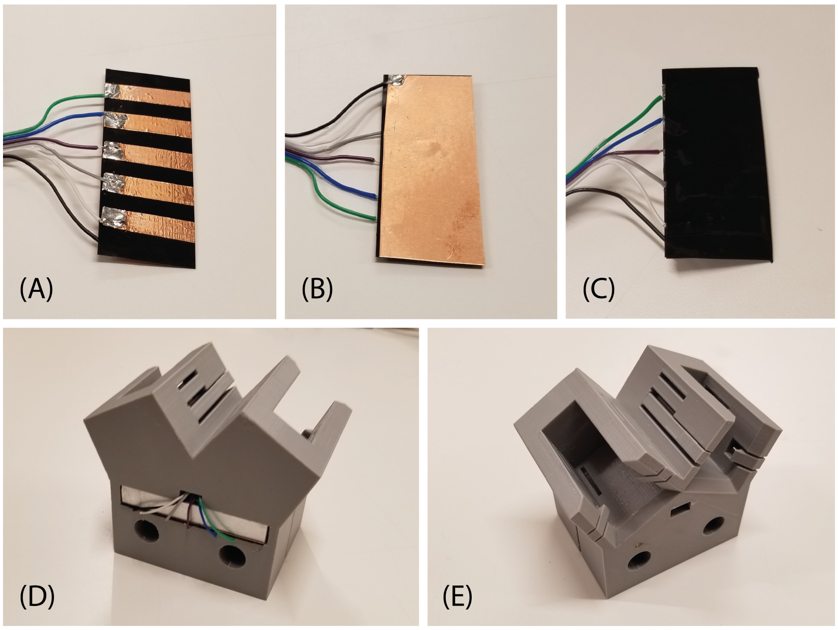

Figure 2.3: Fabrication process for an array of five capacitance-based force sensors installed in a custom node. (A) Five strips of adhesive copper foil are evenly distributed on one side of a piece of polypropylene. (B) Copper foil applied to the reverse side of the polypropylene forms a common ground that completes the capacitor for all five sensors. (C) The sensor is wrapped in vinyl for protection and electrical insulation. (D) Before installing the sensor in the node, it is attached to an aluminum bar to avoid deformation (in a more durable demonstration the entire node would be fabricated out of a more rigid material than PETG). (E) Sensor wires are routed to a socket connection on the front of the node to facilitate readings by an autonomous robot.

of the circuit.

The sensitivity of this measurement circuit can be tuned by changing the fixed-value resistor in the circuit. Very large value resistors (10–40MΩ) will result in a circuit that is sensitive to small variations in capacitance. Using a smaller value resistor will result in a circuit that is less sensitive, but able to report values over a larger range, such as might be needed in construction applications. For initial experiments, a 1MΩ resistor is used.

The resistance- and capacitance-based sensors are of comparable thickness, consisting of 2 sheets of 100µm vinyl tape over 2 sheets of 66µm copper foil, in addition to a ~100µm inner layer (totalling ~350µm). The fabrication process for the capacitance-based sensor is shown in Figure 2.3.

Like the resistance-based method, this sensor does not require a dedicated power source or microcontroller, and can instead remain powered off until it is activated by the assembler robot. Completing the circuit, the assembler robot measures the capacitance between two adjacent building elements, which provides a metric of the forces imparted at their interface.

Once a single sensor unit has been designed and calibrated to yield capacitance values in the desired range, multiple sensor units can be arranged to measure different kinds of force patterns that arise in a range of building construction applications.

In order to highlight how the force-sensing components of this thesis could be applied to the developments in autonomous anchoring towards a more complete scenario (such as the autonomous bridge-building scenario proposed in Chapter 1), a custom node was developed to interface the node-and-strut system with a foundation composed of sheet piles (Figure 2.3D–E, Figure 2.4, not presented in any prior work). The interface between the node and the sheet pile is instrumented with an array of 5 capacitive

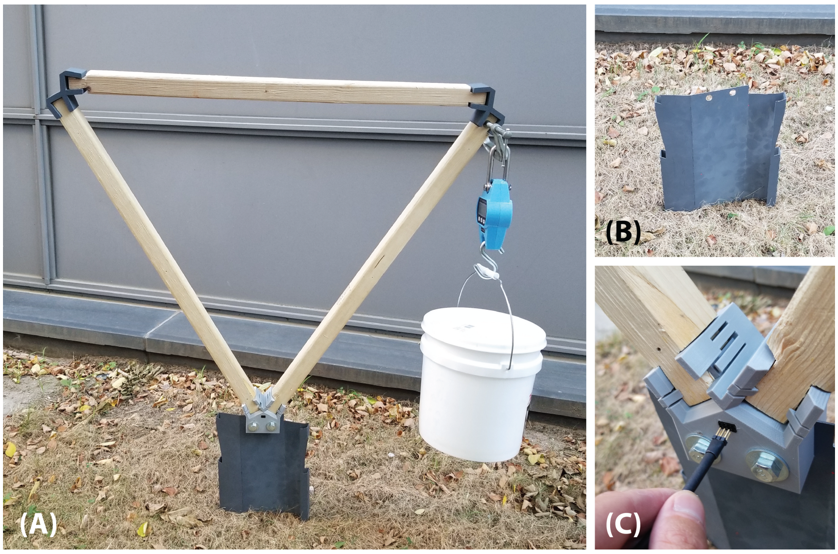

Figure 2.4: (A) The experimental setup for preliminary characterizations of capacitive force sensors installed in a custom anchoring node. (B) The node is bolted to a sheet pile that has been driven into soil. (C) Measurements are taken under various loading conditions by connecting each sensor to a pin on a microcontroller (IC), completing the circuit in Figure 2.2B. In a future system, this would be achievable by autonomous robots.

force sensors. It is hypothesized that the instrumented node-pile interface will be able to provide an indication of excessive axial loading (if the sum of the sensor values exceeds a preset empirical threshold) as well as excessive bending forces (if the difference between the left-most sensors and the right-most sensors exceeds a different threshold). The custom node was installed on a pile driven ~ 20cm into soft soil (Figure 2.4B). Weights were suspended from the left, right and center of the horizontal strut, and the results are reported in Chapter 3.

2.1.2 Possible applications

Preliminary experiments with capacitive sensing suggest that this simple sensor construction can be generalized to a wide variety of building materials so as to better inform their assembly by autonomous robots. A few of the test cases that have been explored are shown in Figure 2.5.

The node-and-strut joint was first instrumented with a resistance-based circuit and later replaced with a capacitive circuit, which yielded more precise results. Capacitive circuits were then used for all subsequent experiments. It was found that installing two sensors at opposing sides of an interface between two building components is sufficient to provide a useful proxy for bending forces between those elements. For scenarios where it is desirable to measure axial forces between building elements, they can be measured either by summing the forces acting on 2 sensors (in the case of blocks) or by adding a third sensor directly in the axial load path (in the case of node-and-strut systems).

2.1.3 Multi-agent simulations

A custom simulation environment was developed in order to study multi-agent deployments for cooperative robotic truss assembly.

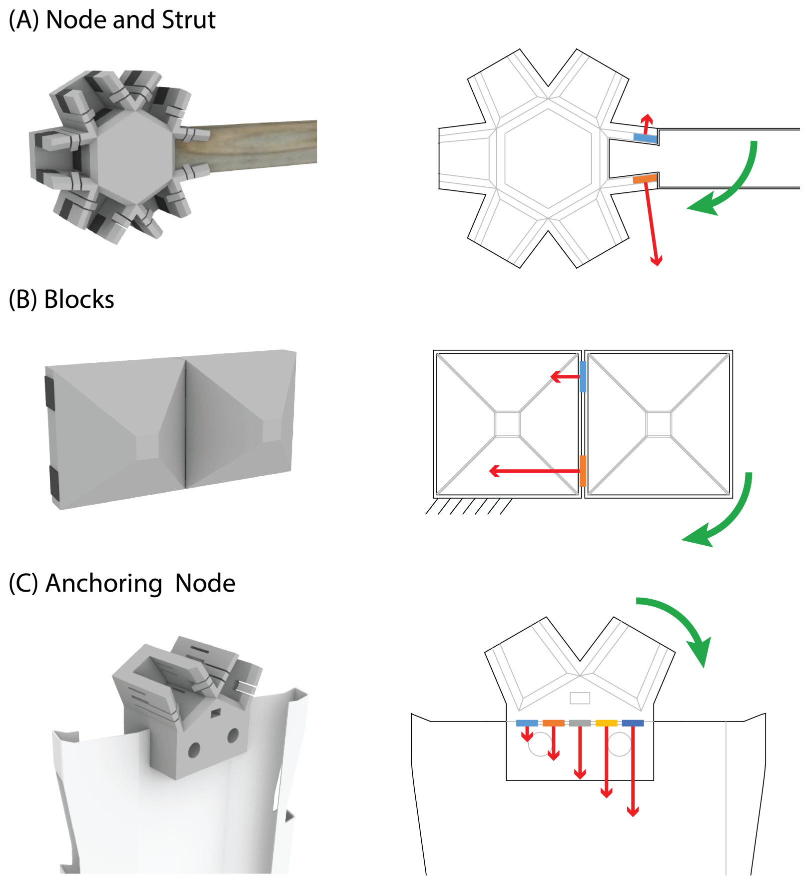

Figure 2.5: Three different implementations of capacitive force sensors applied to passive building materials. Green arrows indicate applied forces, and red arrows indicate reaction forces reported by the sensors. (A) Applying sensors to opposing walls of a socket in a node-and-strut assembly allows for measuring bending forces acting on a strut. (B) In a block assembly, sensors installed on opposite ends of the interface between two units can be averaged to provide a metric of axial forces, or differenced to provide a metric for bending forces. (C) A custom node designed to bolt on to a sheet pile features an interface instrumented with force sensors, which can also be either averaged or differenced to provide axial and bending forces, respectively. Sensor colors correspond to the results presented in Figure 3.2.

These simulations put particular emphasis on using only the kinds of forces that were measurable with the instrumented hardware prototypes.

Importantly, these simulations provide a basis for monitoring building activity throughout the building sequence, paying attention to structural forces during all stages of construction. As mentioned in Article B, simulations initially relied on Finite Element Analysis (FEA) for providing structural state feedback to simulated robotic agents. However, FEA is best suited for measuring plastic deformations within a continuum body, as opposed to forces acting between bodies. It was determined that rigid-body physics methods would allow for a higher fidelity representation of the actual forces acting on the physical prototypes. Therefore, a new simulation environment was built in Unity3D, employing the INVIDIA PhysX rigid-body physics engine. This environment was initially used to perform simulations for multi-agent node-and-strut construction (presented in Article B), where robotic agents must first verify that the bending forces acting on a given strut are below a preset threshold before traversing out on that strut.

The simulation environment was later extended to a construction system in which robots assemble block-based structures in a cellular matrix. This work has not yet been presented in an archival publication, but served as the basis for a 2017 ITECH workshop that yielded the VoxelCrete project (Figure 1.2C [40]) as well as other block-based discrete assemblies. While such discrete assemblies provide conveniently constrained environments for instructional workshops, they cannot comprise a useful structure on their own. A complete proposal for an unsupervised robotic construction sequence may include discrete assembly, but will also need to address anchoring as well as reliable integration between various construction tasks.

2.2 Autonomous anchoring

The original research contribution of this thesis presented in Article C deals with the conceptualization, implementation, and development of robotic hardware capable of autonomous establishing ground anchoring. As with the force-sensing contribution, this work was developed using both hardware and simulations.

2.2.1 On-site Experiments

Figure 2.1 highlights the importance of field experiments to this work. Performing robotics experiments in the field is considerably more difficult than performing the same experiments in a laboratory environment, due to challenging externalities such as weather, dirt and grit, or inconsistent terrain that may confound robot performance in ways that may not be anticipated by laboratory experiments. Of course, encountering these complications is precisely the point of conducting field experiments.

Experiments for autonomous pile driving were initially conducted in an artificial sandbox in a laboratory environment. However, translating the experiments outdoors to various realistic candidate environments was an important objective. Based on literature reports, it was expected that geomechanics in outdoor deployments would be considerably less predictable and repeatable. In order to capture a range of the robot's pile and post driving capabilities, experiments were conducted using a custom-built vibratory hammer to autonomously drive into the ground a range of readily available post samples in addition to a custom sheet pile profile. For each material, pile driving parameters (eccentric mass, bias mass, and hammer speed) are varied. However, the size of the vibratory hammer precluded the ability to increase the eccentric mass to greater than 240g. For each trial, the ultimate driven depth is recorded, as is the force required to extract the post. Five replicates are averaged for each condition.

Initial field experiments sought to demonstrate the ability to autonomous drive a custom sheet pile in a natural environment. A beach environment was chosen due to its proximity and the assumption that the penetrability of sand would be conducive to pile driving experiments. However, it was found that beach sand was considerably less penetrable than the laboratory sandbox, and comparable to other soils in urban environments. Therefore, subsequent field experiments were conducted across four different soil types in order to better generalize results to a range of candidate terrains.

A principle novelty of this hardware design is its ability to drive piles or posts by grasping their sides instead of their tops, so it was important to develop experimental methods that would characterize this approach. As the custom sheet piles were co-designed with the pile-driving robot, it is unsurprising that the robot never lost its grasp of the pile during trials. However, subsequent trials sought to avoid the need for custom-designed posts by employing commercially-available materials instead. Custom grippers were designed to mate with protruding features found on rebar and T-posts (typically used for fencing). The reliability of the gripper's hold on these materials during pile-driving in a natural environment is a further motivation for conducting field trials. If reliable post-driving can be achieved with industry standard materials instead of requiring custom-made materials, that would constitute one less barrier to industry adoption of such autonomous construction methods.

2.2.2 Erosion simulations

A custom simulation environment was developed to study hypothetical multi-agent deployments of small-scale pile-driving robots. Again, the simulations are designed to correspond with the physical abilities of the robot. While autonomously-driven sheet piles or posts are conceived of as providing ground support for subsequent robotic building activity, they can also serve as useful structures in and of themselves. Specifically, small-scale sheet piles can be installed as check dams to, e.g., stabilize a watershed region against erosion (described in greater detail in Article C).

Landscape architects and restoration ecologists rarely rely on large-scale simulations to inform design proposals, as such proposals are typically tied to very local site conditions in a way that would prevent results from generalizing to even an adjacent plot of land. Instead, they generally install a small mock-up of the intervention in-situ. While this method may provide an indication of what effect can be expected for a particular site, it does not facilitate comparative studies. This thesis, on the other hand, is less concerned with any particular landscape than with principles that can be generalized across various terrains.

Therefore, inspiration was taken from the simulated hydraulic erosion algorithms developed by the computer graphics community [28]. When adapted and integrated into the custom multi-agent simulation environment, these algorithms provided the means to run comparative studies on how different robotic landscape interventions would affect hydraulic erosion in a given watershed region. Terrains can be either randomly generated, or imported from GIS data (as reported in Article C). Landscape interventions vary as a function of the behavioral algorithm assigned to each agent in the robot collective. Erosion routines can be run for interventions placed by the robotic agents, or for pre-designed interventions (used as an experimental control). It is hypothesized that having agents programmed to react to features in the landscape will produce results nearly as good as those obtained by pre-designed interventions. (Even if slightly less efficient, reactive behaviors will still be attractive in areas where pre-planning can be compromised by chaotic site conditions, faulty communications, or other unexpected complications.) Experimentation with various robot behaviors will seek to develop principles for reacting to landscape cues (radius of curvature, orientation to slope, placement density, etc.) in a way that produces successful landscape interventions without central coordination.

Figure 3.1: Detailed photograph of measurements being taken from an anchoring node designed to interface a node-and-strut system with a sheet pile. An array of five capacitive force sensors can be independently measured via a multi-pin socket that can be connected to a microcontroller.

3

Results and Discussion

This section highlights and contextualizes the results obtained through this dissertation. Section 3.1 presents results related to embedded force sensing, while Section 3.2 presents results related to anchoring applications. Section 3.3 provides a discussion of how these results fit into a broader research goal of fully autonomous construction.

3.1 Distributed force sensing

Article B presents a strut-climbing robot design and prototype as well as the results of corresponding simulations. These simulations showed that **paying attention to local forces as an agent traverses a structure can reliably forestall local joint failures**. Furthermore, they show that paying attention to forces on the ground-resting nodes of a structure can reliably forestall failure due to global instability (i.e. toppling over).

Article B then presents a novel physical demonstration of slim passive force sensors that can be installed directly at the interface between two building materials. The demonstrated value of this technique is that it can be **applied to a wide range of building materials and does not require constant power to provide meaningful feedback to construction robots**. Article B first presents sensors installed in the sockets of a custom node and strut building system (Figure 2.5A). In this approach, the difference in sensor readings taken from the shear force sensors is used to predict breaking failures. This value approximates the bending force acting on a strut, an excess of which is expected to be the prevailing failure mode of such a truss. This method was found to reliably register even small variations in loading conditions. Article B then extends these principles to cellular unit geometries (Figure 2.5B), which may be more suitable for certain building tasks. The instrumented cellular unit described in Figure 2.5B was evaluated for its ability to reliably predict failures due to breaking by measuring two force sensors. On average, the applied load needed to cross the preset threshold indicating a "warning state" was 224g. The average applied load needed to break the joint was 336g. The joint never broke before reporting a "warning state", suggesting that this would indeed be a reliable method of identifying stressed joints before they break.

A custom node for connecting a truss to a sheet pile was developed to illustrate one possibility of how this sensing technique could be applied to the interface between two dissimilar building components (sheet piles and wooden struts) presented previously in this thesis (Figure 2.5C). Despite the noise inherent to the sensor, the results are sufficient to reliably determine which of four loading conditions was applied (Figure 3.2). It is expected that the reliability of the results would improve considerably by using a more precise and repeatable fabrication method for the sensor, which will be the focus of future work. Furthermore, sensors could be calibrated in their unloaded state in order to provide a

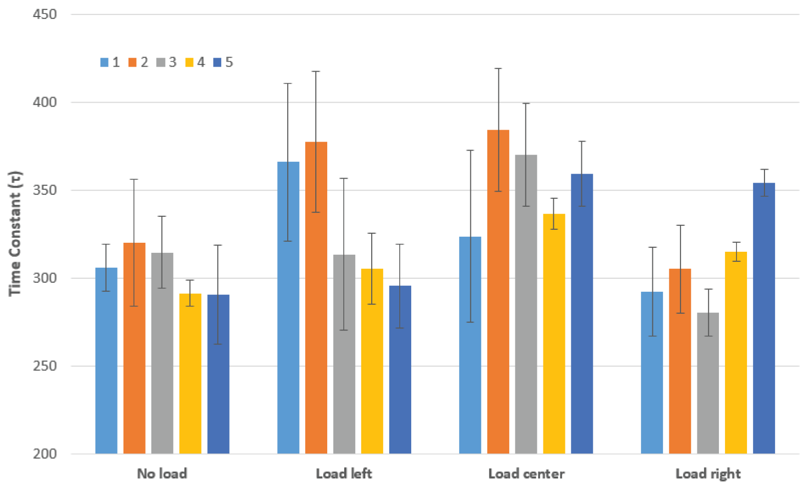

Figure 3.2: Preliminary results recorded using a capacitive sensor array (Figure 2.3) installed in a custom node (experimental setup shown in Figure 2.4). Ten measurements are taken and averaged for each loading condition.

more stable baseline measurement. Further work in this area will seek to identify principles for determining which materials (and dimensions thereof) are best suited to serve as the dielectric layer in capacitive force sensors. Little work has been produced on this topic to date, especially for sensing large loads. In fact, since this thesis work began, UK-based Pressure Profile Systems, Inc. has released a commercially available capacitive force sensor using a silicon dielectric [32]. While this material may be ideal for the tactile applications they market for (in the 1–10N range), it may not be well suited to higher order of magnitude forces that would be of interest in construction applications. Still, the adoption of capacitive force sensing in consumer electronics lends some credence to the suggestion that this technique could be useful in building construction as well.

Having generalized the utility of slim-profile capacitive force sensors to three different building systems (Figure 2.5), it seems likely that **this technique could hold value in a wide range of**

applications, not limited to large assemblies of self-similar components (i.e., “digital materials”). In spite of the recent popularity of digital materials in certain design schools, it remains the case that useful structures are not composed of digital materials alone. Future directions for work in this area may want to consider a recommendation from Article A to emphasize auxiliary construction tasks (such as formwork and scaffolding) that are critical to construction processes yet not required to permanently bear structural loads. Robotic automation of such auxiliary tasks was a theme of a 2017 ITECH workshop that seems increasingly relevant as a direction for future work.

3.2 Autonomous anchoring

Article A describes an overemphasis within the research community on superstructures, and a corresponding shortage of work on site preparation and foundations. This thesis has addressed this gap in the body of research by presenting Romu, a custom-purpose built robot capable of autonomously driving posts and sheet piles to provide ground support (Article C). This novel hardware was evaluated in both laboratory settings and in field experiments, and leveraged a custom simulation environment to study hypothetical large-scale multi-agent deployments.

In contrast with the inefficient weight distribution of the large, typically diesel-powered machines commonly used for pile driving, Romu is capable of leveraging up to its entire body weight for driving piles. Furthermore, its **unique morphology and custom-designed sheet piles allow it to drive piles by grasping their sides** instead of their top, thereby avoiding the typical limitation in industry that a piece of pile-driving equipment needs to be at least as tall as the piles it drives. Independent of the peer review process, the novelty of these contributions has been further validated by the International Searching Authority's recent opinion that they constitute patentable claims under the Patent Cooperation Treaty (PCT) [24].

Romu is initially presented as a material-robot system in the sense that it was intended to drive a custom sheet pile with which it was designed in coordination. However, Article C goes on to present modifications that allow the robot to drive discrete posts instead of interlocking piles, while still leveraging its ability to drive elements of any length by gripping them from their sides. Unlike sheet piles, many types of discrete posts come readily available to consumers for use in gardening, landscaping, surveying or fencing tasks. Many common building supplies used for these tasks (such as rebar and T-posts) are already designed with features that can facilitate their being grasped from the sides. Therefore, it was determined that there would be little added value to designing and fabricating custom posts, when the desirable features can be obtained by re-purposing existing products already sold on the mass market. Rather than needing to redesign both the robot and post material, the **robot was able to reliably drive rebar and T-posts by simply replacing its custom grippers**. The success of re-purposing existing products may be instructive for the development of future material-robot systems, where maintaining a tie to products typically used in the industry may afford a better chance that the technology will be adopted.

The performance of the robot's vibratory hammer was characterized using force plate sampling, lab tests and field tests. These measurements revealed the relative influence of the three parameters of (1) bias weight, (2) eccentric weight and (3) hammer frequency. The maximum downward force exerted by the robot can be augmented by increasing any of these parameters.

A custom simulation environment was developed to run experiments on the effectiveness of hypothetical deployments of multiple robots performing simple landscape construction tasks such as driving sheet piles to form check dams. Experiments probed the necessity of providing robots with information about the environment such as the topography, presence of built interventions, and presence of other robots. It was found that collectives of robots operating with no such information were able to install interventions that were 80–90% as effective as interventions that were designed in advance. These results suggest that for sufficiently constrained construction tasks, distributed robots can act in response to conditions encountered on site, alleviating the need for high precision and careful advance planning. Maintaining simple control logic for such a system would likely be all the more important if it were to become part of a more complex unsupervised construction project. Therefore, for the development of such a system, it may be useful to look to biological role models as precedents for evaluating the trade-offs between agent complexity and parallelism.

The results presented in Article C address gaps in construction automation research that were identified in Article A. Specifically, the work addresses the need for automated solutions for substructure tasks like establishing anchoring, and adheres to the suggestion that emerging technologies should be designed at the task-appropriate scale (recognizing the unique opportunities afforded by small-scale post driving and developing novel hardware at this scale). Future efforts will work towards full-scale on-site demonstrations in order to better understand the design parameters, power requirements and material considerations for reliable deployments. Advancing towards this goal will require hardware modifications as well as the incorporation of a localization and navigation system.

Article C emphasizes the automated construction of simple structures like check dams or sand fences that can be built by pile driving alone, thereby serving as a potentially complete demonstrator for, e.g., a hypothetical environmental restoration project. However, posts and piles are most typically used as components of more complex construction projects. An important direction for future work will be coordination of multiple types of task-specific robots. For example, a future demonstration could include autonomously-driven posts to serve as a foundation for subsequent superstructure assembly (such as the bridge-building scenario presented in Figure 1.3). Coordinating these tasks would likely require the different task-specific robots to share a localization system and maintain some kind of awareness of all robots and building elements on site. This represents a considerable increase in complexity over a single robot performing a specific task in isolation.

Future work will also seek to incorporate the embedded force sensing techniques presented in this thesis. While not yet tested, in theory these slim force sensors could be installed between the sheet pile and the robot's vibratory hammer, providing verification that hammer forces are being evenly distributed to the pile. Additionally, the development of a more complete unsupervised construction system may require custom joints to be designed in order to interface various building components (such as the anchoring node presented in Chapter 2). The results presented in the previous subsection could be mapped to anticipated failure modes of a pile foundation, such as excessive loading that would cause the pile to sink, or differential loading that applies a bending moment to the pile. Taken together, these two developments could facilitate the autonomous construction of verifiable ground anchoring, an important step towards the goal of unsupervised robotic construction.

3.3 Towards unsupervised construction

Academic review papers in the field of construction automation tend to focus on relatively narrow technologies or techniques such as 3D printing or advances in sensor fusion. A major contribution of Article A was that it identified a broad organizing goal of unsupervised construction, and used this goal to identify gaps in the body of research (in addition to providing a framework for this thesis). Unsupervised robotic construction would enable building in environments that are too remote or dangerous for conventional construction, such as building remote research outposts in challenging environments (e.g. deserts, the Arctic, or deep space), responding to natural disasters, or the installation and maintenance of critical infrastructure like dams, roadways or utilities. Article A emphasizes the gap that exists between academic research (which typically focuses on discrete assembly in laboratory environments) and industry research (which prioritizes automating conventional construction equipment). It suggests that in isolation, neither of these methods will lead to fully autonomous construction and recommends instead to reconsider emerging technologies based on the fundamental requirements of construction tasks.

Article A provides a metric for evaluating the autonomy of a given robotic construction task, based on the system developed by the Society of Automotive Engineers (reproduced as Table 3.1). This ranking could serve as the basis for evaluating future efforts towards increasing autonomy in construction.

However, a major finding of Article A that is not captured by ranking the autonomy of an individual construction task is that the integration of various automated construction tasks has been al-

Table 3.1: Levels of Autonomy (LoA)

LoA	Description
0: No automation	The system does not control any DoF, even if it is capable of enhanced sensing.
1: Operator assistance	The system adjusts a single DoF (such as raising or lowering a leveling bar) while the operator controls the rest.
2: Partial automation	The system is able to control multiple DoFs simultaneously, but requires a human operator to recover from failures and manage other functions.
3: Conditional automation	The system is capable of operating all DoFs simultaneously under some conditions. The system may be programmed to request operator assistance when needed.
4: High automation	The system can autonomously execute tasks under certain site conditions. The system does not require human assistance and can adapt to unexpected disturbances.
5: Full automation	The system can autonomously complete tasks under any site conditions where construction could reasonably be expected to take place.

most entirely overlooked. Even temporary or remote construction projects are typically composed of many different construction tasks, which not only need to be completed, but also need to be precisely coordinated with each other. Robotic task integration has only recently emerged as an active research topic at academic institutions (such as ICD's Multi-machine Fabrication project [9]) and in industry (including Volvo's THOR project [38]). However, no such projects to date seem to feature full unsupervised autonomy as a research objective.

While robotic task integration is a motivation for this thesis, its demonstration was considered beyond the scope of the work (and could certainly form the basis of a separate dissertation in and of itself). Instead, the bridge-building scenario presented in Figure 1.3 provides an organizing goal for future developments in this direction (of course, other concepts for unsupervised construction scenarios may require different material-robot systems). Work toward this goal included the design and characterization of a custom anchoring node that integrates both the pile-driving and force-sensing hardware contributions presented in this thesis. However, considerably more work would be needed to demonstrate this unsupervised construction scenario. The node-and-strut system presented in Article B is not designed for 3D assemblies. The proposal to attach 2D vertical trusses with horizontal struts (Figure 1.3C) may be possible, though it would require a corresponding node redesign as well as a robot capable of locomoting and placing struts in three dimensions. Depending on the application, this solution may be less desirable than one that avoids node-and-strut construction entirely, and instead deals with 3D assemblies of block structures. Further developments toward an unsupervised system include the design of a supply cache of building materials that facilitates robotic manipulation, in addition to consideration of how robots mount or dismount the structure. Initiating a new structure may require cooperation between robotic agents (for example, a terrestrial robot that positions a strut-climbing robot atop a sheet pile in order to begin building a new truss).

The remaining work needed to realize such a demonstration reveals the importance of designing for autonomy in the progression towards an unsupervised construction project. Conventional construction materials such as concrete masonry units or threaded fasteners have evolved over centuries to facilitate manipulation by human construction workers. There is no evidence to suggest that these same materials and methods would be optimal for robotic manipulation in any way. Instead, more promising advancements are being made with machines and materials designed specifically for autonomous operation. In particular, the recent development of material-robot systems for specific assembly tasks seems to hold considerable promise. These systems have already demonstrated full autonomy, though only in structured laboratory environments and with simulant building materials [41; 14]. Future proposals designed around durable building materials will likely be required to enable fully autonomous construction of useful real-world structures. These future proposals may wish to employ more sophisticated building materials to facilitate robotic manipulation. The work on embedded force sensors presented in this thesis provides one possibility for such instrumentation.

Achieving full autonomy remains a distant goal for most construction tasks, though some important steps towards a limited demonstration have already been established. It can be assumed that neither the materials nor the robots that would most effectively be engaged in an unsupervised construction scenario have yet been invented. Developing these enabling tools and techniques will require skills in architecture, design, and material science as much as in robotics and mechanical engineering. While it is possible to make substantial advancements in any of these fields alone, initiatives such as IntCDC seem uniquely capable of bringing together these skill sets in a way that has so far largely eluded both industry and academia.

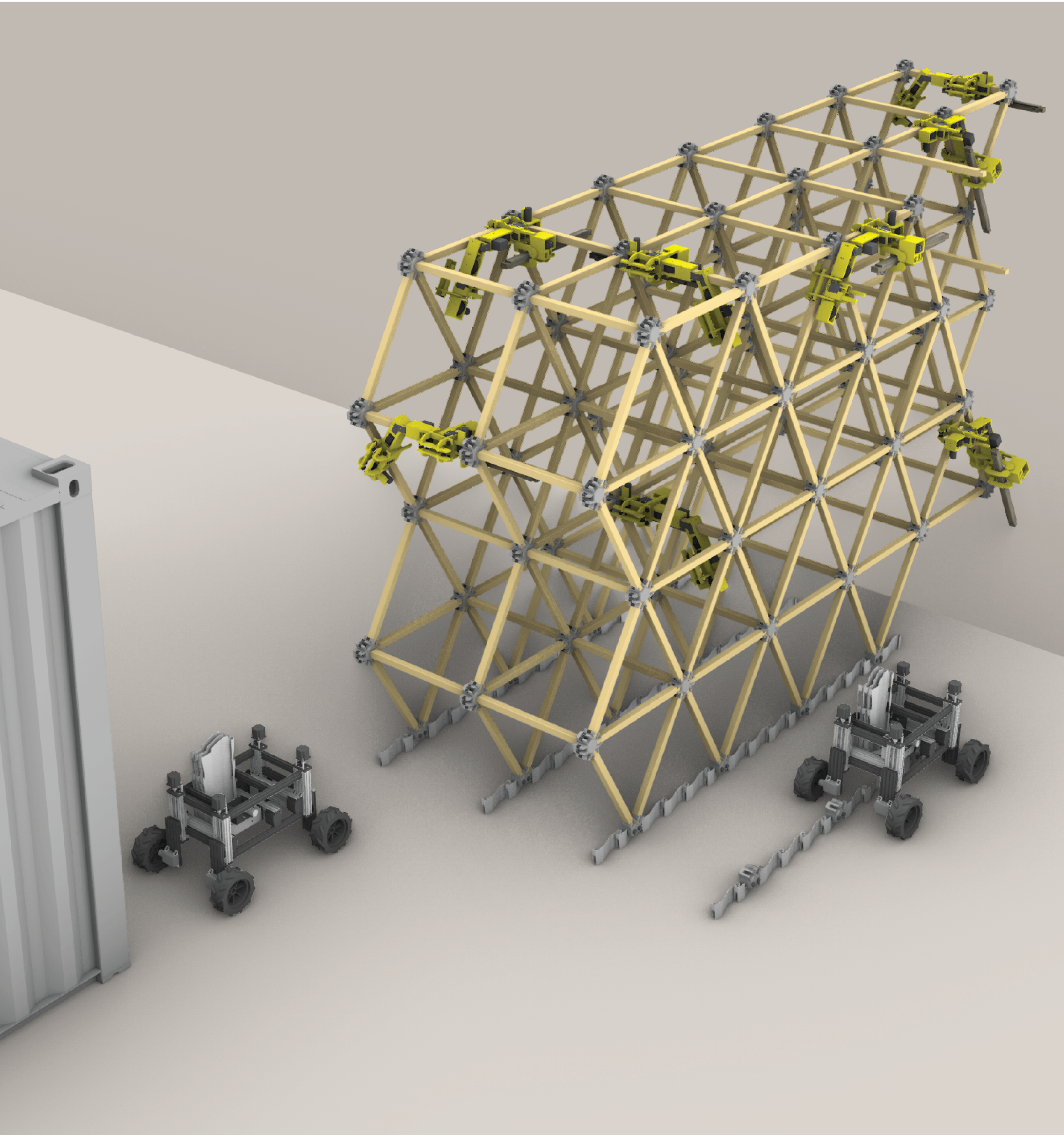

Figure 4.1: Rendering of a possible bridge-building application where the nodes and struts used in Article B are attached to the sheet piles used in Article C with a custom connector (see Figure 2.5).

4

Outlook

This thesis has taken a broad look at both mature and emerging technologies in the realm of construction automation, with the aim of identifying gaps in the fundamental construction processes that would be required to design and implement a fully autonomous unsupervised construction sequence. Article A tracks current trends in both industry and academia, and provides recommendations for bridging these gaps. Some of these overlooked requirements are addressed in this thesis, namely the need to provide distributed force sensing to verify alignment and structural stability of robotically assembled building components (Article B), as well as the need for an autonomous solution for anchoring structures to the ground (Article C). These contributions represent possible solutions to significant obstacles that had not yet been addressed, but future work (by the author and by many others) will require both further development of these solutions as well as alternatives. Of course, unsupervised construction will require advancements in areas that were beyond the scope of this thesis, such as autonomous excavation [13], concrete placement [29] and latching mechanisms for stable discrete assemblies [14].

Academic research is often conducted without attention paid to realistic materials and environments, while industry research maintains a short-sighted focus on incremental improvements to mature technologies. Generally, a promising long-term outlook is provided by research projects that remain bound to conventional material systems yet liberate themselves from legacy tools and processes. For example, the Mesh Mould project is concerned with rebar placement, a well-established requirement for reinforcing concrete that is overlooked by many on-site 3D printing projects [10]. The Mesh Mould approach can be contrasted with the TyBot project, a commercial endeavor for automating the tying of rebar for roads and large slab foundations [5]. While the TyBot approach of introducing a small degree of autonomy in a mature construction process may be quite profitable in the short term, it is clear that it is limited to a narrow set of form factors, and will remain dependent on adjacent legacy processes (such as human workers laying out the rebar to be tied). On the other hand, while the Mesh Mould project may not directly automate any specific conventional construction process, its ability to address the fundamental construction requirement of rebar placement can be generalized to a far greater range of form factors and applications than the TyBot solution. The work in this thesis, as well as future developments in this area, seek to maintain a similar long-term focus on the development of robust solutions to fundamental construction needs, as opposed to conforming to the conventions of industry.

As the research community continues to make progress toward increasing autonomy in on-site construction, seeing some adoption of the tools and techniques presented in this dissertation would provide a welcome validation of these contributions. As mentioned in Article A, the unique and demanding challenges of extraterrestrial construction have already given rise to earthmoving robots that are more efficient than automating conventional machines. It is reasonable to expect that international space agencies will continue to play a significant role in funding the development of emerging construction technologies, which will be required to supplant the mature technologies that presently dominate the construction industry.

The research trajectories of these and other agencies make clear that the fundamental sciences will continue to make considerable advances within the domains of their respective disciplines. What remains to be seen, however, is how well these advances will be adopted and incorporated into emerging applications in building construction. While roboticists and engineers may be capable of optimizing mechanical performance for a given task, architects and designers with an understanding of realistic and reliable material systems seem to be indispensable partners for developing new enabling technologies. Newly launched initiatives such as the NCCR for Digital Fabrication at ETH Zurich and the IntCDC at the University of Stuttgart address the issue of compartmentalization of university departments by collecting relevant domain experts in organized cross-disciplinary research projects in construction automation. Future progress toward the goal of unsupervised construction will almost certainly be aided by contributions facilitated by this essential mode of collaboration.

5

Article A

N. Melenbrink, J. Werfel, A. Menges, 2020. **On-site autonomous construction robots: Towards unsupervised building.** *Automation in Construction*

The scope and organization of this review originate from N. Melenbrink under the advising of A. Menges. Literature review for this publication covered a broad range of advancements for both mature technologies and emerging technologies. The findings of the survey suggest a need for emphasizing material-robot systems, embedded sensing, and coordination between different task-specific robot systems. In support of these findings, 208 references were included in the initial submission (trimmed down to 176 at the editor's request). The majority of these references were researched by N. Melenbrink. A. Menges recommended many additional references to fill gaps in the initial draft, as well as content revisions such as an added emphasis on the need for cross-disciplinary research. J. Werfel added further contributions. All authors participated in revisions and responses to peer review.

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Review

On-site autonomous construction robots: Towards unsupervised building

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ABSTRACT

Real-world construction projects typically require three groups of tasks: site preparation (earthmoving, leveling), substructure (anchoring, foundations), and superstructure (load-bearing elements, facade, plumbing, wiring, etc.). Advances in construction automation have revealed a gap between industry and academic research, where industry efforts have been focused on automating conventional earthmoving equipment and embracing prefabrication in order to reduce the amount of work that needs to be done on site, while academic efforts have largely concentrated on proposals for on-site additive manufacturing or discrete assembly, which may be of limited applicability to industry. This review presents a broad range of advancements in construction automation research, and finds that achieving fully autonomous construction in unstructured environments will require considerably more development in all three groups of construction tasks, as well as a particular emphasis on coordinating myriad construction tasks between different task-specific robots. Consideration is given to both mature technologies (conventional equipment widely used in industry) and emerging technologies (novel machines designed for autonomy). Key findings from the survey suggest that achieving the goal of fully autonomous construction will require more attention to be paid to site preparation and substructure tasks, material-robot systems (co-designed robots and building materials), embedded sensing, auxiliary construction tasks, and coordinating operations between robot systems. More general lessons from the literature indicate that making incremental improvements to mature technologies may benefit the industry in the short term, but there are considerable limitations to adding autonomy to equipment designed for human operators. Instead, we perceive a demand for novel hardware to be developed for specific tasks, in each case based on fundamental principles and at the appropriate scale, as well as for an increase in interdisciplinary research. We suggest that the reported shortage of skilled labor in the industry can be met with an increased emphasis on training for leveraging advances in automation.

1. Introduction

In the construction industry, the role of on-site robotic automation so far remains very limited. Increasing robotic automation on construction sites could carry substantial advantages such as reducing injury rates, handling repetitive tasks, and helping to enable construction in settings not currently feasible, e.g., for use in disaster relief, exoplanet construction, or other dangerous or challenging environments. A fully autonomous construction system, able to operate without supervision or intervention, would be best suited for these kinds of scenarios. Such a system would need to be able to handle unpredictable and changing conditions during the course of a project.

Despite being heavily reliant upon mechanical operations, construction ranks as one of the least digitized industries [1]. Many tasks associated with the construction industry fulfill the canonical "dirty, dangerous and dull" criteria of tasks ripe for automation, which leads economists and investors to expect an imminent robotics revolution in the Architecture, Engineering and Construction (AEC) industry [2]. There is, however, very little compelling evidence to suggest that this is happening. While incrementally introducing robotic automation to construction sites has occurred in certain high-budget projects, there are limits to automating mature technologies like conventional heavy equipment. In fact, the current state of automation in the AEC industry has been impacted less by on-site robotic actuation than by other trends that are both outside of the scope of this survey and have already received a good deal of attention in the form of their own dedicated review papers. These trends include the increasing adoption of Building Information Modeling (BIM) [3,4], additive manufacturing (3D printing) [5–7], and on-site sensing [8,9]. Still other review papers have focused on academic research involving robots operating in controlled

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laboratory environments [10,11].

Author Richard Foster described the development of new technologies over time as following an S-curve; development is very slow at first, until a tipping point is reached, causing a flurry of new investment and development. Once the technology reaches a point of maturation, progress levels off (the top of the S-curve) and it becomes more difficult and expensive to make even incremental improvements [12]. Cash registers are an example of a mature technology; while incremental improvements have been made to cash registers over the past several decades, their dominance in the retail industry could only be challenged by a fundamentally different technology (such as mobile payment apps or cryptocurrency). Thomas Bock describes the current state of construction automation as consisting of two distinct paradigms, each represented by its own S-curve [13]. The mature technologies paradigm includes the suite of tools and techniques that have remained relatively unchanged over recent decades, such as heavy equipment designed for diesel engines and human operators. The emerging technologies paradigm reconsiders construction processes from fundamentals and offers the potential to supplant legacy tools and techniques with new building materials and custom-purpose built autonomous machines. While these nascent technologies may seem to offer solutions that are inferior to the status quo, often these are due to economic or organizational inertia of the mature solutions. Most importantly, this latter paradigm is untethered from industry conventions and therefore suited to fully autonomously complete construction tasks in settings that are too dangerous, hostile, or remote for conventional construction to take place, such as decommissioning nuclear power plants, disaster relief/preparedness, building remote research outposts in challenging environments like the Arctic, deserts or even deep space, or installing, maintaining and protecting critical infrastructure like dams, roadways or utilities.

This paper will cover advancements in both paradigms as both will continue to impact the industry, but seeks to highlight the latter paradigm as it uniquely carries the potential to advance the goal of fully autonomous construction. While there have been a range of prior reviews related to robotic construction, none have been conducted from the perspective of the fundamental technologies needed to achieve a fully autonomous construction process. While fully autonomous construction processes have been demonstrated using simulant building materials in laboratory environments [14–16], considerably more work would be needed to advance these systems to operate in unstructured environments and with realistic building materials.

While there are different systems for characterizing a robot's level of autonomy (LoA), the most widely recognized metric is the scale from 0 (fully non-autonomous) to 5 (fully autonomous) that has been employed as a standard by the Society of Automotive Engineers (SAE) [17]. Work reviewed in this paper is characterized according to its level of autonomy in Section 5.

Useful structures, even temporary ones, typically require three distinct phases of construction to be executed in sequence. This review paper is arranged accordingly. Section 2 covers site preparation tasks such as clearing debris, earthmoving, and leveling. Section 3 discusses anchoring methods such as concrete foundations and driving piles. Section 4 covers the construction of superstructure elements, including the assembly of load-bearing structure, additive manufacturing, finishing tasks and the trend of moving tasks off-site to prefabrication facilities. Section 5 discusses trends and offers suggestions for future research in the field. Our main objectives in conducting this survey are to (i) discuss developments in three areas of construction (site preparation, substructure and superstructure) paying particular attention to the under-development of the first two categories, (ii) chart trends that will lead to fully autonomous construction, and (iii) cover developments both in industry and academic research, identifying gaps and possibilities for new directions.

2. Site preparation

Site preparation refers to the group of tasks that may be needed to treat a construction site prior to establishing a foundation and subsequent superstructure. These tasks may include clearing brush and debris, earthmoving and leveling, and soil stabilization. The past century has seen the work of many hands replaced by that of few machines, as these tasks have become increasingly reliant upon heavy equipment (specifically bulldozers, excavators, loaders and dump trucks).

Increasing automation in the realm of site preparation has primarily come in the form of the mature technologies paradigm, retrofitting existing heavy equipment with increasing levels of autonomy. Recent reviews of earthmoving robots for military applications focus largely on teleoperation of conventional earthmoving equipment and characterize those efforts in greater depth than provided here [19,20]. Other recent surveys focus less on autonomous applications and instead cover developments related to conventional heavy equipment used for earthmoving, such as hydraulic control [21], energy storage [22], and hybrid electric systems [23]. Examples of emerging technologies for site preparation come mostly from space applications, which have also been covered in reviews [24].

In some contexts, site preparation may initially require land clearance, including the extraction and removal of rubbish, vegetation, topsoil or other undesired terrain features. Much of this work is typically accomplished with bulldozers, excavators, and front-end loaders. In the case of larger timber, feller-bunchers (machines used for clearing trees and brush) have been deployed to clear nearly 1000 acres of trees from a military test site, using teleoperation to control one machine fitted with a disc saw head for handling larger timber and two others with mulching heads for clearing smaller brush [25].

Site preparation may also require the demolition and removal of existing structures. Teleoperated demolition robots were an early arrival in the construction industry, with the first mass produced model released by Brokk hitting the market in 1981, responding to a clear safety benefit of physically separating workers from loud and dangerous demolition tasks [26]. Subsequent iterations of Brokk machines are still in use today (Fig. 1A), for which a variety of end effectors have been produced, including hydraulic shears, diamond wire and disc cutters, grapples, crushers and even plasma cutters. Diesel versions are recommended for outdoor use, while electric models are made for indoor use. These machines are typically run with an operator on site at a safe distance from the demolition, or may be teleoperated, but so far have not been programmed for any degree of autonomy [27].

Teleoperated robots have been used to clear rubble following volcanic eruption of Mount Unzen in 1994 [28]. More recently, the initial restoration from the 2016 Kumamoto earthquakes was conducted by 14 teleoperated construction machines working simultaneously [29]. PackBots, which were expressly developed for teleoperated surveying tasks, were deployed in the wake of the Fukushima nuclear disaster in 2011, adding considerable value to the cleanup tasks [30]. Retrofitted excavators were also teleoperated for a number of debris clearing tasks [31]. However, these machines were not designed for teleoperation and proved challenging to control, in one case resulting in the accidental explosion of an oxygen cylinder [32].

2.1. Heavy equipment for earthmoving

A good deal of attention in both industry and academic research has gone towards automating existing heavy equipment (excavators, bulldozers, front-end loaders, graders, and dump trucks) to perform common earthmoving tasks [19]. Most of these developments can be categorized as functional-assist platforms. For example, using automated GPS guidance to a human operator in real-time greatly improves speed and accuracy.

Literature on earthmoving equipment distinguishes between “scrapers” and “scoopers”. Scrapers (e.g., levelers or bulldozers) feature a

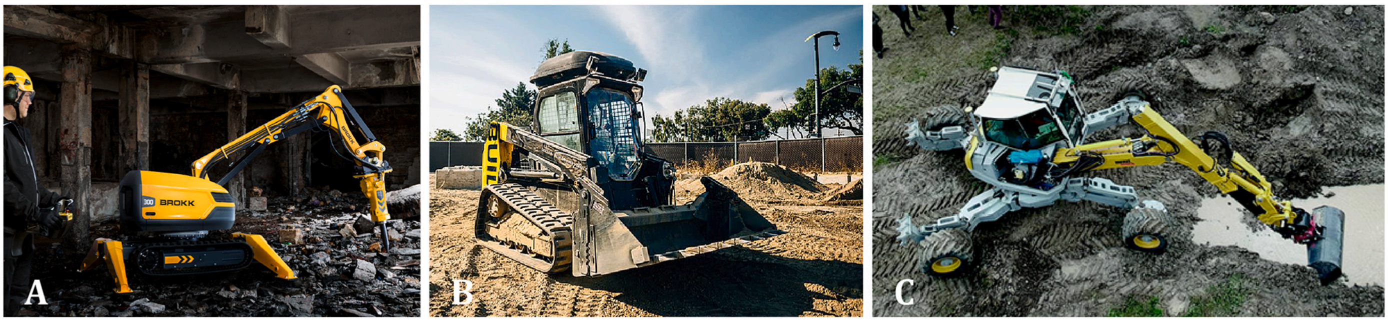

Fig. 1. Automated mature technologies used for site preparation. (A) Brokk robot with an jackhammer attachment used for demolition, operated from a distance. (B) Built Robotics retrofits conventional earthmoving equipment with autonomy kits. (C) The Hydraulic Excavator for an Autonomous Purpose (HEAP) is capable of autonomously digging trenches defined in a CAD model [18].

kind of leveling bar that can be raised or lowered relative to the chassis of the machine. Scoopers typically have a shovel bucket as well as an extra degree of freedom, allowing them to, e.g., raise their bucket and then empty it into a dump truck. Scoopers can act as scrapers simply by disabling this degree of freedom, which is commonly seen both in industry and academic research [33,34].

Most loaders or excavators are discrete rather than continuous. Discrete excavation consists of distinct cutting operations, where the operator typically commands a cut depth and rate of advancement intuitively, and usually needs to empty the bucket between each cut. Continuous excavation, on the other hand, typically consists of a series of blades arranged along a wheel or belt, such that at least one blade is always in contact with the soil.

Payload ratio (the weight of the maximum payload divided by the weight of the empty vehicle) is a useful proxy for efficiency for earthmoving tasks. Payload ratios for haulage vehicles in the mining industry and dump trucks used in construction range between 100% to 140% [35]. Payload ratios for loaders (typically used to fill dump trucks) are much lower, between 15% to 25% [36].

Mathematical and simulation models of conventional earthmoving equipment such as loaders, excavators and bulldozers have been developed extensively, providing a robust foundation for their autonomous control. By 1998, a conventional excavator was equipped with autonomous control and demonstrated the ability to load a dump truck as fast as a skilled human operator [37]. The demonstration featured adaptive control based on laser range finding used to avoid obstacles, detect the truck, and measure the volume of soil contained inside it. More recent advancements include achieving reliable pose and position estimation using sensor fusion of IMUs and differential GPS [38,39], improved real-time modeling of soil parameters [18,40], and advancements in path planning algorithms [41].

Equipment manufacturers such as Caterpillar and Komatsu have been incrementally adding autonomy such as grade-assist systems to some of their existing line of equipment. Grade-assist systems automate the control of vertical boom movements and horizontal bucket movements (in/out) such that they lock to the desired grade while the operator controls the speed of forward advancement [36,42].

Other companies such as ASI Robots, Inc. have developed autonomy kits that can be integrated into generic heavy equipment, and are used in construction mining and agriculture [43]. A recently launched startup company called Built Robotics has focused on the construction industry and broadened the appeal for autonomy kits for existing heavy equipment (Fig. 1B). Their product includes GPS, WiFi, lidar and other sensors contained in a box, which so far has been used for excavators, bulldozers and loaders. They follow a subscription model, charging a usage fee whenever the machines are in autonomous mode [44].

Volvo Construction Equipment research prioritizes the full electrification of heavy equipment, though introducing autonomy is also a goal. In 2014 Volvo released a fully electric compact excavator called GaiaX, which makes use of the heavy batteries as a counterweight to the arm and boom. However, no development on this concept has been published since the initial press release [45]. Volvo unveiled the compact excavator ECR25 Electric, which started seeing deployment to construction sites in late 2019. This model is the first excavator to replace a combustion engine with fully electric power. It runs on 48 V lithium-ion batteries that power an electric motor that runs hydraulic actuators. The machine is claimed to last 8 h for common applications, and recharges with a standard electric socket. Volvo's Electric Site Project features autonomous dump trucks that work in concert with electric wheel loaders that are driven by human operators [46]. Volvo's THOR (Terraforming Heavy Outdoor Robot) project has demonstrated software that autonomously moves the bucket to a given height in real-world coordinates without operator input [33], and in 2016 demonstrated multi-robot task integration with its prototype autonomous wheel loader and autonomous articulated hauler working together (though both machines were following pre-planned trajectories, and had no awareness of each other) [46]. These demonstrations took place in relatively structured outdoor environments; this degree of autonomous task integration has not yet been observed on conventional construction sites.

Site preparation may also require digging trenches to hold footings and foundations (discussed in Section 3). This task could in theory be performed by a number of construction machines, but has only seen limited demonstration. Researchers at ETH Zurich have retrofitted a walking excavator with autonomously controlled hydraulic joints (Fig. 1C) [18]. Since soil interaction forces are notoriously difficult to predict, it is considerably more energy efficient to employ reactive planning based on soil parameters encountered in real-time. An iterative planner was developed to execute discrete digging operations until a target ground geometry was achieved. Ultimately, the machine demonstrated reliable execution of free-form trenching from defined CAD models [18]. Design studio courses were developed to pursue applications for robotically mediated dynamic landscapes that change over time [47].

Automating grade-assist functionality for heavy equipment has been demonstrated to be effective in road construction. However, even though grade-assist technology is equally applicable to both site grading and road grading, these systems are not available for road graders as most road construction is under government management, and demand for automation is not high. Other civil engineering applications have so far resisted automation. The Tiger Stone paving machine is often misreported as an automatic road builder [11,48], when in fact it simply drives forward slowly while providing an elevated working platform such that workers can stand rather than kneel [49]. Bricks still need to be arranged manually.

In general, the construction industry lags behind the mining industry in terms of automating earthmoving equipment. In the mining industry, autonomous haulage trucks have been commercially available

Fig. 2. Emerging technologies for site preparation. (A) The NASA "Glenn Digger" mounted to the Centaur 2 mobility platform [50]. (B) The NASA RASSOR excavation robot [51]. (C) Centrally mounted bucket-wheel allows for a larger payload [52].

for many years from suppliers like Hitachi, Caterpillar, Komatsu and others. However, these vehicles operate within the structured environment of the mining site and maintain a precise understanding of the terrain. The primary obstacle to increasing automation in conventional site preparation is the chaotic conditions that characterize most construction sites.

2.2. Novel actuators (emerging technologies)

A number of research projects have sought to increase autonomy in site preparation tasks from basic principles rather than retrofitting existing machinery. The first demonstrated autonomous excavator was REX in 1986. REX used a supersonic air-jet cutter to dislodge material, avoiding the direct contact intrinsic to bucket excavation, which was intended to simplify path planning and prevent the robot from damaging itself [53].

Other projects have demonstrated spraying foams to smooth rough terrain at a small scale, a means of site preparation which could, e.g., build ramps conforming to unstructured terrains using amorphous materials [54]. Similar operations could be achieved at a larger scale with the Digital Construction Platform, a mobile robot capable of both excavation and depositing structural foam (Fig. 12A) [55]. These operations may be useful for site preparation on uneven terrain, though the technique of spraying foam for ground support or soil stabilization is not currently used in industry.

Future applications of building in extraterrestrial environments, as for a future hypothetical moon base or Mars colony, are a particular opportunity for construction automation in the emerging technologies paradigm because of the lack of established construction infrastructure in such settings. Working with regolith in low-gravity extraterrestrial environments such as the surface of the moon or Mars introduces a more stringent set of restrictions that are not well addressed by conventional heavy equipment, such as the need for equipment to be lightweight for transport into space. Consequently, a range of novel robots have been developed for extraterrestrial (most commonly lunar) construction tasks [56,57]. Robots may be required for tasks including clearing a landing area, building berms to control dust, excavations required for building permanent structures, or other site work. Robots may also be useful for soil sampling, mining, or collecting regolith to use for additive manufacturing or other construction tasks [24].

A number of studies have evaluated the feasibility of using conventional heavy equipment in extraterrestrial environments. One study compared the suite of conventional heavy equipment that would be needed to build a lunar base with nine sets of novel construction equipment conceptually designed specifically for lunar construction. The study suggested that such novel custom-purpose built actuators would be able to perform the necessary construction tasks while requiring considerably less launch mass than typical heavy equipment [57]. Further work disregarded conventional earthmoving equipment and instead compared robotic excavators that had been previously proposed for lunar construction, including augers, bucket ladders, bucket wheels/bucket drums, draglines, overshot loaders, and scrapers. The designs were scored in a number of metrics, and the authors concluded that a multi-use robot with both an excavator arm and a bulldozer blade was most suitable for lunar site work [56]. Other research used simulation to evaluate the potential advantages of an autonomous multi-robot approach to excavation as opposed to the default approach of a teleoperated single vehicle. Analysis considered launch mass, power, efficiency, reliability, and overall mission cost, and showed that the autonomous multi-robot approach could have a considerably higher productivity rate, lower equipment cost due to the smaller, less complex machines, and further cost savings due to a lower launch mass [58]. Another multi-robot approach to site preparation takes biological inspiration from the "blind bulldozing" behavior of *L. albipennis* ants [59]. Model bulldozers are placed in the center of a site to be cleared and push debris outwards until force sensors on their blades indicate a threshold has been crossed, after which they switch direction. Over time this has the effect of building a circular wall or berm around the center of the site. While this approach could in theory be applied to earthmoving, it has not yet been demonstrated outside of laboratory environments.

A number of proposals for lunar site preparation have been presented. The NASA Chariot, a general purpose lunar exploration vehicle, was outfitted with a lightweight bulldozer blade to evaluate the feasibility of excavation for site preparation [34]. Finite element analysis (FEA) was used to model the interactions between the surface of the soil and the cutting edge of the bulldozer blade. The Cratos robot features an operable open bucket in the center of its body [60]. It is capable of articulating its bucket to scoop and hold regolith, then depositing it elsewhere to, e.g., build a berm or ramp. Juno rovers, early prototypes developed by the Canadian Space Agency, have been equipped with shovel buckets similar to those found on terrestrial loaders. However, the only operable degree of freedom (DoF) is the cut depth, rendering it effectively a discrete scraper [61]. NASA's Centaur 2, a general purpose rover platform, has been equipped with a 2-DoF front-loader bucket capable of collecting soil and depositing it into a hopper up to 1 m tall (Fig. 2A). The vehicle can operate autonomously, using sensors to assess digging forces and adjusting accordingly in order to prevent excessive power consumption or equipment damage. The empty vehicle weight is 94 kg, with a 32.6 kg nominal bucket capacity [50].

NASA has sponsored student competitions where lightweight excavators must collect as much regolith simulant as possible in a limited time. Winning teams tend to rely on bucket ladders though the exposed chains or belts needed to drive them are considered to be ill-suited for practical deployments [62]. Prototypes based on bucket-wheel excavation seem to hold more promise, especially for lunar excavation. Bucket-wheel excavators, often employed at very large scales in the mining industry, consist of a wheel arrayed with blades that collect soil as the wheel spins. In miniaturized bucket-wheels used on mobile vehicles (Fig. 2B–C), the soil is contained inside of the wheel with the use of internal baffles. Rotating the drum in the opposite direction allows for deposition of the contained soil. This concept was first presented by

Lockheed Martin, with a single drum excavator featuring small scoops mounted on its exterior [63]. The idea was further developed as NASA's RASSOR robot (Fig. 2B), which features two drums that counter-rotate in order to balance horizontal excavation forces [51]. The drums can be lifted to, e.g., deposit the contained soil into a haulage vehicle. Yet another bucket-wheel variation features a single centered wheel mounted orthogonal to the direction of travel (Fig. 2C) [52]. Discrete scraping is the most commonly proposed technique for extraterrestrial excavation [34,61]. Even robots capable of scooping have only been used for scraping in experiments [50]. However, quantitative analysis and experiments with simulated low-gravity excavation showed that discrete scraping is not practical for low-gravity operation because the excavator will stall before enough payload can be collected to be productive [52]. Continuous excavation (Fig. 2B–C) is recommended instead.

Other work has evaluated the effectiveness of introducing vibratory excitation to lunar digging tasks, and found a 15× reduction in the downward force needed to penetrate a compacted lunar regolith simulant. The researchers found that vibratory or impact assisted excavation is of greater advantage in stiffer, more compacted soils, and that these techniques are able to drastically reduce the energy required for a given excavation task. They conclude that this improvement is sufficient to enable robot morphologies that would not otherwise be feasible [64]. Further information on the goals and challenges of extraterrestrial mining equipment is provided in a 2012 review [24].

Novel lightweight excavators developed for lunar operation have demonstrated payload ratios of 30% [60], 40% [50,51], and 50% [52], generally better than terrestrial loaders (15–25%), but not as efficient as bulldozers or haulage vehicles (100–140%). Of these excavators, only the RASSOR (Fig. 2B) and the Centaur 2 (Fig. 2A) are able to lift their payloads such that they could be deposited into a haulage vehicle [50,51].

It is clear that incremental improvements to mature technologies such as automating retrofitted conventional earthmoving equipment has the potential to benefit contractors and developers in the near term. However, there are limitations to the improvements that can be made to machines that were not designed for autonomous operation. Smaller projects in environments that are dense or cluttered will still require human operators to deal with novel problems, edge conditions and other challenging situations. It is not clear that retrofitting existing earthmoving equipment with autonomous features is the most effective path to reach the ultimate goal of fully autonomous construction. On the other hand, the extreme challenges of extraterrestrial site preparation have generated a suite of novel proposals for autonomous robots. These emerging technologies may lend themselves to other challenging environments including terrestrial settings, and may ultimately supplant the mature technologies that currently dominate the industry.

3. Substructure

As a rule, useful terrestrial structures need to be anchored to the ground, typically by means of a foundation or other substructure. Simple methods of anchoring such as earthfast posts date back to the early Neolithic period. Earthfast posts (also called post-in-hole construction) are structures that achieve anchoring by simply driving wooden posts into the ground, which then support the roof of a superstructure [67]. Later developments included elevating structures on simple fieldstone foundations so that they wouldn't wash away with the eroding topsoil [68]. Over time, these simple methods evolved into elaborate, complex processes needed to form durable concrete and steel foundations. While the results of these mature technologies have been remarkable, the complex array of tasks that must be correctly orchestrated (and the range of specialized heavy equipment needed to do so) presents an obstacle to automation.

Section 3.1 discusses incremental approaches to introducing autonomy in mature technologies used for shallow concrete foundations, following any requisite excavations or other site work. These tasks include building formwork, positioning rebar, pumping and placing concrete, and other related processes. However, not all anchoring tasks are necessarily quite so complex. Though typically less permanent and robust, anchoring can be established through more straightforward processes like pile or post driving. Such techniques are commonly used to anchor temporary structures, and may be applicable to many situations where fully autonomous or unsupervised construction is desirable, such as building temporary shelters for disaster relief or for extraterrestrial construction. These techniques are covered in Section 3.2.

3.1. Concrete foundations

Shallow foundations typically transfer structural load to the ground with a concrete footing. Footings are usually placed about a meter below the surface of the soil, or at greater depths if needed to extend below the frost line. Footings can be established by pouring concrete directly into an excavated trench, though occasionally additional formwork is introduced to, e.g., shape pad footings into square or circular elements. Alternatively, trenches can be filled with rubble or stones, known as rubble trench foundations, which are cheaper and more environmentally sustainable than concrete, but may not meet building codes in many regions. Stones may be covered in mortar for added stability. Automating the dry-stacking of stones as a method of foundation support has recently been the subject of academic attention [69,70]. Other laboratory demonstrations have focused on the ability to autonomously stack small sand bags [54,71]. However, industry processes remain heavily dependent on concrete foundations established using heavy machinery.

Vehicle-mounted manipulators with concrete pumps are generally used for the pumping and placing of concrete into formwork. These manipulators have become semi-automated with reactive pump control features and semi-autonomous boom control. Autonomous pump control ensures consistent delivery of concrete despite shifting angles. Semi-autonomous boom control allows the operator to specify a deposition height in real world coordinates, which is maintained as the operator manipulates the end hose in horizontal directions with a single joystick (Fig. 4A). Real-time stabilization (featured in products like Putzmeister's Ergonic system [72]) dampens boom vibrations commonly encountered when pumping concrete, and compensates for changing concrete weight in the delivery line. Operators can also increase safety by specifying bounding zones that will not be exceeded during the boom operation, and automated hydraulic control reduces wear on equipment [72]. A number of competing companies have developed similar products, such as Zoomlion's Smartronic system [73]. Many of the techniques used for foundation walls can also be used for building concrete superstructures, and therefore would be applicable to Section 4 as well.

Research teams have retrofitted conventional concrete placement machines for automating shotcrete, a construction technique where concrete or mortar is pumped through a hose and sprayed onto a surface. Shotcrete is commonly used in substructure applications such as slope stabilization and tunnel reinforcement. A conventional concrete placement machine was retrofitted with autonomous pump and boom control in the TunConstruct project [74]. A control system measured parameters related to pump operation, such as pressure and concrete flow rate. Quality was controlled by adjusting the spray trajectory and velocity of the manipulator in real-time in order to enhance homogeneity of the shotcrete layer thickness. The results revealed substantial improvements in layer homogeneity compared to human operators. However, the researchers discovered that the smoothness of the autonomous trajectories was disturbed by the limitations of the retrofitted machine, which did not supply enough hydraulic power to operate all of the manipulator's joints simultaneously. Furthermore, the boom arm was not equipped with proportional control and had to be operated in on/off mode, resulting in bouncing and jerking that caused errors of up to 50 mm. The authors concluded that though it is possible to automate mature technologies designed for human operation, unexpected difficulties and performance limitations are likely to arise [74].

While automated tunneling in general has been advanced primarily through the mining industry, tunneling is an important technique for the construction of infrastructure elements used for transportation and utilities. There has been a considerable amount of work in automated tunnel inspection and monitoring [8], which falls outside of the scope of this paper's focus on on-site physical tasks. Many tunneling operations rely on teleoperation, from large-scale tunnel boring machines to small-scale impact moling (a pneumatic hammering technique for running pipes or cables underground across short distances) [75]. The BADGER project proposes a novel method for smaller-diameter autonomous trenchless tunneling operations using a segmented worm-like morphology [76]. While development and prototyping of this project is ongoing, it has been deemed to be currently infeasible in industry [75]. Large tunnel boring machines are often outfitted with laser guidance systems and hundreds of sensors but remain dependent on human operators (or teleoperators) to make control decisions [77]. A semi-automated pilot system has been proposed for long tunnel boring machines [78], and the use of robotic total stations has been proposed as being more suitable for autonomous navigation than conventional laser guidance [77]. More recently, the autonomous locomotion of a tunnel boring machine has been demonstrated by MobileTronics in Austria. The system controls steering for 18 independent axles, and allows for human teleoperators to take control in exceptional situations [79]. Malaysian contractor MMC Gamuda has also developed an autonomous tunnel boring machine (A-TBM), and is operating 10 autonomous machines throughout the country [80].

3.2. Pile driving

Deep foundations are typically used where structural loads are very large, soil is weak at shallow depths, or site constraints present a challenge to excavation and concrete placement. Rather than excavating a trench to such depths, deep foundations are typically achieved through pile driving, the task of sinking posts or similar building elements firmly into the ground. Pile driving is a ubiquitous part of nearly every construction project and is used for a range of applications.

Common methods for pile driving in commercial construction include drop hammers (heavy rams that are repeatedly lifted and dropped), air hammers (pneumatic jackhammers), hydraulic impact hammers, and vibratory hammers (eccentric weights that generate downward forces, usually powered hydraulically). More recent innovations include acoustic pile driving, which uses the changing natural frequency of a steel pile to facilitate driving into the ground [81]. To date, no examples of autonomous solutions have been presented, but the variety of commercially available pile–driving tools suggest a broad demand for such automation at a range of scales.

The construction industry has made few attempts to introduce automation in pile driving. A Finnish research group has developed methods for automating impact pile driving for foundations, and estimated that introducing automation in the form of 3D positioning systems, real-time measurements of pile resistance, and autonomously cutting piles to length after driving could reduce costs by about 40% [65]. Experiments focused on translating pile positions from a 3D model to a semi-autonomous piling machine using differential GPS antennas for positioning (Fig. 3A). Furthermore a wireless system monitored real-time environmental effects of pile driving, including vibrations that could affect other nearby structures, as well as real-time geotechnical bearing capacity of piles while driving. Field experiments compared traditional work processes on four sites and GPS-controlled processes on two sites, and found that while the pile driving time was comparable, the GPS-enabled version saved time otherwise spent surveying and marking the site [65].

Sheet piles are used in commercial construction to provide slope stabilization on uneven terrain or to construct retaining walls allowing for pre-foundation excavation. In ecological applications, they can aid with restoration of degraded environments in the form of check dams (walls anchored in the ground that mitigate erosion by slowing water velocity during storm surges) [82], as well as addressing problems associated with sea level rise such as erosion, inundation, and salinity intrusion by forming structures such as bulkheads, perpendicular groins, offshore breakwaters, and seawalls [83,84].

Introducing automation into sheet pile driving could reduce costs and enhance safety for this critical construction task, as well as increase opportunity for interventions in environments where human presence is challenging. Few alternatives have been proposed to the mature technologies used for sheet pile driving. For impact pile driving, compact gantry systems have been proposed as an alternative to conventional serial-link pile–driving equipment [85]. Another development of interest is the Silent Piler (Fig. 3B), a pile–driving device that anchors into previously driven piles, leveraging downward force to help drive the current pile [86]. While this confers the benefits of requiring less bias mass (and therefore less energy) and reduces construction noise, introducing autonomy does not seem to be a project goal.

A design and prototype for a novel autonomous sheet pile driving robot named Romu has been presented for working with small-scale sheet piles (Fig. 3C) [66]. The robot is designed to carry a payload of sheet piles into a target setting and drive them into the ground in sequence, producing a sturdy wall that could, e.g., serve as a check dam to reduce flash floods in an arid environment. Romu uses a vibratory hammer to insert sheet piles into soil, and makes use of its own weight to help drive piles to greater depth without needing to carry excessive additional mass for that purpose. This represents a departure from conventional pile driving (Fig. 4B), where a heavy crane is used only as a counterweight to the bias mass, which does the work of driving the pile. The effects of mechanical parameters on the depth and extraction force of driven piles were characterized, and operation was demonstrated in both controlled and natural environments. The robot was subsequently modified to drive discrete posts instead of sheet piles [87]. Common examples of light-duty post driving include fencing, stakes for tents and other temporary structures, surveying, staking coir logs for erosion control, and other land management tasks. These examples show post driving as a component of construction projects that require additional tasks. Even so, automating these kinds of tasks is important because they would be necessary in any fully autonomous construction project. At its current scale, Romu is capable of shallow anchoring tasks that require driving rebar stakes ~20–30 cm into soil, such as conducting geological surveys, securing formwork for foundations, anchoring meteorological stations and other landscaping tasks. While this prototype is not massive enough to drive piles to depths typically required in conventional construction, force characterizations are given such that a reasonable scaling could be calculated for a machine sufficient to do so.

Post driving at the scale of fencing is typically conducted with hand tools or vibratory or impact hammers mounted to tractors, front loaders or similar equipment (sometimes pre-drilled post holes). While this equipment has been previously equipped with GPS-enabled operator-assist (semi-autonomous) functionality, this has not yet been demonstrated in literature for the application of post or pile driving.

While pile and post driving have largely resisted automation, alternative techniques for anchoring temporary structures may be more easily automated. A Hesco basket (Fig. 5) is a steel gabion basket lined with fabric, which is filled with soil and used for applications like temporary flood barriers or military fortifications. However, recent research evaluated the load-bearing potential for Hesco baskets and found them capable of supporting modest structural loads [88]. Hesco baskets are simple to deploy, making them conducive to automation. While it has not yet been demonstrated, it is plausible that with existing

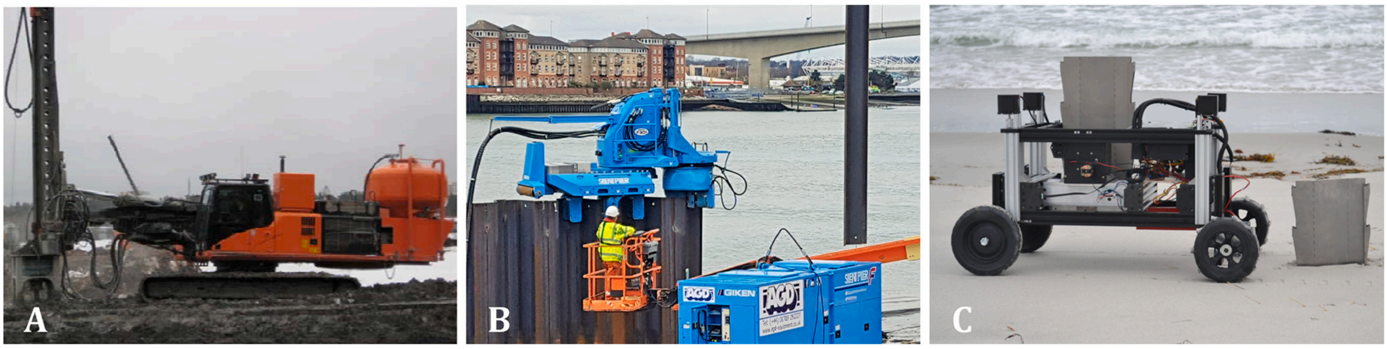

Fig. 3. Establishing anchoring on construction sites. (A) A GPS-enabled pile driving machine places piles in precise locations [65]. (B) The Silent Piler leverages against previously driven piles to press piles deep into soil. (C) Romu, an autonomous robot capable of carrying a cache of small sheet piles and driving them using a vibratory hammer and its own body weight [66].

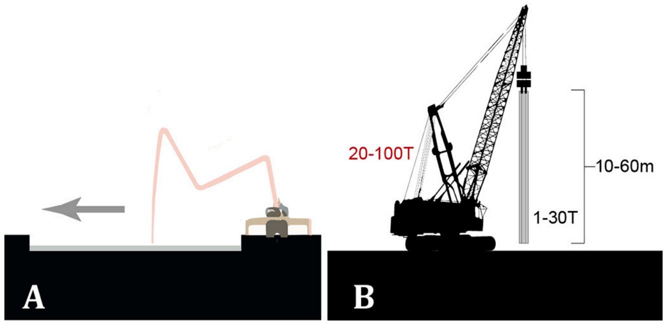

Fig. 4. (A) Semi-autonomous boom control allows operators to specify a fixed height, which is maintained as the operator moves the boom horizontally. (B) Conventional pile driving uses the large mass of the crane only as a counterweight; only the bias mass is applied towards the primary goal of pile driving.

Fig. 5. Collapsible Hesco baskets can (A) be expanded and then (B) filled with soil and used to provide anchoring [88].

technology, Hesco baskets could be deployed and filled by autonomous earthmoving robots in order to establish a suitable foundation for subsequent superstructure construction.

Establishing anchoring through concrete foundations or driven piles is an integral part of almost all construction projects. However, due to regional variation, difficulties in predicting soil mechanics, and the complexity of introducing automation into the mature technologies that execute these tasks, there has been little advancement towards autonomy in this domain. The example of the semi-automated concrete pump [74] highlights the difficulties and limitations of automating equipment designed for human operators, and suggests that a fully autonomous anchoring solution may require custom actuators.

4. Superstructure

Assembly of superstructure elements represents the final stage of most construction projects. It is the most visible and often the most expensive phase of construction, and consequently has received considerably more attention in the literature than site preparation or anchoring tasks. Academic reviews have tended to focus on additive manufacturing (3D printing) [5–7], autonomous mobile robots in controlled laboratory environments [11], or more specifically on biologically inspired algorithms and collective robotic construction in controlled environments [10]. On the other hand, literature that is more focused on industrial applications tends to highlight the impact of centralized Building Information Modeling and how on-site sensing technologies could augment BIM to extend beyond the design and engineering phases and into construction and occupancy phases [3,4].

Section 4.1 discusses site factories (temporary factories built on site) and prefabrication. While prefabricated construction is essentially the opposite of on-site construction, understanding which tasks are easily moved off-site gives insight into which tasks will likely continue to be performed on site. Section 4.2 covers autonomous robots that assemble load-bearing structures, typically using “discrete” or “digital” materials. Section 4.3 discusses robots that perform on-site additive manufacturing. Finally, Section 4.4 covers robots that navigate existing structures, performing additional construction and finishing tasks.

4.1. Prefabrication and site factories

Over the past several decades, a number of approaches have been developed for moving construction tasks off of construction sites and into the more productive structured conditions afforded by indoor factories. These approaches include (1) prefabricated low-order building elements such as wall panels (Fig. 6A), (2) prefabricated high-order building blocks such as bathroom modules or complete housing units (Fig. 6B), and (3) building temporary site factories that encompass the building footprint and are incrementally raised after each floor is completed (Fig. 6C).

Prefabricated or modular construction carries the benefits of guaranteeing a highly controlled environment for fabrication (increasing productivity by not needing to stop during inclement weather), removing costs associated with transporting workers and equipment to site, and allowing for equipment to be set up permanently for mass production, further increasing efficiency over on-site construction. Modular construction is often touted as being more environmentally friendly due to reduced construction waste. Drawbacks to prefabricated construction include the cost of transporting modules, which when assembled tend to require a larger transport volume than raw materials. Allowable transport volume itself is a limitation that varies according to local regulations, which means designers may have fewer options for customizing layouts. Finally, adapting to errors or abnormal site conditions is more difficult than with conventional construction [92].

The adoption of modular construction varies considerably due to economic incentives. The portion of construction tasks for new residences conducted in off-site factories is estimated to be 45% across Scandinavian countries, 15% in Japan, 10% in Germany, and less than

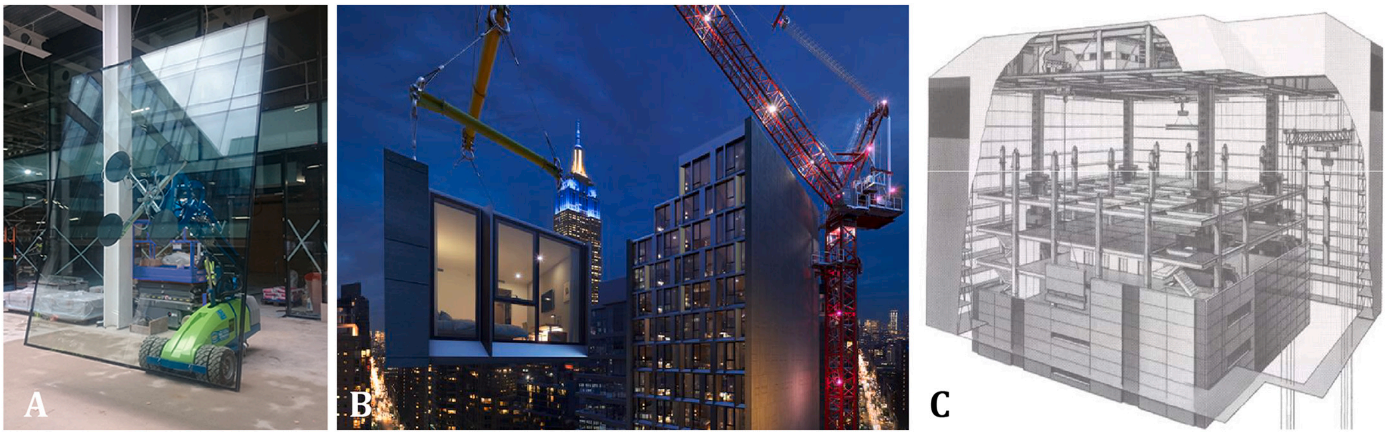

Fig. 6. Prefabrication and site factories. (A) The Winlet robot helps maneuvering and positioning of prefabricated low-order building elements such as windows and wall panels [89]. (B) A new hotel in Manhattan is composed of fully finished load-bearing units (high-order prefab) [90]. (C) Temporary site factories that encompass the building footprint are incrementally raised after each floor is completed [91]. The Shimizu SMART system shown here was developed in the 1980s. Its successor is called the "Shimz Smart Site" and is currently under development.

5% in the US and UK. It has been projected that modular construction could reduce construction costs by up to 20%, principally by reducing the duration of on-site construction by as much as 75%, and total construction time by as much as 50% [93].

Prefabricated low-order components consist of wall panels, window-unit assemblies or other modules, and are often designed to facilitate non-expert assembly. The early 20th century saw considerable interest in "kit homes" in the US (especially those commercialized by Sears and similar companies), which shipped with wall panels pre-assembled. Despite much optimism in the future of kit homes, this step towards prefabrication was largely abandoned in favor of conventional on-site timber framing, which currently remains the dominant mode of new residential construction in the US [94]. Prefabricated construction saw more interest in the post-WWII era, especially from academics and Modernist architects, such as Konrad Wachsmann and Walter Gropius' "Packaged House System" that never went into production [95]. More recent efforts to commercialize low-order prefab house kits include a recent startup called Node, which ships flat-pack kits in standard shipping containers that can be assembled by four untrained workers, though some skilled labor (i.e., plumbers and electricians) is still required [96]. While most lower-order prefabricated components are not intended for robotic assembly, their emphasis on ease of assembly may lend itself to robotic manipulation.

Some efforts have been made at semi-automated on-site assembly of lower-order prefabricated components. Japanese construction firm Fujita has developed a "shuttle method" by which large exterior wall panels are arranged around the perimeter of a structure and then hoisted and precisely positioned automatically, one panel at a time from the top of the structure on down [97]. Another firm, Kajima, has used an automated positioning arm called the "Mighty Hand" to retrieve concrete or glass curtain walls from hoisting cranes and precisely position them [98].

High-order prefabrication ranges from room-sized modules (such as bathroom units) to fully finished multi-room units, complete with exterior cladding. Prefab units are often designed to be structurally load-bearing, such that they support subsequent levels without requiring additional structural support. Compared to low-order prefabricated components, they require more time for off-site preparation, can be more complicated to transport to site and may be less conducive to customization, but offer faster on-site assembly, higher construction quality, and often lower costs overall [99]. Japan has developed a strong prefabricated housing market, which by 2008 was sufficiently developed that industry leaders joined together to form the Quality Housing Stock Association. In addition to setting quality standards, the QHSA established a secondary market for the buyback, renovation and resale of prefabricated housing. These homes now typically come with long-term warranties, options to purchase or rent new plug-in components and other services [100].

Modular prefabricated homes remain a popular choice in developed countries, though the rate of adoption has not seen any meaningful change in recent decades [93]. However, recent flagship projects in major US cities may work towards reversing the poor public perception of modular building. Despite even recent faltering by modular homes manufacturers, investors remain optimistic that modular construction will surge in the US market, especially as more manufacturing facilities open and owners, lenders, construction firms and architects become accustomed to the idea. According to the non-profit trade association the Modular Building Institute, the modular construction industry has doubled in the US between 2013 and 2018 [101]. Since its establishment in 2015, the California-based company Katerra has raised $1.2 billion in venture funding and aggressively bought out architecture firms and general contractors, though it has struggled to maintain a rapid growth rate. In 2019, it closed a factory, lost clients and laid off hundreds of employees [102]. California-based Dvele focuses on single-family housing and North Carolina-based Prescient concentrates on multi-family, student housing and senior living [103]. A New York City development consisting of 56 units manufactured in Pennsylvania by DeLuxe Building Systems was assembled in 19 days (not counting time for site preparation and foundation) [104]. More recently, modular building manufacturer Skystone has completed a new hotel in Manhattan where each load-bearing steel module contains a guest room so fully decorated and finished as to include toiletries (Fig. 6B). Once the hotel's foundation, first floor lobby and restaurant were completed using conventional methods, installation took place at a rate of one floor per day [90].

Site factories (Fig. 6C), also referred to as "site automation" or "sky factories", involve extensive structuring of a construction site, such that its conditions are comparable to those of a conventional manufacturing facility [105]. This approach saw considerable development in Japan in the 1970s and 1980s. The technique of vertically mobile "sky factories" involves lifting the entire factory up by one level after construction of the prior level is complete, and is particularly relevant to high-rise construction in dense urban environments. A typical example of this method is the Automated Building Construction System (ABCS) developed by the Obayashi Corporation [91]. However, building this mobile factory on site can take weeks to months, and is not suitable for smaller structures or sites that do not readily support such extensive structuring. Site automation is proven to reduce costs for towers with sufficient repetition by effectively moving tasks that could otherwise be conducted in offsite prefabrication facilities directly onto the

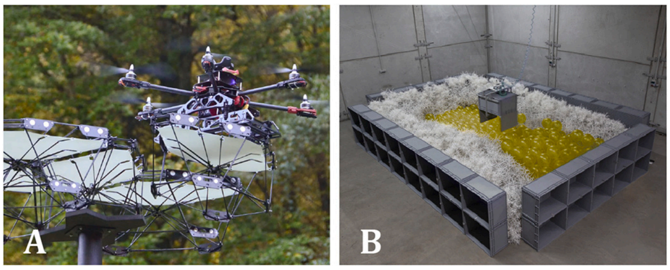

Fig. 7. Performing assembly tasks with UAVs allows for a virtually unlimited workspace, but comes at a great energy expense. Examples like (A) employ custom lightweight fiber modules that allow for building cantilevers [118], while examples using foam [119] or concrete blocks [120] do not. (B) Cable-driven robots are lighter, more versatile and easier to deploy than gantry systems, and easier to control than mobile robots. This demonstration consists of four actuated rotors (not visible) that drive a gripper (grey) to precisely place its payload of an amorphous interlocking granular material (white) [117].

construction site. Therefore, the construction tasks and corresponding robotic manipulators are indistinguishable from those used in controlled factory environments, and share the same limitations. While this model of site automation is effective for towers of sufficient height and geometrical conformity, it does not advance tools or techniques that could be more broadly generalized to on-site automation of other types of structures. While the "sky factory" techniques are limited to tower typologies with limited geometrical complexity, modular prefab construction is able to accommodate a wider range of building shapes and sizes, including office and retail, single- or multi-family homes, senior living and student dormitories [99,106].

4.2. Structural assembly

Perhaps the most challenging aspect of fully autonomous superstructure construction is the assembly of structurally load-bearing elements. In conventional construction, load-bearing elements are typically made of steel, timber or concrete, transported from the manufacturing plant and assembled on a site that is typically prepared with the necessary formwork, scaffolding or other auxiliary structures and equipment that help workers to assemble the structure. Such an extensive array of auxiliary construction tasks hinders the goal of a fully autonomous construction sequence. Therefore, many projects propose robots that are able to navigate the structure as they build it, acting as its own scaffolding [15,107–109].

In parallel, there is a growing body of work on self-assembly, systems composed of robots that configure their bodies to form temporary structures. Examples include cubic robots that assemble voxel structures [110], or robots that mimic army ants, climbing on each other to form bridges [111]. This body of work has not been included in this review, as it is more geared towards very temporary assemblies (e.g., those that require a constant electric current draw in order to maintain structural integrity), or systems that require tremendous energy inputs that prohibit on-site deployment.

Demonstrations that involve the assembly of load-bearing elements can be grouped into those that rely on gantry systems that encompass the build volume and those that rely on mobile robots to avoid the workspace limitations imposed by gantry systems. Gantry systems are a logical choice for controlled factory environments, but transporting to site and erecting a gantry system without human supervision would be especially difficult and perhaps prohibitive in remote or challenging environments where autonomous construction would be desired. Gantry systems typically have 3 degrees of freedom (DoFs) and cannot reach around or under objects in their workspaces. Collision avoidance is a principal consideration, even if additional DoFs are added. These workspace limitations preclude producing complex overhang geometries or working on existing buildings. Gantry systems are relatively simple to control and are capable of efficiently carrying heavy loads. In industry, gantry systems have only been employed on-site as components of "site factories" (Section 4.1, Fig. 6C). In academic research, gantry systems have been proposed for additive manufacturing (Section 4.3), and large-format indoor gantry systems have been proposed as simulators for on-site gantry systems [112]. A variant of the conventional 3-DoF gantry are cable-driven parallel robots (CDPR). Compared to conventional gantries, cable-driven robots are relatively lightweight and therefore easier to transport and deploy on a construction site. Many cable-driven robots require existing attachment points for pulleys, but these can be nearby trees or other vertical elements as cable-driven systems can easily adapt to irregular geometric configurations. Cable-driven robots have been proposed for on-site installation of large arrays of photo-voltaic panels, a task for which it is estimated that they could outperform the workspace and payload limitations of industrial robots by more than one order of magnitude [113]. The Hephaestus project is a proposed cable robot that will be installed on building exteriors in order to install curtain wall modules [114]. Recent developments include a passive damping system to minimize vibration caused by wind loads [115]. The IPAnema cable-driven parallel robot is marketed for lease for construction projects that may require custom setup requirements [116]. More recent work has demonstrated the viability of cable-driven robot systems to accurately place designed granular materials to form in-situ architectural-scale enclosures (Fig. 7B) [117].

More recently, mobile robots have gained in popularity for work on construction jobsites. Mobile robots can be classified as aerial (i.e., drones, UAVs), terrestrial (rovers, track vehicles) or climbing robots. While all three types are currently being used for sensing and monitoring on construction sites, assembly of load-bearing building elements has seen little automation in industry. Compared to gantry systems, mobile systems tend to be more complex to control, less precise, and less power efficient. However, advances are being made in these areas, making mobile systems increasingly more attractive. Mobile systems are able to access parts of jobsites that are unreachable by gantry systems because of overhangs or other obstacles, and may be required on-site for finishing tasks. Many mobile robots can build structures much larger than themselves, and don't require the setup and take-down time usually required of gantry systems. In a fully autonomous scenario, a gantry system would likely need to be assembled by mobile robots, which draws into question the suitability of gantry systems for such scenarios.

The load-bearing elements of a building's superstructure can be classified as blocks (volumes), panels (surfaces), or nodes and struts (lines and points). Buildings are rarely built exclusively with blocks, typically requiring at a minimum some kind of beams for doorways and roofs. While structures for large buildings are by now almost always built with steel, small buildings are very commonly built with wooden frame (or stick-built) construction, though building load-bearing walls with concrete masonry units (CMUs, i.e., cinder-blocks) is occasionally more practical. (A number of examples of semi-automated brick laying are not intended to build load-bearing structures, and are covered in Section 4.4.) Principal advantages of CMU block construction include greater resistance to fire, moisture and pests. Disadvantages include a considerably greater cost and build time than wood frame construction, principally because block walls typically still require wood framing and finishing to complete a secondary interior wall to accommodate mechanical piping and wiring. Furthermore, the cost of block construction is greater than that of wood, except in regions where wood is extremely scarce. Block walls require more labor and equipment such as scaffolding, and masonry requires more training time than wood framing. Even where block walls provide an added benefit of thermal mass, wood-frame buildings were found to have lower life cycle energy costs (primarily due to less embodied energy, which outweighs the energy-saving benefits of thermal mass) [121]. While block-wall construction is not well-suited to most residential construction, it remains a popular

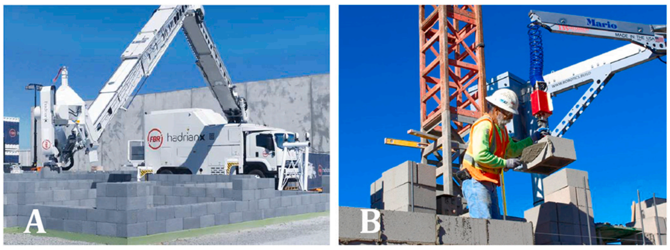

Fig. 8. Robots used for laying CMU blocks. (A) The Hadrian X uses a 30 m-long telescoping arm to convey CMUs. Blocks must be arranged in the correct order in advance. They are stacked on site according to a predefined plan, using a polymer adhesive instead of conventional mortar [122]. (B) The MULE135 is a general purpose lift-assist and precision placement arm that is designed to work with human masons, rather than replace them directly [123].

choice for big-box retail and warehouses that don't require thermal regulation.

Residential block wall construction has been a focus of industry research, pioneered by Australia-based Fastbrick Robotics. Their robot, the Hadrian X, uses a 30 m-long telescoping arm to convey CMUs, which it then stacks according to a predefined plan, using a polymer adhesive instead of conventional mortar (Fig. 8A). Blocks must be arranged in the correct order beforehand, which is not accounted for in time estimates. Site foundations must be conventionally prepared in advance, and errors must be dealt with by human intervention. A primary technical achievement is the robot's ability to dynamically stabilize its arm, maintaining precision in spite of wind and other perturbations [122]. While initially focused on the residential market, Fastbrick has not seen sufficient interest from residential developers and are now marketing a "Wall-as-a-Service" model to general contractors. US-based Construction Robotics has unveiled a robot called MULE135, a general purpose lift-assist and precision placement arm that has also been used for on-site placement of CMUs (Fig. 8B). This robot is designed to work with human masons, rather than replace them directly, and features a range of attachments designed for other construction applications [123]. While the Hadrian X may perform faster on site for a specific wall-building task, the MULE135 is more flexible, and has a better market foothold by being more in line with conventional construction practices. It remains unclear that there is a market demand for residential structures made of block.

In conditions where it is difficult to transport bulky materials to the construction site, blocks may not be as well suited as panels or node-and-strut systems, which can typically deliver comparable structural performance in a more compact transport volume. However, if resources on or near the construction site can be utilized (termed in-situ resource utilization or ISRU), block-based construction may be a suitable choice. Compressed earth blocks (CEBs) are widely used for construction and infrastructure, especially in developing nations. Small, portable equipment has been developed for automating on-site manufacturing of CEBs, complete with with interlocking geometric features and through-holes [124]. Typically, workers manually fill a hopper with soil (and any binding agents if needed), but this step could be automated using the earthmoving equipment described in Section 2. Compressed blocks have also been proposed for extraterrestrial construction, though accommodating the transport volume that would be required for the necessary binding agents remains a challenge [125].

Most examples of aerial robots for construction demonstrators have not focused on industry–relevant building materials, choosing instead to use lightweight simulants such as string or foam blocks in order to demonstrate a proof of concept [126]. Compared to terrestrial or climbing robots, drones offer a virtually unlimited workspace. However, material transport requires a tremendous energy cost and more control complexity to deal with the environmental hazards of construction sites. Regardless, the idea of drone-based construction assembly tasks has gained substantial media attention.

Some efforts have sought to use teams of UAVs to assemble truss structures using lightweight simulant building materials attached with magnets [127]. Foam blocks made to visually resemble concrete blocks were stacked by a team of UAVs to form a preplanned structure [119]. A study was conducted using large-scale UAVs to stack blocks that were actually made of concrete, though special electromagnets and embedded steel plates were needed to get the system to operate correctly. UAVs were tethered for experiments and power expenditure was not reported, and the authors suggest that non-aerial robots, especially those that might localize themselves by climbing on the existing structure, would have an advantage for localization [120]. The use of real building material was instructive in understanding unforeseen difficulties, such as the inability for the UAV to counter the rotational torque of heavy concrete beams to align them correctly. Further work with UAVs employed a custom polyhedral module made of lightweight carbon fiber (Fig. 7A) [118]. Each unit contained magnets for alignment and attachment as well as onboard sensing and communication, and the system's ability to extend and reconfigure a self-supporting roof canopy was demonstrated.

Appropriating general-purpose actuators like UAVs may not be suitable for many construction tasks. Some jobs may require custom-purpose material-robot systems, i.e., systems where both a construction material (such as a block or voxel) and a novel robot are designed in coordination with each other. (This idea has also been referred to as robot-oriented design (ROD), though this term captures only the idea that a building material be designed with robotic manipulation in mind, and not vice versa [128].) Material-robot systems, especially those designed to simplify the robot locomotion on and manipulation of cellular structures, have been termed "relative robots" [109].

The TERMES system is composed of distributed climbing robots and corresponding customized foam blocks (Fig. 9A) [15]. Capable of 2.5D locomotion and assembly, these robots use local information drawn from the built structure itself to guide building activity, rather than any centralized source of control or information. A compiler automatically translates a user-specified 3D blueprint into low-level rules for independent robots that reliably produce the desired outcome. The Automatic Modular Assembly System (AMAS) consists of inchworm type robots and corresponding bricks that interlock with each other [16]. A similar robot morphology has been utilized by a more recent research thrust, showing considerable progress in building 2.5D structures (Fig. 9B) [109]. Robots (called BILL-E) rely on the mechanical intelligence of the voxel dimension for navigation and localization/positioning, and demonstrate coordinated assembly with multiple robots. Unlike TERMES, it used a centralized control system, though proved capable of more quickly assembling structures of a similar size, and is capable of building tower structures by stacking blocks more than one level higher than their neighbors, which TERMES cannot do. All of these examples rely on magnets for connecting blocks, and none are

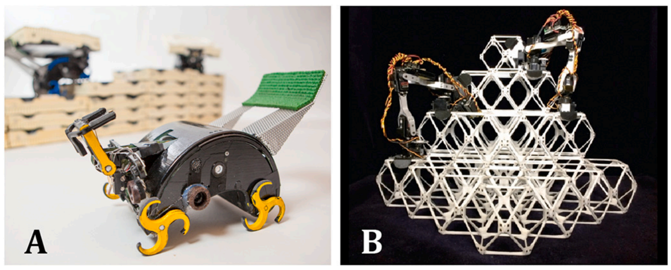

Fig. 9. Examples of relative robots, where the robot and its building material are co-designed to coordinate assembly and locomotion. (A) The TERMES system is composed of 3 distributed climbing robots and corresponding customized foam blocks [15]. (B) More recent work allows for faster assembly [109]. Both examples would require a more robust connection detail in order to produce unsupported spans.

capable of building cantilevers or unsupported spans. While magnets may remain useful for alignment, a more robust attachment method will be required for structural connections. These material-robot systems used for block assembly are uniquely promising for fully automated construction by virtue of their demonstrated ability to quickly and reliably assemble structures without the need for auxiliary tasks such as building scaffolding.

Various attachment methods have been proposed for reversible assembly, including custom integrated latching devices, threaded fasteners, or press-fit connections. Irreversible attachment methods, such as hot-melt adhesive (HMA), have also been proposed [129]. Other work has proposed leveraging 18th-century developments in stereotomy to design custom masonry structures with interlocking blocks, which robots could stack together on-site without the need for scaffolding or formwork [130]. Block stacking construction tasks have been developed to a point of maturity (using both distributed and centralized control) in laboratory environments, but developing a reliable attachment method will be crucial to achieving more structurally performative structures and leveraging this advanced research thread outside of laboratory environments.

Climbing robots have also been used for truss structures composed of nodes and struts, a construction system that lends itself more naturally to building cantilevers and overhangs (the principal limitations of block systems). NASA's Automated Structural Assembly Laboratory used an industrial robot mounted to a mobile platform to conduct the autonomous assembly and disassembly of an 8 m planar structure composed of 102 truss elements and covered by 12 panels [14]. Later efforts have focused on climbing robots that accelerate truss assembly with multi-agent systems. Researchers at Cornell developed a climbing robot and custom 3D-printed node-and-strut construction system [107]. The hardware was demonstrated to be capable of detaching and reattaching a strut. The approach, however, was limited to attaching struts at 90 degree increments. Truss structures without diagonal cross-bracing have limited use. Algorithms for controlling the building activity of a multi-agent collective of such robots were also proposed. Work was conducted to adapt a similar robot morphology to operate on triangular truss structures and to work with readily-available building materials (Fig. 10A), though locomotion was found to be much more challenging due to the dimensional variation of commercially available lumber [108]. Reliable assembly of truss structures may require an alternative method of locomotion.

An alternative morphology for locomotion on truss structures was presented as Shady3D, which featured two strut grippers connected by a rotational degree of freedom. By gripping the opposite end of the same strut as another robot, the two can combine to form a 6-DoF kinematic chain [131]. A similar morphology was appropriated specifically for the construction task of stacking wooden struts to make layered structures (Fig. 10B), though the system is limited to operation in a single plane and is not capable of mechanically attaching struts [132].

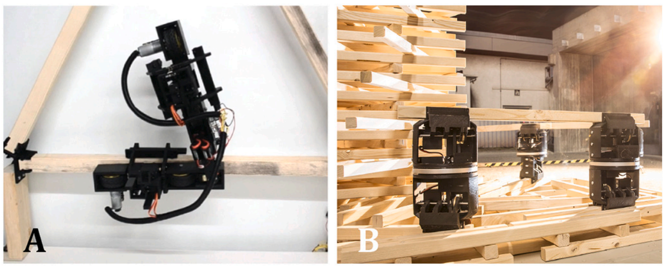

Fig. 10. (A) A strut-climbing robot navigates a custom node-and-strut construction kit configured into a triangular truss [108]. While previous strut-climbing robots employed rolling locomotion with custom 3D-printed toothed struts [107], this mode of locomotion was found to be intractable with struts made of common building materials. An alternative method of locomotion that involves grasping struts at discrete intervals may prove more viable. (B) This demonstration adopts a similar morphology as Shady3D [131] but adds the ability to stack struts, thereby building simple structures [132].

Robots that build fully supported structures out of stacked blocks don't need to understand the forces acting on the structure, as there is generally no chance of unexpected structural failure. On the other hand, climbing robots that assemble truss structures need to have some understanding of the forces acting on the structure to guarantee that, e.g., extending a cantilever will not cause it to break. While a number of technologies exist for visual monitoring on construction sites, vision-based systems can neither measure structural forces nor reliably predict if a joint is about to fail. In conventional buildings, structural measurements are taken only after construction is complete, using finely calibrated strain gauges and looking for deflections in known potential points of failure. However, structural failure is rarely a concern during conventional construction processes, which are heavily reliant upon redundant scaffolding, formwork and other auxiliary aids to support building components during construction. Demonstrations have considered pre-planning a structure throughout each step of a robotic construction sequence, though this approach was centralized and not reactive to perturbations [133]. Considering internal truss forces at each stage of assembly was considered only for controlled laboratory environments in a centralized pre-planned manner [134].

For the assembly of cellular lattices like those mentioned previously in this section, it is desirable to verify structural connections or even report structural forces between units in real-time during the construction process. Dynamic feedback and control allows for the ability to react to unforeseen conditions on the fly, and is particularly attractive for harsh or remote environments where it may be difficult to obtain sufficient information about site conditions in advance or during construction, compromising the ability to plan a structure.

Distributed real-time sensing can be achieved by embedding sensors in individual building blocks. In some cases, these sensors stream data to a central control station [118], though this method will ultimately run into scale limitations, and active data transmission may be prohibitive in terms of cost and energy consumption. An alternative method is to install passive force sensors between building elements, which don't consume power or transmit data, but which can be activated by a climbing robot and polled for the forces acting on a given joint [108].

While most structural monitoring instruments report bending forces within structural elements, contact forces between elements are also of relevance to autonomous robots assembling a truss structure. Researchers have developed custom force sensors for a node and strut building system to measure both axial and bending forces acting on joints between load-bearing components [108]. These cheap capacitive sensors, composed of layered copper kapton foil, are slim enough to be placed in the axial load path at the interface between two discrete components without compromising the integrity of the joint. Sensors are passive, and only temporarily powered by a robot as it traverses the truss structure, measuring forces as it goes. Algorithms were developed to enable a distributed team of such robots to read the aforementioned force measurements and employ them to inform building rules and improve the reliability of building cantilevering truss structures. These principles were extended to apply to other building materials beyond node and strut systems, such as blocks [108]. The development of custom passive sensing systems to integrate into building materials facilitates fully autonomous construction, but requires more development across integrated building systems.

Another category of mobile robots, terrestrial (ground-based) robots, often consist of a mobile platform with a mounted arm (serial-link manipulator). Robotic arms are able to replicate many human tasks on construction sites, and tend to offer greater precision and extend the workspace and access to complex sites of mobile platforms, while being easier to control and more power efficient than aerial robots. Industrial arms have been outfitted with custom task-specific end effectors and employed on site to build structures using cutting-edge techniques such

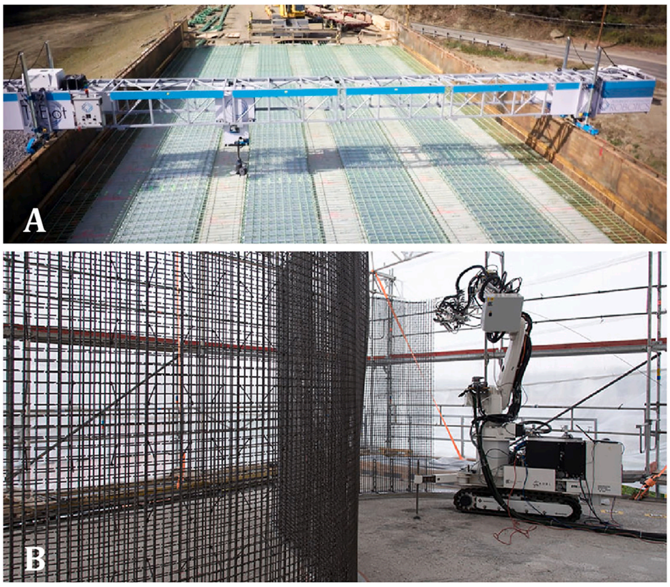

Fig. 11. (A) The TyBot is a rail gantry system that can be installed on site and rolls along rails. Rebar first needs to be arranged by hand, after which the robot ties each intersection [135]. (B) In the Mesh Mould system, a robot called the In Situ Fabricator welds short lengths of rebar together to form complex geometries [136]. While (A) is more effective for working with mature technologies for large projects, (B) is more versatile and capable of achieving a wider array of forms.

as forming a fiber composite shell over a pneumatic mould on site [137]. Other examples include a terrestrial robot called the In-situ Fabricator (IF), an arm mounted to a mobile platform that serves as a general autonomous localization system, delivering sub-centimeter accuracy over long build sequences [138]. This platform was later utilized in the Mesh Mould project (Fig. 11B), an innovative concept that arranges rebar in a way that serves as containment (formwork) while the concrete cures and remains in place as reinforcement for the finished structure [136]. The robot's custom end effector is capable of bending, cutting and welding 6 mm steel rebar in vertical layers. This method enables the construction of waste-free freeform load-bearing concrete structures, where complex geometries incur no additional cost. The technique has been demonstrated in the construction of the DFAB House, where it forms a load-bearing wall, and authors expect to explore future applications on construction sites [139]. While the current stage of development still requires human workers to apply concrete both with conventional hose pumps and shotcrete, both of these methods are being developed for autonomous operation as discussed in Section 3, and could be automated in future work. This system has not been demonstrated for foundation work, though in principle it could work together with a trenching or excavating robot to build steel-reinforced concrete foundations.

An alternative method of automating concrete reinforcement is a 3D printing technique that embeds steel mesh in the extruded concrete [140]. Rebar placement and tying is an important and time-consuming step for concrete structures. While rebar placement still requires manual labor, approaches to traversing a grid of pre-positioned rebar and tying connections include large gantry systems such as the TyBot (Fig. 11A) [135,141] as well as mobile robots [142]. Other developments include serial-link robots that bend rebar to custom shapes in factory settings [143].

4.3. On-site structural additive manufacturing

Additive manufacturing (3D printing) has been proposed for both structural and non-structural applications on construction sites. A number of review papers have covered different aspects of this area, which continues to receive considerable attention. These reviews draw attention to the lack of scientific research and material characterization that would be needed before additive manufacturing is accepted in mainstream construction [5], the challenges of including conventional functions of wall sections (electrical conduit, plumbing, etc.) into 3D-printed structures [6], and barriers that make construction more difficult to automate than manufacturing [7]. Other reviews focus on specific materials for additive manufacturing, like concrete [146,147] or

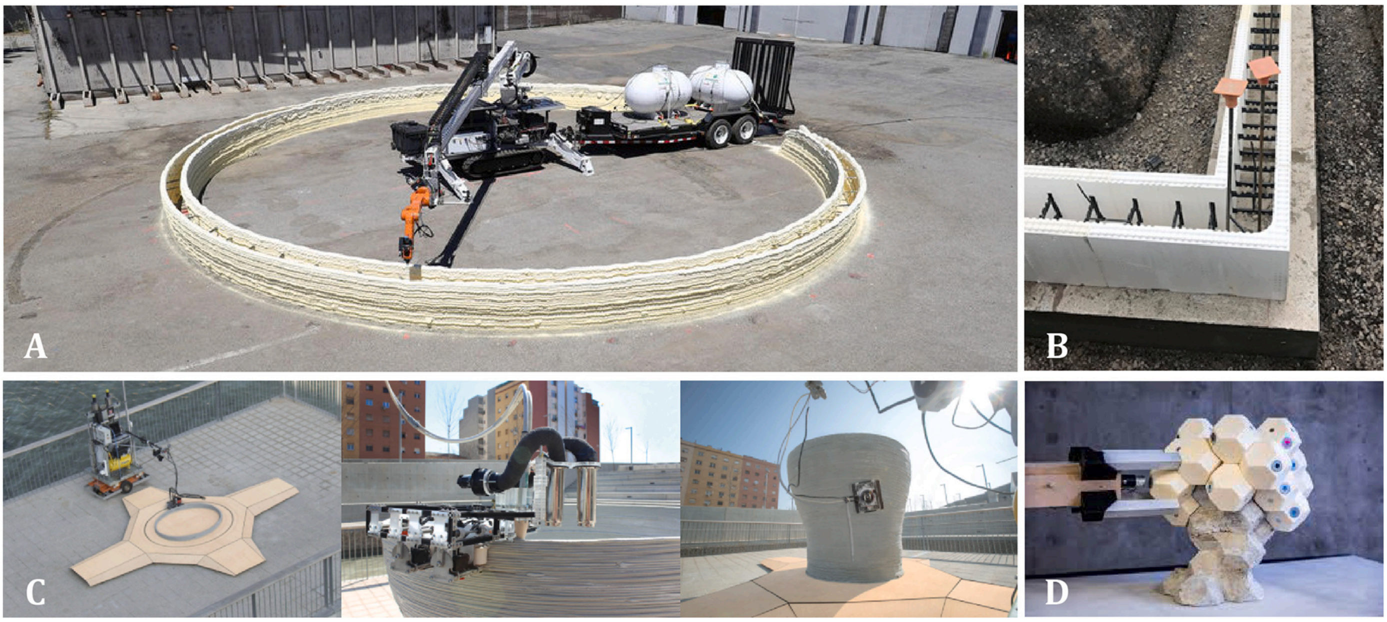

Fig. 12. Robots used for additive manufacturing. (A) The Digital Construction Platform constructs a two-layer dome structure by precisely extruding foam [55]. (B) Insulated concrete formwork (ICF) blocks were the inspiration for the structure in A. The formwork remains in place after concrete has cured, serving as insulation. (C) The Mini-builders project consists of three unique task-specific robots that coordinate to print large-scale ceramic structures [144]. (D) VoxelCrete is an adaptive formwork system. Concrete is cast into the cavity formed by the voxels. After curing, the bottom layers of voxels are robotically moved to the top, creating another void, and the process repeats [145].

clay [148], or multi-material additive manufacturing [149].

The D-Shape technique produces forms by selectively binding sand with a magnesium-based binder [150], and was an early demonstrator of architectural-scale additive manufacturing. However, more recent developments tend to follow the layered deposition techniques spearheaded by the Contour Crafting project [151]. Both of these techniques conventionally require building a gantry system larger than the printed object itself. Variations to the contour crafting technique using mobile robots seek to overcome this obstacle. The Mini-builders project (Fig. 12C) is a 3-robot team for 3D printing large-scale ceramic structures, which was demonstrated in outdoor environments [144]. This system overcomes the workspace limitations of gantry systems by enabling mobile robots to move along the sides or tops of walls as they extend the structure.

Examples of additive manufacturing in industry have been largely limited to off-site prefabrication. Prefabricated housing sections were demonstrated by the Chinese manufacturer WinSun in 2014, and subsequently by other companies such as CyBe (Netherlands). The Danish company COBOD has demonstrated on-site additive manufacturing with large 3-axis gantries [152]. Russian-based Apis Cor has demonstrated on-site additive manufacturing using a custom serial manipulator instead, and has attracted considerable media attention. While the product is promised to greatly reduce costs, most construction processes in their demonstrator projects are identical to conventional processes (conventional foundation, manually placed rebar, precast floor slabs, and conventional doors, windows, and electrical/plumbing) [153]. There has been some academic interest in modifying conventional heavy equipment for on-site additive manufacturing with concrete. The CONPrint3D (Concrete ON-site 3D-Printing) project from TU Dresden considers conventional placement machines such as a Putzmeister mobile concrete pump [154]. While this team heavily advocates for maximal usage of conventional construction machinery, they have not yet developed a solution for reinforcement or demonstrated on-site operation.

Industrial and academic partners at TU Eindhoven have constructed a bicycle bridge made out of prefabricated 3D printed parts and assembled on site in Gemert, Netherlands. They used prestress tendons run through the cavities of the 3D printed bridge segments. Significantly, this project required new failure testing protocols to be proposed and accepted into local building code. As load testing of the final installed bridge resulted in deflection too small to measure, the bridge was considered to comply with Dutch building regulations and opened to the public in late 2017 [155]. Another bridge has been manufactured by MX3D with gas metal arc welding using basic elements of 5 mm stainless steel rods that are extruded to form an 8 m-long bridge to be installed as a single piece on site [156]. The project was intended to be completed on-site, but has been fabricated in a controlled factory setting instead.

The Digital Construction Platform (Fig. 12A) is a serial manipulator mounted to a mobile platform, with a number of end effectors including a bucket shovel and an extruder for expanding foam. The platform was used to construct a nearly 4 m-tall dome using a two-part spray polyurethane to build a cavity in a process termed print-in-place (PiP). The cavity could then be filled with cast concrete, then left in place as insulation around the concrete wall. This process is analogous to insulated concrete formwork (ICF) blocks (Fig. 12B), allowing a foothold to be used in conventional construction processes. It can also readily accommodate plumbing, electrical and air conditioning, minimizes waste, and avoids the complications of direct extrusion additive manufacturing of concrete, like optimized cure time, slump and flow characteristics [55]. Another example of using robots to create formwork instead of attempting to directly 3D print concrete is an adaptive formwork system called VoxelCrete (Fig. 12D). Concrete is cast into the cavity formed by the voxels. After curing, the bottom layers of voxels are robotically moved to the top, creating another void, and the process repeats [145].

On-site additive manufacturing is extremely difficult. Common issues that persist for architectural scale 3D printing include maintaining suitable material consistency outside of controlled factory settings, the placement of suitable reinforcements, especially continuously over long spans, and integrating other building functions such as air conditioning, electrical, and plumbing. Additive manufacturing has demonstrated utility for certain prefabrication processes in controlled environments, but has yet to demonstrate its value over conventional on-site processes. More promising projects are those that use robots to automate the placement of formwork [55,136,145] and reinforcement [136,139,140]. It is well understood that concrete performs best when it is embedded with reinforcement and cured in a mould. Directly automating concrete 3D printing requires additives that compromise its performance, while automating auxiliary tasks like formwork and reinforcement allow for increased productivity and new on-site construction scenarios that leverage the natural strengths of the material.

4.4. Structure-dependent robots and finishing tasks

Robots that are used for finishing tasks (such as laying tiles, leveling flooring or painting) are typically mobile, as they are required to navigate existing structures.

Section 4.2 discussed robots that stack blocks to build load-bearing structures, though further work has been done to stack brick for facades or other non-structural applications. This work dates back to an automated rail-mounted bricklaying machine developed by Demarest Machines in 1958 (Fig. 13A) [157]. This machine gained little traction in the commercial market, though variations were in use at least through 1967 [159]. Interest in mobile bricklaying robots resurfaced in the 1990s, with hardware and controls demonstrated in a prototype called the BRONCO [160]. Two decades later, US-based Construction Robotics has developed a bricklaying robot called SAM100 (Semi-Automated Mason), which still requires at least one human operator, but is claimed to boost productivity by 3 to 5 times [158].

Industrial robots mounted to mobile platforms have also been used for precision brick-placing tasks. A system developed by ETH packs into a custom shipping container and rapidly deploys on-site for bricklaying work [161]. Further work has focused on simulated site conditions, localization capabilities using solely on-board sensing, dimensional tolerances and response to uncertainties [162].

Single-Task Construction Robots (STCRs) have been developed for more specific tasks like laying floor tiles with autonomous wheeled robots [163] as well as with a humanoid robot (Nao), though its advantage for the task of laying floor tiles is unclear [164].

Other than laying brick or tiles, finishes can be achieved using sprayed materials; for instance, the shotcrete spraying robots [74] discussed in Section 3 could also be applied to certain superstructure tasks. A related process is the robotic application of foam concrete onto bare walls of existing buildings to increase insulating capacity, while simultaneously allowing for a high degree of customization and the

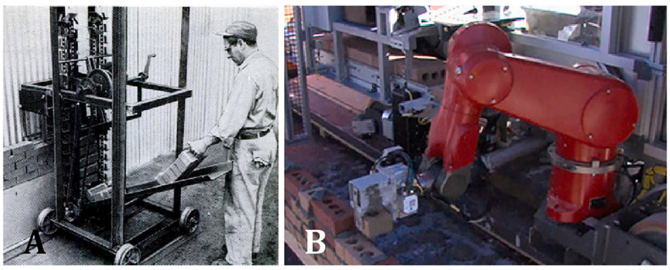

Fig. 13. Robots used for laying bricks. (A) The Robot Bricklayer was first demonstrated in 1958, but still required a great deal of manual assistance [157]. (B) The SAM100 (Semi-Automated Mason) rolls on wheels instead of rails and uses an industrial arm instead of a gantry system [158].

potential to be recyclable [165]. Small, portable gantry machines that place tiles or paint predefined patterns are readily available on the consumer market, but are only capable of treating a small area before needing to be repositioned [166]. Robots that autonomously navigate buildings and reliably coat their walls with paint are not yet a commercial reality. So far painting robots have been prototyped and tested only in controlled environments [167].

The MoRPHES project is an ecosystem of novel task-specific robots that have been developed from fundamentals for collaboratively fabricating filament structures to form enclosures or partitions on site. The project has demonstrated successful coordination between different "species" (Wall Climbers, Thread Walkers, Sheet Climbers, etc.) for a range of complex thread winding procedures [168].

Efforts have been made to utilize humanoid robots for simple construction tasks such as hanging drywall. Japanese firm AIST has demonstrated the ability to hang drywall, although only in prepared conditions; its operation is considerably slower than a human worker [169]. Many of these applications would only be feasible for large scale, repetitive projects that don't represent the bulk of the industry. On the other hand, many of these tasks can be performed more cheaply and reliably in factory settings, and might be more effeciently automated with a gantry system.

5. Discussion

In this section, we discuss trends and present observations related to increasing automation on construction sites. We first discuss specific trends and developments that may lead to full autonomy, then offer more general observations from the literature.

5.1. The road to autonomy

In this review, we emphasize technologies that could lead to fully autonomous construction. The categorization system developed by the Society of Automotive Engineers, which ranks self-driving vehicles on a scale of 0 to 5, provides a widely recognized metric for autonomy [17]. While these standards were not designed for construction equipment, they can be reasonably approximated. Our modified ranking considers the following Levels of autonomy (LoA):

- LoA 0: No automation. The system does not control any DoF, even if it is capable of enhanced sensing.
- LoA 1: Operator assistance. The system adjusts a single DoF (such as raising or lowering a leveling bar) while the operator controls the rest.
- LoA 2: Partial automation. The system is able to control multiple DoFs simultaneously, but requires a human operator to recover from failures and manage other functions.
- LoA 3: Conditional automation. The system is capable of operating all DoFs simultaneously under some conditions. The system may be programmed to request operator assistance when needed.
- LoA 4: High automation. The system can autonomously execute tasks under certain site conditions. The system does not require human assistance and can adapt to unexpected disturbances.
- LoA 5: Full automation. The system can autonomously complete tasks under any site conditions where construction could reasonably be expected to take place.

Table 1 presents a selection of machines covered in this review along with their highest demonstrated Level of Autonomy. Semi-automated concrete placement boom pumps such as the Putzmeister Ergonic system or competitor Zoomlion's Smartronic system have been demonstrated for both substructure and superstructure tasks, and have therefore been listed in both columns. Other projects could conceivably be used for both categories, but so far have only been demonstrated for substructure tasks and are therefore categorized accordingly [55,123,136,151]. For the purposes of this categorization, hardware that has been demonstrated only in controlled laboratory environments is not considered to be capable of operating under all conditions, and therefore subject to a maximum of LoA 4. Systems that require extensive preparation of either the construction site or the mechanical system itself before they can operate autonomously (e.g., building a gantry system for on-site 3D-printing [151]) are considered to be at maximum LoA 3, as such preparation presumably requires either human workers or sophisticated robots that have yet to be demonstrated.

Table 1 highlights the shortcomings in the current state of the art and gaps in current research trajectories. In order to make continued progress towards the goal of fully automated construction, we suggest increasing emphasis on the following topics.

5.1.1. Material-robot systems

While previous authors have advocated for robot-oriented design [128], more recent works have suggested going a step further, considering material-robot systems that consist of both custom robots and corresponding building materials designed in coordination, such that the machine, material, and method are developed co-dependently, the limitations and parameters of one continuously informing the others [168]. The notion of a material-robot system is not unique to construction; a parallel can be observed in the field of agricultural automation. While the harvesting of grains has been heavily mechanized for decades, other crops such as peppers have proven considerably more difficult to manipulate. Realizing that the current state of the art in robotics is incapable of reliably picking chili peppers, researchers are using genetic modification to create chili plants that are more readily accessed by harvesting robots [170]. Several examples of material-robot systems have been covered in this review, including brick systems [15,16,109], node-and-strut systems [107,108] and fiber-winding systems [168].

Conventional construction techniques have evolved over centuries to facilitate human workers, and there is no evidence to suggest that these same methods would be optimal for robots. It is reasonable to assume that the building materials that would most effectively be employed in a fully automated construction scenario have not yet been invented. Architects and designers who may be interested in automating construction but lack skills in robotics can still contribute to this important aspect.

5.1.2. Embedded sensing in building components

Digitization in commercial construction hinges on a single centralized building information model, which reinforces the inertia of the construction industry with its embrace of mature technologies [3]. While it seems this goal is the foregone conclusion in industry, an alternative could be a distributed model where building systems consist of discrete parts capable of communicating with each other but without a single centralized authority. Such a system would still be capable of fault detection and repair, and would not risk a single point of failure that would be presented by a centralized control. Industry developments seem to assume that robots require a high degree of knowledge of the environment. However, research has shown that within a sufficiently constrained building system, distributed teams of construction robots can operate with very limited information about their environment [15,16,71].

In order to extend these achievements to other emerging construction techniques, new methods of embedding sensing within building materials will be required. Methods for integrating active sensors into discrete building components have been demonstrated [118], though passive sensors may provide a more cost-effective and energy-efficient approach [108].

5.1.3. Auxiliary construction tasks

Auxiliary construction tasks that are not readily visible in completed

Table 1
Levels of autonomy.

Level	Description	Site preparation		Substructure		Superstructure	
1	Operator assistance	Tiger stone	[49]	Boom pumps	[72,73]	Boom pumps	[72,73]
		CAT grade asst.	[42]	Impact driver	[85]	MULE135	[123]
2	Partial automation	Cratos	[60]	POHVAII	[65]	SAM100	[158]
		Centaur 2	[50]			TyBot	[135]
		Juno	[61]			Cable robot	[117]
						Flight. assmb.	[119]
						Mini-builders	[144]
						DimRob	[161]
						MoRPHES	[168]
3	Conditional automation	RASSOR	[51]	Romu	[108]	Contour crafting	[151]
		Polaris	[52]	A-TBM	[80]	Hadrian X	[122]
		ASI kits	[43]	TunConstruct	[74]	BILL-E	[109]
						ISF/mesh mould	[136,139]
						UAV assmb.	[118]
4	High automation	Built robotics	[44]	–	–	Dig. constr. plat.	[55]
		HEAP excavator	[18]			TERMES	[15]
		Volvo THOR	[33,46]			NASA ASAL	[14]
5	Full automation	–	–	–	–	–	–

buildings (such as temporary scaffolding and formwork for cast-in-place concrete) have seen only limited consideration from researchers. Tasks such as the assembly of node-and-strut structures [107,108] may be more applicable to temporary scaffolding than as part of permanent structures. Other tasks like the assembly of foam blocks [15,16,119] may not be appropriate as finished structures, but may be more readily considered as insulated concrete formwork (ICF), commonly used to shape concrete walls and foundations (Fig. 12B). Emerging formwork technologies include the use of flexible formwork on site to economize the use of concrete [171], the Mesh Mould project where formwork also serves as reinforcement [136], the dual-wall insulating formwork created with the Digital Construction Platform [55], and the VoxelCrete modular robotic formwork system [145]. While these examples may require new sets of tools and techniques to be developed, they are rooted in well-established material systems and processes.

5.1.4. Site preparation and substructure tasks

There is an overemphasis within the research community on superstructures, and a misconception that superstructure alone is sufficient for creating useful structures. Correspondingly, there has been a shortage of work on site preparation, foundations, and integrating them with superstructure-associated tasks, especially from roboticists and computer scientists who may be less familiar with construction processes. Even temporary buildings require site preparation and anchoring. While this may not have received much attention from academics, robots for earthmoving tasks are seeing rapid investment and industry adoption rate [44], which has not been observed for startup companies working on superstructure tasks [122]. Research on novel machines has mostly come from space applications where using mature technologies (conventional heavy equipment) is impractical. Once these emerging technologies receive sufficient investment to produce a viable alternative to conventional heavy equipment, this could trigger a rapid adoption that could fundamentally transform the industry's approach to site preparation and land management.

5.1.5. Task integration

Dozens of skilled trade workers are required for even the most simple residential construction. These tasks not only need to all be completed, but coordinated among each other. Task integration has been demonstrated with homogeneous distributed systems (swarms) [15], heterogeneous systems [168], multi-machine fabrication of fiber structures using UAVs and industrial robots [172]. Examples of task integration in industry include Volvo's THOR project, which features autonomous excavators and haulage trucks operating simultaneously, though machines are not capable of communicating or sensing each other and simply follow pre-planned paths [46]. This level of task integration is years behind the level achieved with similar machines in the mining industry, due largely to the fact that pit mines are more easily structured environments than construction sites [173]. For full autonomy, future systems will need to achieve coordination among heterogeneous machines performing many different tasks (Fig. 14).

5.1.6. Interdisciplinary fundamental research

In both the US and Europe, the advancement of emerging technologies in construction automation has been hindered by the compartmentalization of university departments. Meaningful advancements in construction automation may require contributions from architects, civil engineers, mechanical engineers, computer scientists and roboticists. The inherent requirement for interdisciplinary research has not been well served by conventional university divisions, which over recent decades have contributed mostly incremental advancements to mature technologies. While there is value in increasing automation in construction as we know it, there is a clear need to simultaneously conduct fundamental research to lay the foundations for future emerging technologies. A considerable share of the emerging technologies presented in this survey were sponsored by coordinated efforts at interdisciplinary research in construction automation launched by the Swiss National Centres of Competence in Research in Digital Fabrication (NCCR DFab) [136,138,139,162] as well as the German Excellence Cluster on Integrative Computational Design and Construction for Architecture (IntCDC) [87,117,118,132,168]. While the US has supported industry advancements in mature technologies, it has yet to

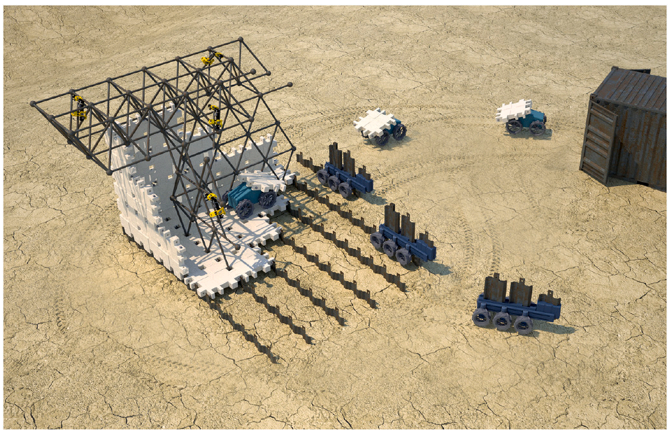

Fig. 14. Vision for fully-autonomous task integration.

produce a comparable platform for fundamental research on emerging technologies.

5.2. Lessons from the literature

In addition to the above recommendations related to the path to fully autonomous construction, the trends observed in the course of this review point to more general observations on research in construction automation.

5.2.1. Emerging technologies should be designed at the appropriate scale for the task

Historically, the effectiveness of construction machinery has been limited by its size; larger machines meant that a single worker could be more productive, creating an economic incentive for "mechanical gigantism", as has been witnessed over the last 100 years. One advantage of autonomy is the ability to disregard this economic incentive and reconceptualize the scale and scope of construction tasks from fundamentals. For example, the ideal solution for some excavation tasks might be a single, centrally controlled large robot, while another context might require a collective of hundreds of excavation robots at a much smaller scale. Not only might smaller machines be better suited to a particular task, smaller machines are more safely able to access sites where geotechnical or other conditions are not conducive to heavy equipment. This principle has been demonstrated by a suite of novel machines developed for extraterrestrial site preparation (Section 2.2), which in many cases feature superior payload ratios to conventional heavy equipment. Furthermore, automating conventional heavy equipment can have limitations, as observed with the retrofitted concrete placement machine that was unable to operate all of its joints simultaneously, resulting in unacceptable error in the completed result [74].

5.2.2. Building life-cycles (maintenance, repair and recycling) have been overlooked

The maintenance, repair and recycling of architectural elements is critical for advancing carbon-neutral construction. Mature technologies have not offered advancements towards this goal in recent decades. On the other hand, emerging technologies have an opportunity to address this goal by incorporating principles like reversible assembly (enabling structures to be decomposed and reassembled for other uses) or in-situ resource utilization to reduce the energy spent on material transport. Prefabrication companies have developed methods that offer greater potential for the recycling of building materials than any known on-site solution [100].

5.2.3. Prefabrication will have a huge impact

The construction industry expresses optimism that the 2020s will be the decade that prefabrication finally goes mainstream in the US. While similar waves of optimism in the 1920s, 1950s, 1970s, and 2000s failed to bear significant market change, there is considerably more investment this time. Once companies are able to demonstrate their products and establish an economy of scale, costs for prefabricated building components could fall considerably. A frequent criticism of prefabricated housing is that it lacks the flexibility of on-site construction. This limitation is being addressed in Japan with a robust secondary market for the buyback, renovation and resale of prefabricated housing, which allows homeowners to modify their homes with minimal expense and site disruption [100]. There are overwhelming reasons to move almost any construction task into controlled factory conditions if possible. Even projects that are initially intended for on-site construction may be required to be moved to off-site prefabrication facilities. For example, MX3D's plan to 3D print a metal bridge across a canal in Amsterdam was denied permitting because of safety concerns, and had to be built off-site [156]. While robots are widely used inside prefabrication facilities, little attention has been given to the on-site robotic assembly of prefabricated modules. In addition to making secure structural connections, this process also tends to involve making connections to mainline building services (mechanical, electrical and plumbing). To date, a good deal of academic research has proposed foam blocks as a stand-in for load-bearing masonry. These efforts may be better aligned with the future of the industry should they consider blocks to represent prefabricated building modules instead.

5.2.4. Remote applications should be prioritized for automation

Curiously, a number of works referenced in this survey cite the global trend of urbanization as motivation for increasing automation on urban construction sites [10]. In fact, the opposite trend has been evident; as populations urbanize, demand for automation increases in more remote areas where people no longer desire to live. Construction in remote areas tends to involve earthwork tasks that were mechanized many decades ago with serial-link manipulators like backhoes and excavators. These mature technologies are most easily automated for remote jobs with repetitive operations and few obstacles. The closer these tasks move to urban centers, the more attention needs to be paid to obstacles like buried pipes and electrical lines, navigating tighter property boundaries and other complications that make automation less feasible. Other primarily urban construction tasks like those performed by roofers, electricians, carpenters, and plumbers are even more difficult to automate because they require solving unique challenges in uncertain environments. Industry reports confirm that smaller construction firms (i.e., carpenters, roofers, electricians) have proven to be more resilient to automation than companies that execute large-scale projects, which have already seen a shift to more capital-intensive investment [1]. Excavator operation is a task that requires skilled human operators and is often needed for large and/or remote projects. Robots have been outperforming skilled human operators at this task since the 1990s [37]. On the other hand, hanging drywall is a very low-skill task that is required for nearly every urban construction project. Attempts to automate this task have not come close to matching the speed of human workers [169]. Rather than confronting the inertia of the mature technologies that still dominate construction sites, researchers may be better advised to focus on remote applications, especially those in harsh environments where construction is not currently feasible. Eventually, technologies forged in a crucible of harsh environments will be poised to perform reliably in more moderate conditions once their utility is demonstrated and costs come down. This strategy may be the only way to supplant the inefficient, fossil-fuel based ecosystem of mature technologies currently in wide use.

5.2.5. Consider decentralized or distributed control for challenging environments

Biologically-inspired distributed control algorithms (i.e., the swarm approach) is an emerging technology that has been applied to construction tasks (collective robotic construction), which has shown great promise in laboratory environments [10]. Primary advantages of the swarm approach include avoiding a single point of failure, scalability and the ability to react to changing conditions (construction sites are notoriously unpredictable environments). However, despite decades of academic research the swarm approach has not made an impact in industry, where mature technologies rely upon centralized information and large, complex machines. While today's mature technologies require more direct control than can be managed by simple agents, in many cases these processes lack the responsiveness demonstrated by nature's collective builders like weaver birds, termites and beavers. Certain tasks may continue to require centralized and sophisticated sensing and actuation, but the swarm approach may be better suited to large, spatially distributed tasks in unpredictable environments, which offer the potential to enable infrastructure projects that are not currently feasible with existing methods. For example, collective robotic construction may prove to be an ideal solution for autonomously managing coastal protections against rising sea levels [87], especially during storms where human labor is risky. Collective robotic construction could also extend the measurable success of interventions in China's Kubuqi Desert, where short fences are arranged in a grid pattern to combat desertification [174]. Large-scale planning would be near impossible, as dunes shift rapidly, but autonomous robots would be able to install interventions in useful locations reacting only to local environmental cues.

5.2.6. Too little consideration is given to added value

In order to understand if it is worth developing a robot to automate a construction task, one must first understand the task well enough to judge whether robotic automation would add considerable value; otherwise, the innovation will not be adopted by the industry. Among academic research projects that present emerging technologies for on-site automation, only a minority consider how that technology will engage with existing building materials and construction processes [55,130,136,145,151]. Even technically impressive industry research advancements such as automated building of CMU walls [122] or 3D printing with concrete [153] have not seen widespread adoption, likely because they have not been able to demonstrate cost savings over conventional methods.

Correctly identifying the added value in a construction task is not necessarily obvious. For example, the invention of the concrete hose pump was a transformative innovation, because it meant that the many workers who were once needed to shuttle wheelbarrows full of concrete around the construction site could be replaced by a single worker with a hose. The hose operator's work can be further automated with semi-autonomous mechanization or be completely replaced with a fully autonomous solution, but neither would have as dramatic an effect on the productivity (i.e., value add) of the task.

Similarly, the invention of drywall (sheetrock, plasterboard) replaced the time-consuming processes of lath and plastering walls, drastically reducing the amount of labor required for wall finishing. Replacing a drywall worker with a current state-of-the-art humanoid robot does not add value [169]. Even in the best case, the value added over a single human laborer would be minimal. Conversely, automating drywall hanging in a prefabrication factory could substantially increase productivity.

5.2.7. The industry suffers from a shortage of training, not labor

There is a tendency for works cited in this review to mention a perceived labor shortage in the industry as motivation for increasing automation [7,10]. New entrants into the industry require vocational training, which is primarily provided by the state in some developed economies such as Germany, but has been historically provided by labor unions in the US. However, union participation in the US construction industry has plummeted from 40% in 1973 to 14% in 2016. Unions have been left unable to provide critical entry-level training or defend worker's wages, which have fallen 15% over the same period [175]. After having worked for decades to weaken labor unions, 95% of contractors now express concern over their inability to find skilled workers [176]. It is hardly surprising that an industry that offers lower wages and fewer training options than it did in past decades is struggling to attract new workers.

But regardless of the cause of the current lack of skilled workers, it is clear that the solution requires enhanced vocational training mechanisms. Based on current US industry trends, it seems unlikely that either industry or unions are in a position to initiate new training programs; perhaps the industry will look to the German model and demand a state-sponsored solution. But rather than bemoaning the current low productivity of the industry [2], the industry should see this need for training as an opportunity to overhaul vocational mechanisms with a focus on emerging technologies, preparing workers for careers of working with automation, as opposed to training them to operate outdated machines.

5.3. Summary

This review has outlined research efforts to increase automation in construction, and highlighted emerging hardware developments that illuminate a path towards fully autonomous construction. While achieving full autonomy for most construction tasks remains in the distant future, a number of important steps have already been taken towards on-site autonomy. It is not clear that automating existing machinery will ultimately advance the goal of fully autonomous construction. Rather, more promising advancements are being made with machines explicitly designed for autonomous operation. We see particular promise in the growing trend towards designing material-robot systems for specific assembly tasks. While these systems have so far been demonstrated primarily in laboratory environments, we expect that future proposals designed around durable building materials will enable the fully autonomous construction of useful real-world structures. We also see great potential in efforts to embed custom sensors in building materials to facilitate their robotic assembly. The trend towards increasing prefabrication suggests that over time, many tasks currently performed on site will be largely moved off site. We expect this to skew the landscape of on-site construction tasks away from lower-order tasks that deal with raw materials and towards the assembly of higher-order building modules. At the same time, several important areas of construction have been largely neglected, such as substructure construction, auxiliary tasks like formwork and scaffolding, and coordinating operations between different robot systems. These areas will likely need to see increased attention in order to significantly increase on-site autonomy. Finally, new types of training opportunities are called for, to prepare workers to operate in an industry that will become increasingly automated over the course of their careers.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Article B

N. Melenbrink, P. Kassabian, A. Menges, J. Werfel, 2017.
Towards force-aware robot collectives for on-site construction.
Proceedings of the 2017 Association for Computer Aided Design in Architecture (ACADIA)

This original research originates from N. Melenbrink under the advising of A. Menges and J. Werfel. It builds upon prior work on a strut-climbing robot design and prototype (initially presented in [25]) as well as the results of corresponding simulations (initially presented in [26]). Pursuant to conversations with A. Menges, this article presents the motivation of fully autonomous or unsupervised construction. The research contributions are contextualized within a broader trajectory aimed at exploiting the affordances of distributed on-site construction in the built environment. N. Melenbrink created a custom simulation environment, developed and tested behavioral algorithms, and extended hardware applications from node-and-strut to block-based building materials. P. Kassabian offered structural engineering advice. J. Werfel provided research funding. Preparation of the manuscript was conducted by N. Melenbrink with advising from A. Menges.

Towards Force-aware Robot Collectives for On-site Construction

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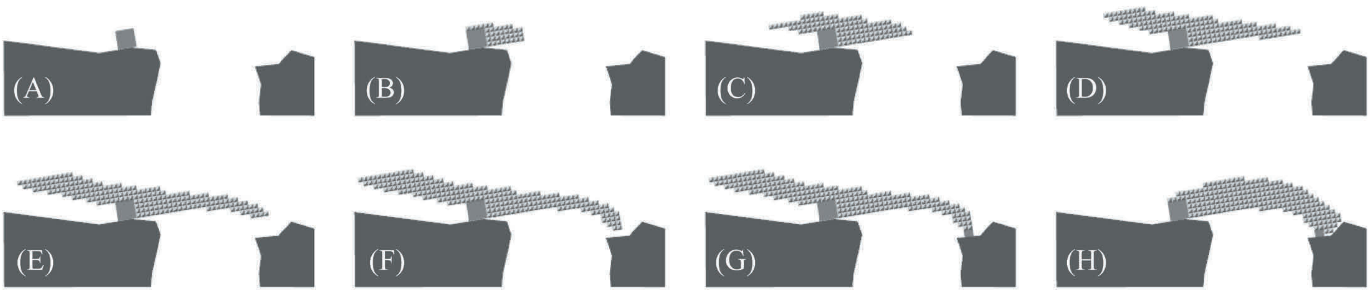

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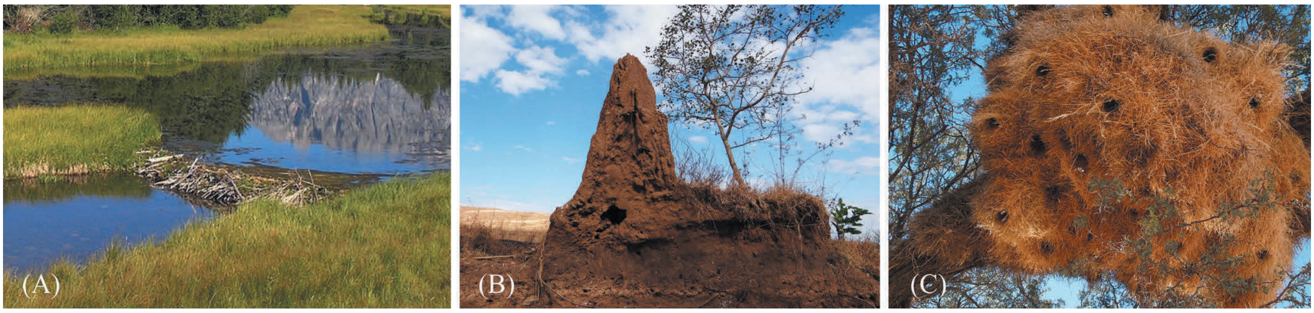
ABSTRACT

Due to the irregular and variable environments in which most construction projects take place, the topic of on-site automation has previously been largely neglected in favor of off-site prefabrication. While prefabrication has certain obvious economic and schedule benefits, a number of potential applications would benefit from a fully autonomous robotic construction system capable of building without human supervision or intervention; for example, building in remote environments, or building structures whose form changes over time. Previous work using a swarm approach to robotic assembly generally neglected to consider forces acting on the structure, which is necessary to guarantee against failure during construction. In this paper we report on key findings for how distributed climbing robots can use local force measurements to assess aspects of global structural state. We then chart out a broader trajectory for the affordances of distributed on-site construction in the built environment and position our contributions within this research agenda. The principles explored in simulation are demonstrated in hardware, including solutions for force-sensing as well as a climbing robot.

1 An example sequence showing how a swarm of construction robots might use forces to maintain stability in a building sequence that uses generic square blocks. In (A) a cache has been deposited on one side of a chasm. (B) Agents retrieve blocks from the cache and begin building a cantilever. (C-D) Agents read force sensors at the cache that indicate a danger of toppling into the chasm and begin counter-balancing. (E) Agents determine that the cantilever is near ground support on the far side and (F) start building downward. (G) Ground support is established on the far side (e.g., by inserting a special expanding unit to take up the remaining space between the cantilever and the ground). The force sensors now indicate that there is no longer danger of toppling, so agents accordingly begin disassembling the now-redundant counterbalancing blocks and (H) use them to strengthen the bridge. The work presented in this paper focuses on steps (B–E); the rest will be the subject of future work.



2 Examples of structures built by nature's collective builders: (A) beaver dam, (B) termite mound and (C) social weaver bird nest.

INTRODUCTION

Social weaver birds, beavers and termites are examples of nature's most accomplished cooperative builders, achieving large and resilient structures through parallel execution of simple tasks. Advances in electronics, sensing technologies, manufacturing methods and agent-based computation have only recently validated the feasibility of emulating such emergent building techniques through robotics. This affords us the opportunity to advance automation in construction in order to bring substantial advantages such as reducing cost and time on site, reducing risk related to unknown conditions, and reducing the risk of danger or injury. If full autonomy is attained, it can enable building in dangerous, remote, or otherwise challenging settings where construction is not currently feasible. When applied to architecture, it offers the possibility of conceptualizing the building process not as a binary distinction between construction and completion, but rather as an ongoing, persistently shifting response to variable high-level functional requirements.

On-Site Automation

Most evidence of robotic construction in the built environment comes in the form of off-site prefabrication with stationary robotic arms, which do not easily lend themselves to construction sites. The conventional understanding of robotics in the AEC industry tends not to consider other classes of robots that would be better suited to construction sites; for example, the Rob|Arch conference is explicitly focused on industrial arms (Rob|Arch 2014). On-site construction is typically changeable and prone to found conditions, and therefore also not typically suited to preplanned routines. Though challenging, on-site automation could enable a broad new range of building practices. The use of aerial robots in construction is starting to receive more attention; UAVs are currently being used on site for surveying, and are in development for light construction tasks (Augugliaro 2014). However, the industry tends to overlook other classes of robots, such as cable-driven robots or climbing robots, which could be more impactful than aerial robots for contemporary building practices (Sousa 2016).

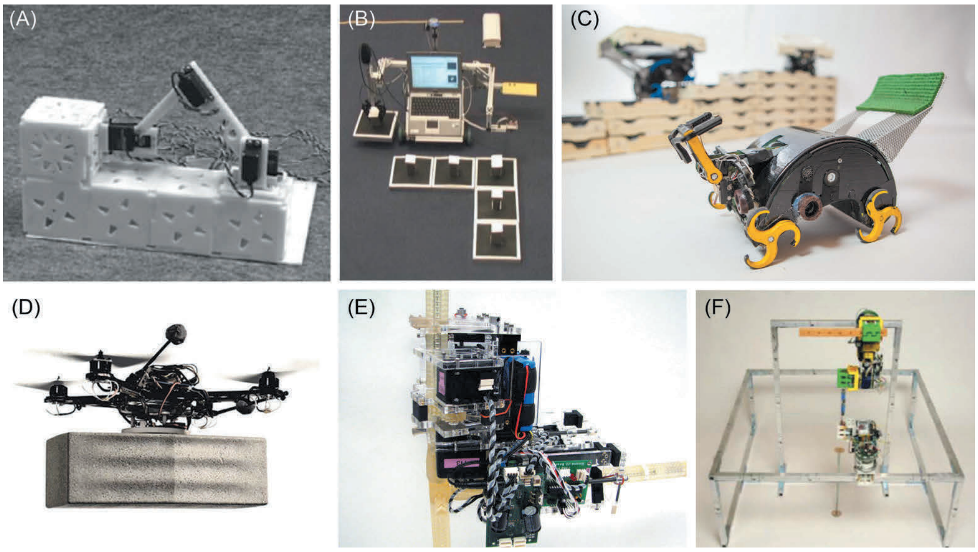
Swarm Robotics

The AEC industry, being typically risk-averse, has little precedent for innovative solutions for large-scale on-site automation, so we turn to biology for inspiration (Figure 2). The two features discussed above, responsiveness to environmental conditions and agent mobility, are well-addressed by the swarm approach. Beyond merely automating existing construction practices, looking at the ways that collectives build in nature suggests a new process-model for building, inviting new control methods, construction methods, and construction machinery to challenge existing models.

While a number of classes of robots might be conducive to on-site automation, climbing robots allow for a significant expansion in the viable building height over ground-based robots, and allow for greater local accuracy and more economical power consumption than aerial or cable-driven robots (Sousa 2016). We select reactive control over predetermined building sequences, as the former is more robust to environmental perturbations. Decentralized control is more attractive than centralized control, because requiring robots to report to a centralized system would limit both the workspace and the number of robots the central control could support. Instead, a decentralized system allows for building to continue, resilient to failure of any individual robot. Robotic agents are provided with high-level user-specified requirements instead of precise blueprints; this compromises the user's design agency, but increases the likelihood that the high-level goal could be attained. Eventually, with increasing labor costs, increased safety concerns, and financial pressures, the AEC industry will almost certainly place more emphasis on distributed robots for on-site automation; one of the aims of this work is to push forward that required shift in thinking.

Irregular Environments

This research trajectory presents a theoretical framework for autonomous construction in general, though first applications may be specifically for disaster scenarios in particularly hostile environments (e.g., building a bridge across a chasm as described in Figure 1). We are interested in considering a broad range of



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3 (A) AMAS robot and blocks (Terata and Murata 2004). (B) GER1LLA robot and blocks (Werfel et al. 2006). (C) TERMES robots and blocks (Werfel et al. 2014). (D) Quadrotor aircraft and block (Willman et al. 2012). (E) Truss-reconfiguring robot (Nigl et al. 2013). (F) Shady3D robots on struts (Yun and Rus 2008).

applications in the built environment, with a particular focus on the challenges of autonomous building in unstructured terrains. This requires the consideration of problems that largely have not been previously addressed, such as maintaining stability throughout an autonomous assembly sequence, which is the primary focus of this research. If the default options of scaffolding, formwork, or temporary bracing are not available, the structure itself must always be self-stable.

A fully autonomous building system would need to operate without supervision or intervention, and would need to pay attention to forces at every step of construction in order to ensure its resiliency to environmental hazards. Truss structures have been identified as an ideal entry point to on-site construction automation, because they can span long distances without requiring supplementary structures. However, if the desired structures are not trivially stable, their construction requires either anchoring or counterbalancing. Since we want to reduce the risks associated with the unknown on-site environment and the number of tasks that autonomous robots must manage, this work assumes there is no preparation of the environment before construction nor ability to anchor during construction, and instead seeks to maintain overall stability through counterbalancing. This affords the swarm the possibility of building sturdy structures that conform to challenging topographies as opposed to leveling them.

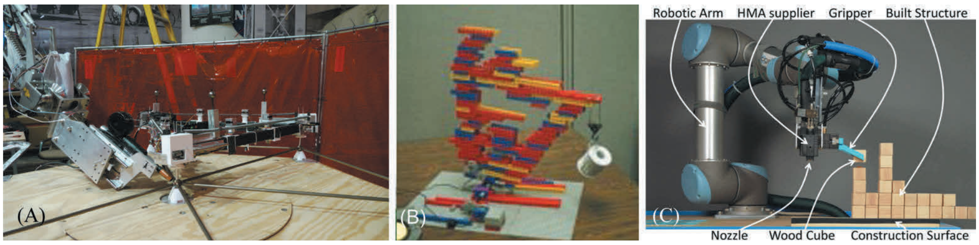
This conceptual shift towards unsupervised automation reopens exciting opportunities to rethink building life cycles or revisit, in a more serious way than previously possible, the feasibility of adapting to changing environments or functional requirements. Furthermore, it is increasingly critical to recognize the implications of impending automation, and, as architects and experts on the built environment, work with engineers from a fundamental level—or risk losing relevance in a world increasingly shaped by automation. In this paper we present an approach for maintaining stability during an autonomous building sequence generated on the fly, generalize it to other geometries and unstructured terrains, and show hardware that supports the theory.

BACKGROUND

Distributed Robotics

Significant achievements relative to this research agenda can be grouped into those pertaining to distributed robotics, responding to forces, and on-site robotics. Research in robotics has produced a variety of experimental hardware demonstrations (Figure 3), with multiple autonomous robots building three-dimensional structures, including climbing robots building with struts (Yun and Rus 2008; Nigl et al. 2013) or blocks (Terada and Murata 2004; Werfel et al. 2014), as well as flying robots building with struts (Lindsey et al. 2011) or blocks (Willmann et al. 2012). These research prototype systems are demonstrated in controlled laboratory environments, using highly specialized bespoke building materials. The challenges to refining any such systems to work reliably outside the lab, to build in natural environments using common materials and without relying on the regularities or tools available in their currently demonstrated test settings, are very substantial. Furthermore, none of these examples consider maintaining stability during construction.

Also of interest to this work is the notion of "digital materials," a discrete set of components that can connect in a finite set of ways (Popescu 2009). Digital materials facilitate automation



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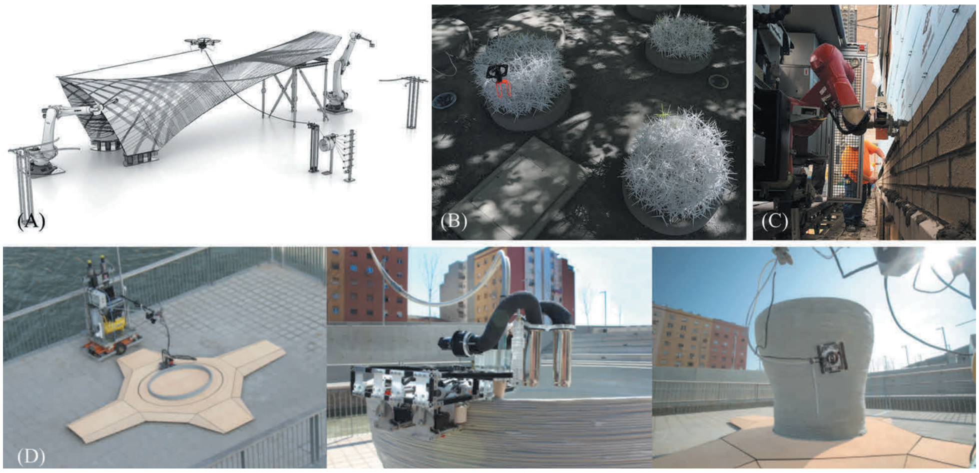
4 Examples of construction processes that take forces into account: (A) Intelligent Precision Jigging Robot (McEvoy et al. 2014), (B) Physical verification of computationally evolved form (Pollack et al. 1999), and (C) a robot arm builds cantilevers according to a preplanned building sequence (Brodbeck and Iida 2014).



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5 Examples of construction-site-ready robots: (A) Aerial robots used in concert with stationary arms to expand the workspace (ICD/ITKE Research Pavilion 2017), (B) Aggregate Architecture Pavilion uses a cable robot to deliver materials on site (Dierichs and Menges 2012), (C) SAM bricklaying robot (Peters and Belden 2014), (D) Minibuilders, a heterogeneous team of additive manufacturing robots (Nan 2015).

by enforcing precision while increasing structural performance, when compared to analog assemblies. The construction processes in Figure 3 all qualify as digital materials with the exception of (D), in which the geometry does not encode a finite set of possible connections.

Responding to Forces

Recent years have witnessed a considerable amount of literature on experimental modal analysis (comparing on-site impact frequency response measurements against finite element models), but it is worth noting that these techniques cannot be applied to the domain considered in this research track because they require a priori knowledge of the topology. A smaller number of studies consider responding to forces during a building sequence.

An approach shown in Figure 4A considers forces in sequence, though still relying on centralized pre-planning (McEvoy et al. 2014). Previous work describes counterbalancing features that emerge from an evolutionary algorithm that seeks to satisfy a high-level goal of spanning a gap (Pollack et al. 1999). While the authors demonstrate the stability of the resulting final configurations, they do not consider stability at each step of the building sequence or the feasibility of building each candidate structure. Researchers have extended the principles established by Pollack et al. for the purpose of a single robot arm building a cantilever (Brodbeck and Iida 2014). They consider forces to guide an evolutionary algorithm for material distribution. They discuss the use of counterbalancing for unanchored structures and propose a stability criterion of checking whether the horizontal component of the center of mass is past the edge of the building platform. This is effective in their defined case but would not generalize to an irregular environment.

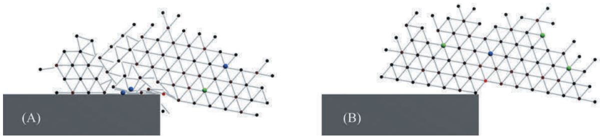
Otherwise there is little research on counterbalancing beyond conventional building practices where counterbalancing is formulaic and predetermined. Self-organized construction is a relatively new field that uniquely demands this research focus.

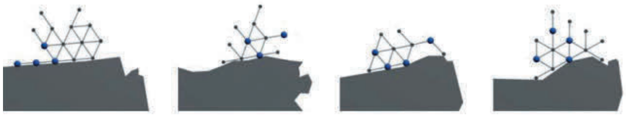
Robotics in the Built Environment

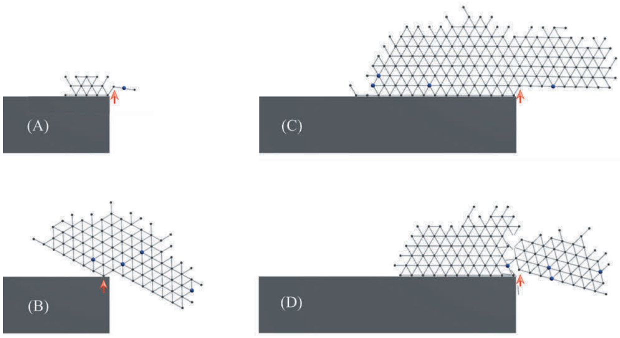
Though challenging, there are precedents for construction-site-ready robots (see Figure 5). A number of these examples do require the environment to be prepared ahead of time, but still present interesting solutions to circumventing the workspace limitations of stationary robots (Keating et al. 2017; Nan 2015; ICD/ITKE 2017; Dierichs and Menges 2012).

SIMULATIONS

A number of different approaches were executed in simulation with the intent of evaluating our hypothesis that paying attention to local forces will allow agents to autonomously build stable structures. Simulation work was first developed with finite







6 Typical failure modes of (A) breaking and (B) toppling.

7 Snapshots of trials with procedurally generated irregular terrains. The blue spheres indicate the presence of an agent at a node.

8 Typical snapshots at the moment of failure for structures under (A) the "force-unaware" variant, (B) the "force-aware" variant (no counterbalancing), (C) the "preplanned balancing" variant (force-aware), and (D) the "reactive balancing" variant (force-aware). All failures included broken joints; in (A) joints typically broke early in the trial, in (B) joints tended to break while toppling, in (C) a joint was broken but the strut did not fall away, while in (D) the joint break happened to cause the strut to fall away, leading to a cascading failure.

element models (Melenbrink et al. 2017) and further developed with a dynamic physics engine (Melenbrink and Werfel 2017). The objective of all simulations was to build a cantilever as far as possible, as if to bridge a gap, using decentralized robotic agents that respond to locally measured forces as cues. A previous consideration had been looking at vibrations to determine stability, but this technique was found to be noisy and unreliable.

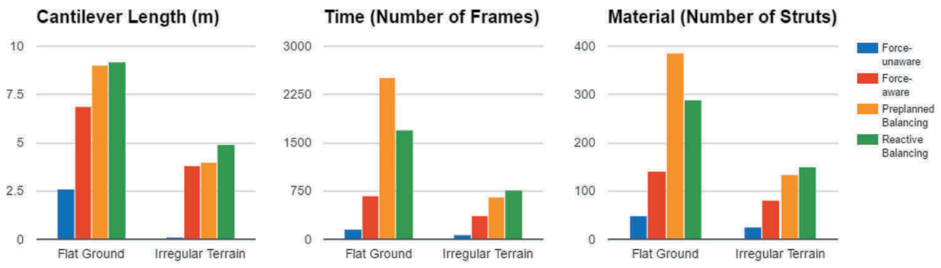
For reasons described in the introduction, we focus on truss structures. Horizontal cantilevers are an apt framework for exploring stability, as they are more challenging to keep stable than fully supported structures, and would be the first step in unsupervised bridge construction, which could be particularly useful in remote or difficult terrain. Typically, bridges in such unstructured environments require scaffolding or other supplementary structural support, but truss bridges could conceivably be built without the need for additional scaffolding. For structural stability, we choose the truss geometry to be a triangular lattice, with horizontal rows. This is broadly an efficient use of material layout with both bending and shear capacity. In this work, as a first step toward developing a theoretical foundation, we considered only building in a two-dimensional vertical plane. The truss (as shown in Figure 6) is composed of individual identical rigid struts and corresponding nodes as opposed to stable cellular units (see Figure 15), though we expect that the findings from the former will generalize to the latter (see the following section on Geometry and Sensing Extension). For physical plausibility, material assumptions were made based on existing, readily available construction materials. Nodes are assumed to be capable of receiving up to six struts and measuring axial and shear forces, as was previously demonstrated (Melenbrink and Werfel 2017).

In the system we propose, agents must be able to detect and prevent structural failures. In these simulations, we consider two types of failure: toppling into the chasm and local breaking. Breaking occurs when forces at a joint between a node and strut exceed predetermined maximum thresholds. Struts are considered rigid bodies that do not buckle, as the system was designed such that this would not be a driving failure mode. Ground support under the structure is assumed to be stable. We seek to use counterbalancing (as opposed to anchoring) to eliminate the otherwise inevitable failure mode of toppling into the gap, and also use local force measurements to prevent or delay the failure mode of breaking.

In these simulations, robots do not communicate directly with each other but indirectly, inspired by the biological phenomenon of stigmergy. The principle of stigmergy is that cues left in the environment by an agent influence subsequent actions of agents that encounter that cue. In our application, robots' actions are affected by force readings they measure through the nodes of the structure, and their actions in turn affect forces throughout the structure. This approach removes the need for direct communication between robots, which therefore eliminates requirements for robots to stay in proximity to maintain connectivity, and avoids the challenges of mobile ad-hoc wireless networks in chaotic environments.

Simulation Environments

We developed two distinct simulation environments to study different aspects of system behavior. The first approximated rigid bodies with linear elements and used finite element analysis (FEA) for structural calculations (Melenbrink et al. 2017). Since FEA returns only overall static solutions, the calculations had to be reset and solved independently for every frame. This method provided significant detail at the element level. However, in order to accurately capture dynamic behavior such as friction against



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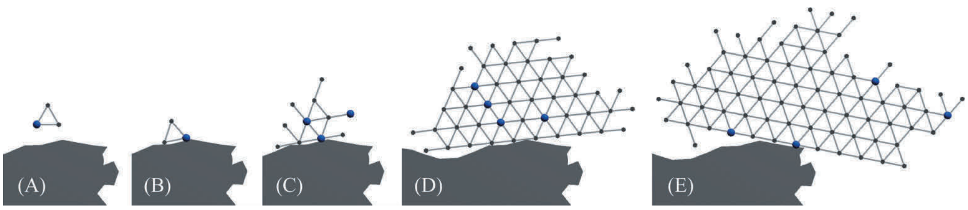
9 Graphs of results. There is consistently less building activity in irregular terrains than flat ground. Both "balancing" variants are able to build longer cantilevers, though at a considerable increase in time and material consumption.



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10 Typical sequence for the "force-aware" (no balancing) variant in an unstructured terrain. The material distribution causes the structure to tilt, exposing newly viable positions to install struts.

the ground or collisions between elements, higher-level FEA would be required (which would be prohibitively computationally expensive for large-scale structures with changing topologies).

Accordingly, a second simulation environment was developed with Unity3D, which uses the NVIDIA PhysX 3.3 engine for rigid-body physics simulations. This simulation environment was better suited to capturing dynamic effects and interactions with an irregular terrain. Rigid-body dynamics is a branch of classical mechanics that focuses on systems of connected bodies and how they react to forces. Discrete bodies are assumed not to deform under applied loads, which simplifies calculations (thereby drastically reducing computational expense, as opposed to FEA or linear elastic models), and is more conducive to representing the discrete, rigid building elements presented here.

Rather than measuring local forces by querying the elastic deformation of node elements as needed with an FEA approach, the PhysX solver allows for direct querying of reaction forces between any two connected bodies. Irregular terrains are generated within the simulation environment for the trials that consider it. A new randomized terrain is generated with each trial, including features at various scales (Figure 7). The terrains are assigned physics properties including a collider and coefficient of friction, which the PhysX engine uses to calculate interactions between rigid bodies.

Baseline Algorithm

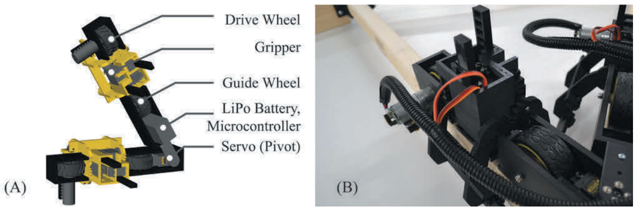
We first present a baseline algorithm for agent-based construction, which attempts to extend a cantilever without any regard for structural forces; it results in two distinct failure modes of breaking or toppling (see Figure 6). We then look at these two failure modes one at a time and propose algorithmic solutions to mitigate each. We propose that breaking can be forestalled by paying attention to local forces at every node encountered, and toppling can be forestalled by paying attention to the forces at the origin node. More detailed explanations of the algorithm and its variants are explained in prior work (Melenbrink and Werfel 2017).

Force Awareness

The baseline, "force-unaware" algorithm will eventually topple or break, though it tends to break before accruing enough mass to topple (see Figure 8A). Under the "force-aware" variant, agents disqualify any locomotion where the forces measured indicate that a potential structural failure might occur if the robot were to move down that strut. We ran repeated trials for both force-aware and force-unaware variants, for both anchored and resting conditions. The results of Figure 9 indicate that the proposed method of forestalling breakage was indeed successful—the length of cantilever achieved by "force-aware" agents was over twice that of the "force-unaware" agents.

Dynamic Counterbalancing

To prevent the structure from falling into the chasm when unanchored, we modify the algorithm so that agents build in a way that counterbalances the cantilever. They do this by adding material in other directions, using the weight distribution of the structure to provide stability. Two additional variants are tested, both with local force-awareness; *preplanned counterbalancing*, in which agents act to keep the structure balanced at all times, and *reactive balancing*, in which agents only add counterbalancing material when the structure is approaching overall instability.



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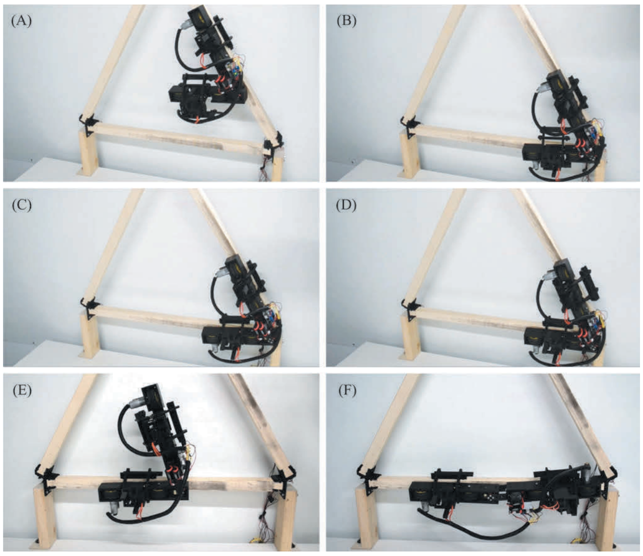

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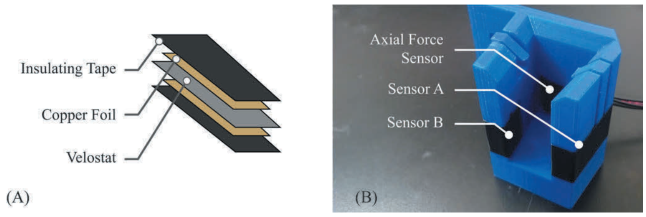
11 A rendering of the strut-climbing robot, consisting of a front and rear carriage, each independently capable of gripping and rolling along a strut. Not shown is a preliminary design for a strut-carrying module, which would be needed to achieve strut placement. (B) Photograph of initial prototype.

12 The locomotion sequence as the robot transitions from one strut to another. (A) The robot uses its rear carriage to traverse down the strut with its front carriage gripper open. (B) The robot has moved until it makes a hard stop at the next node. The motor encoders cease incrementing, indicating to the microprocessor to power off the motor. (C) The front carriage grips the next strut, (D) the rear carriage releases from the previous strut, (E) (taken from a different trial) the robot traverses down the new strut using its front carriage, (F) the rear carriage pivots into place and attaches to the strut. Next the front carriage will detach and pivot, and the sequence can continue. Note that the nodes are simplified to 2 vacancies as opposed to a complete 6, as a single triangle was deemed sufficient for early locomotion trials.

For the latter variant, we found that looking at shear forces can provide cues for when to begin counterbalancing, but do not reliably capture when to cease or re-initiate counterbalancing routines (Melenbrink and Werfel 2017). A more useful heuristic was found by measuring the ratio of the axial reaction forces on struts at the origin node. If this value exceeds a certain quantity, agents inherit a likelihood that they will add counterbalancing material. Otherwise, agents maintain their default bias in the direction of the cantilever.

The "no balancing" variant will predictably topple into the chasm when the cantilever reaches a critical length that is shorter



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13 (A) The layers of the sensor package. (B) A prototype socket used to evaluate the effectiveness of this sensor in a node-and-strut assembly, as described in previous work (Melenbrink et al. 2017).

than the two other approaches. Both counterbalancing variants allow for further cantilevering by eliminating the failure mode of toppling; reactive counterbalancing performs best in terms of building furthest with the least material (see Figure 9). Future work will look at generalizing reactive counterbalancing to other geometries.

HARDWARE

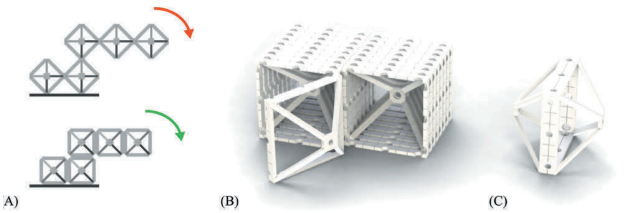
To demonstrate key capabilities in a physical system, hardware prototypes were developed for an instrumented node-and-strut assembly and an autonomous strut-climbing robot. Previous work discusses these prototypes in detail (Melenbrink et al. 2017). In the following section, we generalize our force-sensing techniques to cellular geometries, which may be preferable to node-and-strut assemblies in some cases.

Robot Design

We present a design for an autonomous strut-climbing robot intended to work with the type of triangular lattice described in the Simulations section. The robot consists of two carriages capable of independently gripping struts, allowing transitions from one strut to another (Figure 11). The sequence by which a robot would use pogo pin connectors to attach to a node, measure its forces and save them to the EEPROM memory of the node's microprocessor are described in previous work (Melenbrink et al. 2017). The sequence for installing struts and zeroing sensors is also described. The robot was able to locomote along struts and autonomously transition from one to another; however, the reliability of these operations proved a challenge. Future work will look at redesigning the morphology of the robot.

Sensor Design

A key component of this work is a custom force-sensing method, which would be required for the kinds of building tasks explored in simulation. There are a number of reasons why strain gauges were deemed impractical for this application, and were abandoned in favor of simple force sensors. Strain gauges are difficult to install and calibrate uniformly over multiple elements, and



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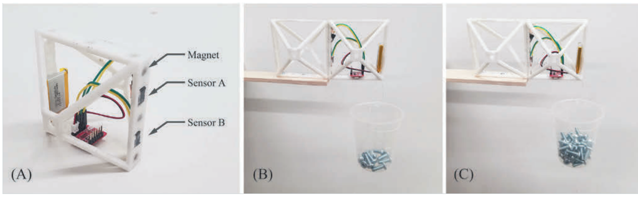

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14 Images describing a preliminary cellular unit. (A) Previous work has determined that vertex-connected octahedra (top) can yield a desirable strength-to-weight ratio (Popescu 2006). While this arrangement is ideal in compression, it is not suitable for resisting bending, which is needed for the cantilevering described in this work. Edge-connected octahedra (below) are better at resisting bending. (B) shows how these shapes could be efficiently stacked for transport, then folded and locked into place to produce a cellular unit (C).

15 (A) Shows the instrumented cellular unit used for this evaluation. The connection to another cell is made by magnetic force, and two sensors (as described in the previous section) installed at the top (Sensor A) and the bottom (Sensor B) of the face report the force exerted on them. In a more complete system, all four edges would be equipped with sensors, and a mechanical connection would replace the magnets; this prototype tests only the accuracy of a single joint. The cell also includes a LiPo battery and a microprocessor capable of transmitting data over Bluetooth. The experimental setup is shown in (B, C); two cells are joined by magnetic force. As weights (assorted hardware) are added to the cup suspended from the cantilevering unit, the force on Sensor A decreases while the force on Sensor B increases. Once their difference crosses a preset threshold, an LED turns on (C), indicating that the joint is in danger of breaking. Known quantities of mass are then added until the joint breaks.

require additional amplification circuitry that is not needed for force sensors. Independent of amplification circuitry, strain gauges themselves range from tens to hundreds of US dollars per unit, while force sensors can be produced for a fraction of a dollar. As a structure may require hundreds of instrumented joints, this difference quickly becomes significant. Thus we instead propose a slim-package force sensor comprising a strip of force-sensitive material (e.g., Velostat) sandwiched between two copper sheets (Figure 13A). When force is exerted on the sensor, the resistance of the material decreases, yielding an increase in the voltage running through the sensor that is easily detected by a microprocessor.

The slim profile of the sensors is also advantageous because it allows the sensors to be placed directly in the load path, enabling them to report axial force, which strain gauges are unable to do.

GEOMETRY AND SENSING EXTENSION

This sensor was previously found to be effective at detecting small variations in applied load on a strut inserted into a socket, such as the one shown in Figure 13B (Melenbrink et al. 2017). This could be considered an early-stage hardware verification for the 2D system described in the Simulation section. However, due to the difficulties of a node-and-strut type system described in the Hardware section, it was deemed worthwhile to consider the possibility of construction with stable cellular units. In this section, we evaluate the same type of sensing system as applied to cellular units. The detailed design of the cellular unit itself is the subject of future work; for now we assume the use of the shape described in Figure 14. Further development will focus on this design in a more principled way—it should be structurally optimal, cost effective, able to facilitate robot locomotion, and should include a mechanical connection in addition to the magnets used for alignment.

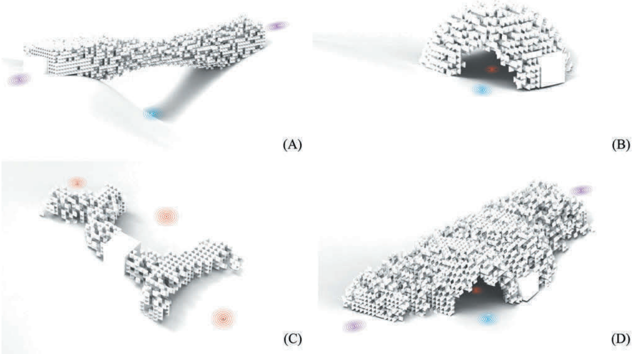
Sensor Evaluation

The instrumented cellular unit described in Figure 14 was evaluated for its ability to reliably predict failures due to breaking by measuring two force sensors (as seen in Figure 15A). The microprocessor turns on its LED when a preset threshold in the difference between sensor readings is exceeded, indicating that the joint is in danger of breaking. We set this threshold value so that this warning occurred when the load was 2/3 of the value at which the joint would empirically break. To evaluate the reliability of both the warning signal and the joint strength, we conducted 20 trials, gradually increasing the load on the joint until failure (Figure 15). The applied load at which the warning state was triggered was 224 ± 18 g; the load at which the joint broke was 336 ± 4 g. The sensing system reliably predicted failure for all trials: the joint never broke before the LED lit, suggesting that such a system could indeed provide a method for identifying stressed joints before they break.

In future work, we will look at extending this sensor configuration to measure forces at the supply cache (similar to what is outlined in the Simulation section) in order to enable dynamic counterbalancing, which has been shown to be useful for maintaining overall stability.

FUTURE WORK

Further research will continue to consider simulation and hardware in tandem. In simulation, we will evaluate the affordances of node-and-strut vs. cellular construction systems, and systematically develop a method for determining safety factors that reliably prevent failures in changing conditions. The resiliency of the system will be rigorously studied in simulation, ensuring the system's satisfactory response to environmental hazards such as sudden gusts of wind or unstable ground. We will attempt to generalize the principle that force-awareness allows for more stable construction to three-dimensional geometries. We expect



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16 These preliminary models are snapshots in three-dimensional building sequences where force-aware robotic agents install cellular units such as described in Figure 14. Remote frequency "instruction beacons" are placed in the terrain and emit high-level distance-based instructions such as *build a wall approximately 3 m away* (red), *don't build anything within 2 m* (blue), or *target for anchoring* (purple). These instructions can be used independently or composited to form various structural typologies such as a bridge (A), canopy (B), wall (C) or hybrid (D). The resultant forms are emergent functions of the swarm's attempt to satisfy the requirements of the beacons while maintaining stability throughout the building sequence.

the results to still hold, as the prevailing failure mode is due to bending imposed by gravitational forces, which is already accounted for in the two-dimensional vertical plane. Another area for further investigation is on architectural-scale instantiations of the construction swarm in simulation. The Introduction section alluded to the possibilities of a persistently changing architecture that responds to high-level user-specified instructions, as opposed to specific blueprints. However, the formal articulation and structural affordances of such a system have yet to be explored. Figure 16 suggests some preliminary possibilities.

Future hardware development will consist of proposing a 3D construction system, either node-and-strut or cellular units. A new robotic agent will be co-designed to work in concert with the work-in-progress construction medium. Ultimately, the system should consist of a swarm of distributed robots and suitable construction materials, which would be able to reliably and autonomously assemble architectural structures that respond to high-level functional requirements while maintaining structural stability throughout the assembly.

While these are formidable challenges, in this paper we have demonstrated that one key step towards this goal, the use of force sensing and a corresponding control algorithm, is feasible, and could potentially be implemented on a variety of construction systems.

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7

Article C

N. Melenbrink, K. Rinderspacher, A. Menges, J. Werfel, 2020. **Autonomous anchoring for robotic construction.** *Automation in Construction*

This work presented in this article was conducted by N. Melenbrink and K. Rinderspacher under the advising of A. Menges and J. Werfel. It builds upon prior work on a novel pile-driving robot design and characterization (initially presented in [27]). N. Melenbrink designed, built, and conducted experiments with the pile-driving robot in both controlled and natural environments. These experiments were conducted with sheet piles as well as with readily available building materials such as T-posts, rebar, and wooden posts. K. Rinderspacher built an experimental wind tunnel at 1:10 scale (using resources provided by A. Menges) and conducted design experiments to inform robot building behavior. In addition to the proposed interventions composed of the single construction task of post/pile driving, the advising of A. Menges inspired an emphasis on how this technique could be incorporated into more elaborate unsupervised construction projects with multiple task-specific construction robots. N. Melenbrink conducted further experiments with computer simulations to explore the potential landscape impact of a collective of robots using a simple reactive approach to dynamically guide building activity. J. Werfel provided research funding. Preparation of the manuscript was conducted by N. Melenbrink and K. Rinderspacher with advising and edits from J. Werfel and A. Menges. All authors participated in revisions and responses to peer review.

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Autonomous anchoring for robotic construction

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ABSTRACT

Advances in construction automation have tended to focus on either automating conventional earthmoving equipment or on the discrete assembly of superstructure elements. Neither paradigm has addressed anchoring introduced material into soil, a critical task for virtually all useful structures. Simple anchoring can be achieved by driving posts (discrete linear elements) or sheet piles (interlocking profiles) into the ground, serving as a foundation for a later superstructure. In this paper we present Romu, a wheeled robot that uses a combination of a vibratory hammer and its own body mass to drive both posts and piles into the ground. We report on the effects of hardware parameters on pile driving performance, and demonstrate operation in both controlled and natural environments. Romu is first configured to drive interlocking sheet piles. In addition to their utility as foundations, such walls could be useful directly as check dams, interventions used to prevent erosion and promote groundwater recharge in arid regions. We use simulations based on real-world terrains to explore the potential impact of a fleet of such robots deployed over a large watershed region, using a simple reactive approach to dynamically determine dam placement. Romu is then configured to drive a range of readily available building materials that commonly serve as posts. These include wooden slats that can be used for sand fencing, an intervention used to collect wind-blown sand to build barrier dunes. Post driving performance is characterized for a range of materials, and finally the use case of sand fencing is evaluated using physical tests at 1:10 scale in order to predict its potential impact. To broaden the utility of such robots in field settings, directions for future work include refinement of the hardware for improved operation in more terrains, increased capabilities for fuller autonomy, and integration with other construction tasks for more complex projects.

1. Introduction

Construction is an important industry that has been slow to automate, due in part to the range and complexity of tasks required to complete typical construction projects. Many tasks associated with the construction industry fulfill the canonical “dirty, dangerous and dull” criteria for tasks ripe for automation. There is an industry trend towards prefabrication (moving certain construction tasks to controlled factory settings where room-sized modules are produced and then shipped to site). This trend has the effect of reducing the number of tasks that must be completed on site, but automating requisite site-specific operations of site preparation and substructure (components that interface the superstructure with the terrain, including foundations and anchoring) has seen little attention. Increasing automation in on-site construction might confer such benefits as reducing injury rates, handling repetitive tasks, and helping to enable construction in locations where it is not currently feasible, e.g., because of challenging geotechnical conditions or other site hazards. A fully autonomous construction system, able to operate without supervision or intervention, would need to be able to handle unpredictable and changing conditions during the course of a project.

So far, academic research has largely neglected the critical construction phases of site preparation and substructure in favor of later stages of construction involved with superstructure assembly. Most work on autonomous robots for construction automation is limited to highly structured laboratory environments, with limited consideration of the practical challenges of real-world construction, and do not consider anchoring into the ground [1,2]. A few systems based on 3D-printing large-scale ceramic structures have been demonstrated outside controlled environments, though still on prepared flat surfaces [3,4]. Some work has considered adapting to uneven terrains by depositing amorphous materials [5,6], building truss structures to conform to terrains [7], or actuating structural elements to conform to new site conditions in real-time [8]. Autonomous site preparation and substructure tasks have been largely absent from academic research, though work on automating conventional earthmoving equipment has

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been proposed [9].

Industry contributions to construction automation, on the other hand, have emphasized earthmoving applications [10], although most recent innovations in the industry have to do with remote sensing and resolving data asymmetries through Building Information Modeling tools as opposed to on-site actuation. Earthmoving processes, in addition to construction, are important to agricultural, mining, and military applications. The value of automating existing earthmoving equipment has been demonstrated by mining companies as well as construction companies [11,12]. However, these efforts consist solely of adding autonomy to existing machinery, neglecting to consider how autonomous machines might benefit from other sizes or form factors than those designed for human operators. Outside of applications that require only earthmoving, fully autonomous robots are not yet actively employed in the construction industry. However, automation is entering the construction industry in the off-site assembly of prefabricated modules [13] as well as semi-automated assistants such as SAM100 and MULE that aid masons in bricklaying tasks [14].

While academic efforts have largely concentrated on automating superstructure assembly and industry efforts have mostly focused on earthmoving applications, typical construction projects have an additional requirement that neither of these components addresses—anchoring. As a rule, useful structures need to be anchored to the ground (typically via substructure elements like piles or poured concrete foundations), yet so far no attempts have been made to introduce automation into this domain. Approaches to anchoring typically rely on heavy equipment and complex processes (such as the excavation, formwork, reinforcement and pouring required for typical concrete foundations). As these methods are limited by site access and availability of labor, we consider if smaller autonomous machines could extend the reach of anchoring operations, which are critical for construction, infrastructure, and environmental restoration.

In this paper, we present a robot designed for light-duty pile-driving tasks in real-world environments (Fig. 1). We consider both sheet piles and posts, the two distinct typologies of commonly driven materials in the construction industry. Sheet piles (or Larssen piles) are linear elements folded from sheet material to form interlocking cross-sections, allowing the formation of continuous walls, while posts are discrete linear elements. In industry, this terminology is applied flexibly and subject to regional variation. For the purposes of this paper, “sheet piles” are taken to be interlocking elements while “posts” are discrete elements (including stakes, poles, slats, rods, etc.). The primary hardware contribution of this paper is the autonomous execution of the operations needed to drive piles in sequence. Future work will focus on incorporating autonomous localization and navigation capabilities, for full autonomy in target environments.

This paper develops and extends previously reported work [15] in four main ways: (1) Section 3 presents hardware to manipulate discrete posts as opposed to interlocking sheet piles, and describes a corresponding application scenario of sand fence installation. (2) Extensive field tests are conducted, for both sheet piles and posts, to characterize performance in natural environments. (3) The forces generated by the vibratory hammer mechanism are characterized in greater detail. (4) Large-scale deployments are modeled to present a more realistic approximation of real-world scenarios than in previous work, including a novel 1:10 scale physical simulation for sand fence placement, as well as computer simulations to evaluate the potential utility of check dam placement in real-world topographies.

Section 2 focuses on interventions made with sheet piles, while Section 3 focuses on interventions made with discrete posts. Each section is structured to present (1) a target application and its motivation, (2) a description of the required hardware, (3) physical tests in laboratory and natural environments and (4) a terrain-scale characterization (computer simulations in Section 2.4 and physical tests in Section 3.4) in order to better understand how interventions in different arrangements might impact future full-scale deployments. Section 4 contains a discussion of results and concluding remarks.

2. Sheet pile driving and check dams

Common uses of sheet piles in the construction industry include stabilizing soil during excavations as well as providing anchoring for subsequent installation of superstructure elements. While sheet piles are most typically used in concert with other building materials, they can also compose useful structures on their own, e.g., in the form of check dams, short walls that slow water flow and promote groundwater infiltration, combating desertification and other forms of land degradation.

This section presents Romu, a robot outfitted with the pile-driving hardware needed to autonomously install such structures in natural environments (first introduced in [15]). Section 2.1 describes the context and motivation for this application, Section 2.2 describes the design and fabrication of prototype hardware to accomplish this task, and Section 2.3 describes the results of lab tests used to characterize the effectiveness of the hardware. Section 2.4 describes computer simulations of deployments at the 1Ha (100m × 100m) scale to characterize the potential efficacy of check dams placed by a distributed fleet of robots operating according to a reactive contour-following behavior.

Fig. 1. Vision for Romu operating in a natural setting. Having installed the three piles it carries in one payload as the start of an erosion barrier, it heads for a supply cache to reload.

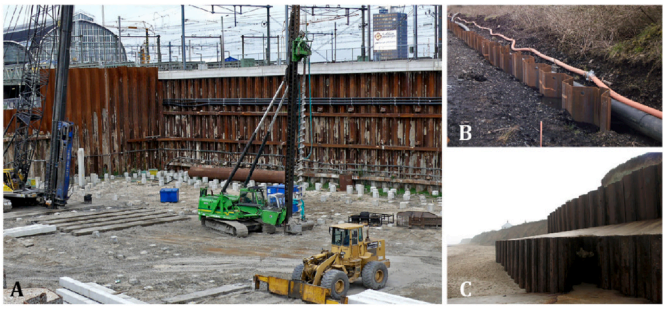

Fig. 2. Some common uses of sheet piling: (A) Retaining walls composed of sheet piles are often used to stabilize soil during excavation in urban construction. (B) Sheet piles can be used in ecological applications such as blocking groundwater seepage. (C) They can also be used as retaining walls to stabilize shorelines vulnerable to erosion.

2.1. Context and motivation

Sheet piles are typically made of sheet steel bent in a profile designed to interlock with neighboring piles. They are driven vertically into soil, and are used for a number of different purposes (Fig. 2). In commercial construction, they serve as retaining walls, permitting excavation for foundations or other subsurface construction. In uneven terrain, they can provide slope stabilization, seen for instance along highways.

Pile driving, especially for establishing deep foundations, typically requires very large equipment and tremendous amounts of energy. In commercial construction, common methods for driving piles include pneumatic hammers, hydraulic hammers, diesel hammers (which use a two-stroke engine to raise and lower a weight), drop hammers (which mechanically lift and release a weight, usually within a cage), and vibratory hammers (which convert angular momentum into vertical momentum using a pair of mated eccentric masses; see Fig. 5). Acoustic or resonant pile driving is a relatively new technique that works by exciting the natural frequency of a steel pile, causing it to drive itself into the ground like a spring. Another recent innovation is a machine that anchors into previously driven piles in order to increase its leverage for driving the next pile [16]. Other researchers have developed a lighter and more compact morphology for an impact pile driver [17]. For the purposes of autonomy and miniaturization, drop hammers and diesel hammers require considerable space to accommodate the hammer's range of motion. Pneumatic and hydraulic systems require pumping systems that are only produced at certain scales, can be difficult to maintain, and run the risk of leaking. Vibratory hammers, however, lend themselves well to miniaturization as they can be manufactured at a range of scales using readily available components and can be driven directly with an electric motor.

While most sheet pile driving is done to support other construction tasks like excavation, certain infrastructural interventions can be constructed with sheet piles alone. Effects of sea level rise such as inundation and erosion can be addressed by using sheet piles to create structures such as seawalls and offshore breakwaters [18,19]. Sheet pile walls can also help restore degraded environments by acting as check dams (Fig. 3E–F) [20]. While some of these applications are well addressed by human workers and heavy equipment, other applications like installing small check dams in remote areas could be better served by smaller-scale autonomous robots.

Check dams are typically constructed in gullies (incising channels) to slow runoff, preventing erosion and promoting groundwater recharge. Slowing the velocity of water flowing through the channel allows sediment to accumulate, letting a damaged landscape naturally repair itself without further intervention. Check dams can be employed to slow desertification, or to mitigate coastal or stream bed erosion. Literature has characterized the utility of check dams for, e.g., slowing erosion and promoting the restoration of vegetation in regions of Ethiopia that are susceptible to desertification [21]. While these check dams are constructed of stacked rocks or other materials found on-site, it is important that they be anchored (or "keyed") into the earth in order to resist lateral forces. The impact of large-scale installations of check dams throughout the Loess Plateau region of China has been found to reduce sediment deposition while supporting groundwater replenishment in upland areas, making agriculture in the region more sustainable [22].

Automating sheet pile driving could enable new types of construction in environments inhospitable to the presence of human workers. The following subsection describes a robot named *Terramanus ferromurus* or Romu (Fig. 4, [15]), which was originally designed to carry a payload of sheet piles and drive them in sequence into soil. The sheet piles interlock to form continuous walls, which could serve purposes such as anchoring for a larger structure or as a check dam (Fig. 3) to prevent flash flooding and promote groundwater recharge. Romu drives piles into soil using a vibratory hammer (Fig. 5) in addition to its own body mass. While conventional sheet pile driving equipment only employs a fraction of its weight towards its primary task, Romu's morphology allows it to leverage up to 100% of its weight to exert downward force for pile driving. We report on hardware characterizations and physical demonstrations with this robot (Section 2.3). The vision is for many such robots to be deployed in collectives in order to increase speed through parallelism; we explore such collective action in simulation (Section 2.4).

2.2. Hardware design

In this section, we focus on the design of the hardware to enable a robot to drive a sequence of sheet piles to form a continuous wall (Fig. 6). In a complete future system, one or multiple such robots would be deployed along with a supply cache of extra piles, to which they would repeatedly return to reload in order to build a set of walls of arbitrary length. The design and autonomous operation of the supply cache will be the topic of future work.

Romu is equipped with a vibratory hammer (Fig. 5). Vibratory hammers are commonly used for large-scale pile driving, though miniaturization and electromechanical (rather than hydraulic) actuation are novel features of this design (we are unaware of other examples). The performance of a vibratory hammer depends upon its eccentric mass, its rotation speed, and its "bias weight" (overall suspended mass used to generate downward force) [26]. With these parameters, it is straightforward to compute the range of forces that a hammer will generate. In commercial construction, piles are often driven to depths of tens of meters using hydraulically powered vibratory hammers suspended from cranes or other heavy equipment. Romu is designed for a miniaturized version of these operations, building small-scale walls to depths on the order of tens of centimeters. In industry, hammers are typically represented in terms of their eccentric moment, which is calculated by multiplying an eccentric mass by the distance from its center of gravity to its center of rotation. Commercial pile drivers are commonly equipped with 2, 4, 6, or 8 eccentric masses (eccentric masses need to be paired in order for their lateral forces to cancel out, see Fig. 5A). The eccentric moment of each is summed to give the hammer's total eccentric moment. Vibratory hammers used in industry feature eccentric moments ranging from 1500 to 8000 kg-cm, while in the experiments described here Romu's vibratory hammer operates between ~0.1–0.2 kg-cm. Bias weights used in industry range from 2500 to 10,000 kg, while Romu's bias weight is considered to be the full weight of the robot (24–48 kg here). The speeds at which Romu's vibratory hammer was tested roughly correspond to the range used in industry (~1000–3000 RPM).

While increasing the hammer's bias weight improves pile driving performance, operators must be careful that the machinery from which the hammer is suspended is sufficiently massive to provide an adequate

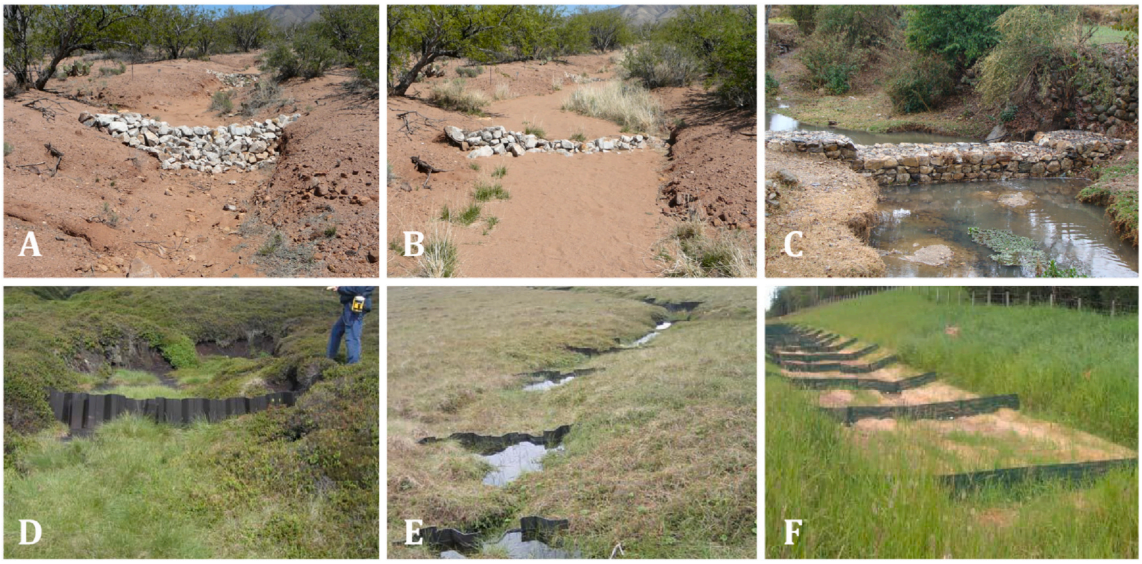

Fig. 3. Field deployments of check dams. Check dams can be constructed out of locally available materials like rocks (A–B), with the help of introduced materials like gabion baskets (C) [23], or out of interlocking sheet piles (D–E) [24]. Multiple dams are often placed in series along a channel (D–F). Check dams are useful in a range of climates, from arid regions with infrequent rainfall (A–B: showing induced sediment accumulation from (A) November 2009 to (B) April 2012 [25]) to regions that receive regular rainfall (C–E).

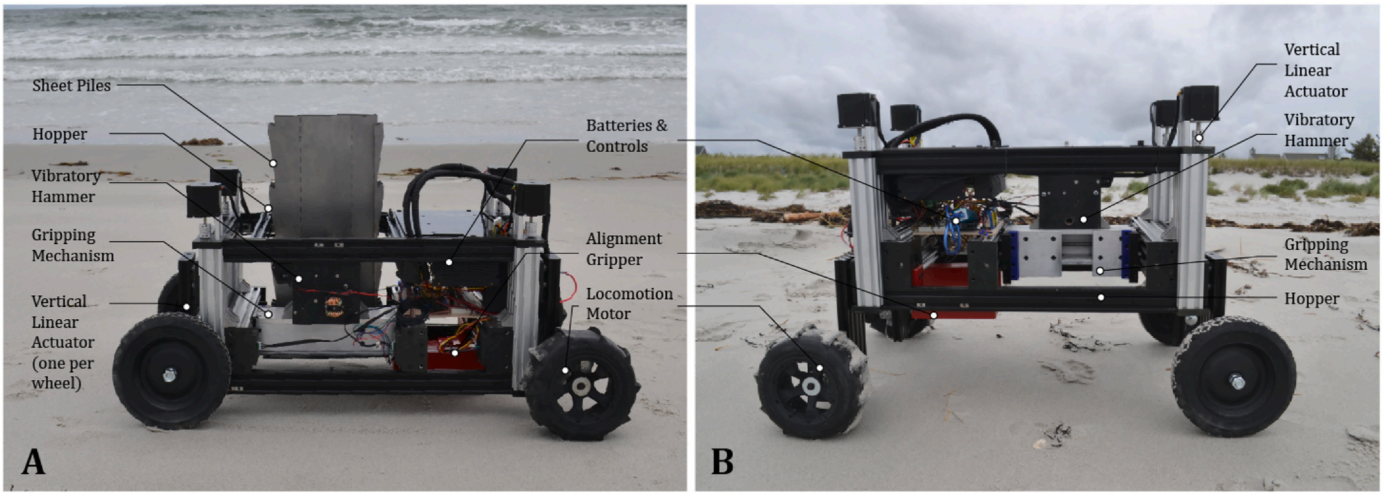

Fig. 4. (A) An image of Romu carrying a supply of sheet piles with relevant features labeled. (B) A view from the opposite direction, with linear actuators raised and sheet piles removed to show the gripping mechanism.

counterbalance. Romu, on the other hand, is designed so that it can leverage its own body weight as bias weight, removing the need to carry additional weight solely for this purpose. When driving a pile, the vertical linear actuators coupled to each of its wheels lower simultaneously (Fig. 4), redistributing the robot's weight from the ground to the pile. Up to 100% of the robot's weight could be used in this way if the soil resistance is very high, though in typical operation only a portion of the body weight should be needed to drive the pile with the remainder distributed among the grounded wheels.

The four vertical linear actuators are independently controlled, in theory allowing them to be set to different heights to compensate for uneven ground. This feature would require the addition of an Inertial Measurement Unit or tilt sensor and is not demonstrated in this work, but could be implemented using existing leveling algorithms [27]. Independent actuation of the four linear actuators allows the robot to drive piles vertically with respect to gravity on inclined or irregular surfaces. The linear actuators are first operated independently to level the chassis, and then extend and retract in unison during the driving process to drive the pile vertically into the ground.

Conventional pile driving methods typically require driving piles by gripping them at their top, meaning that equipment must be at least as tall as the pile is long. By gripping piles at their sides, Romu is able to drive piles of any length, in principle limited only by the soil penetrability. The robot's ability to drive piles by gripping their sides is facilitated by sheet piles that were custom designed and fabricated for this purpose (Fig. 6). The piles are made of 16 ga. steel that is first laser cut and then bent into an S-shaped profile (Fig. 6A). This profile allows for piles to interlock, which can improve the structure's ability to withstand lateral forces. Notches are cut into the sides of the piles at 12 cm intervals (Fig. 6B–C). These notches taper downward in order to direct the jaws of the robot's gripper to the base of the notch, and ensure that the gripper does not slip out of the notches while driving a pile. During a pile driving sequence, the robot advances the depth of the pile 12 cm at a time, repeatedly moving from a grip on one notch to the next (Fig. 7).

In addition to the alignment features cut into the sheet piles, the

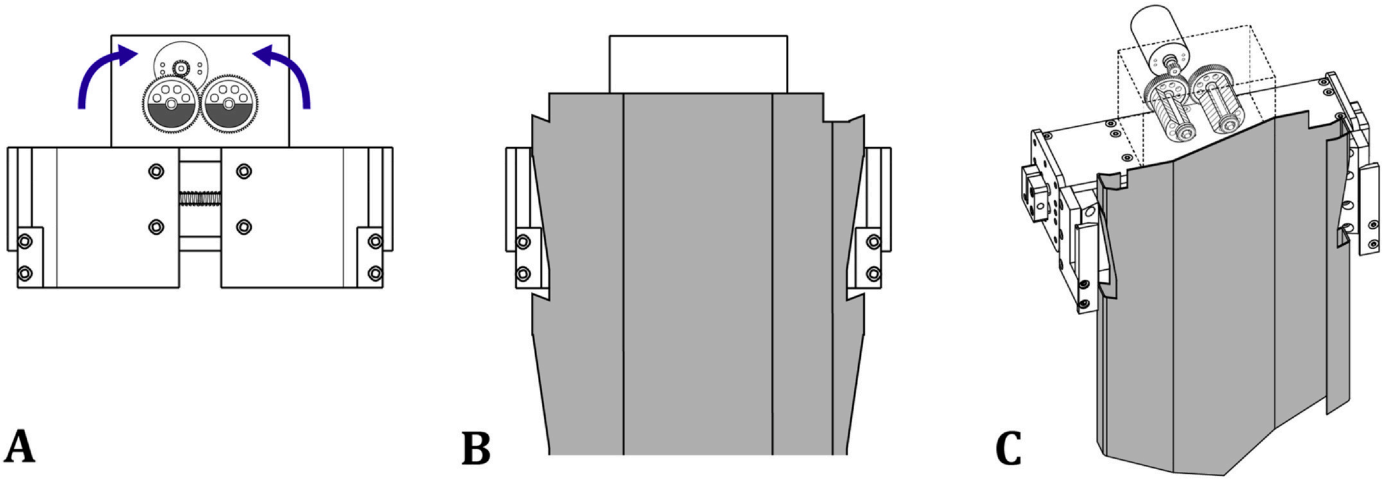

Fig. 5. (A) The gripping mechanism features two opposing jaws, driven by a lead screw, that open and close to grasp and release a pile. Mounted to the top of the gripping mechanism is the vibratory hammer, consisting of two counter-rotating eccentric masses driven by a DC motor. (B) The jaws of the gripping mechanism fit into the pile's notches, which provide a surface to receive the forces generated by the hammer. The notches are slightly angled inward to keep the jaws from slipping out. (C) Perspective view showing the gripper jaws positioned around, but not gripping, the pile.

robot itself is also designed with mechanical features to facilitate alignment of multiple piles in a wall. Towards the rear of the robot is an alignment gripper (Figs.4, 7). This gripper closes around a previously-driven pile, causing the robot to move slightly in the ground plane to ensure that it is properly positioned to deposit the next pile such that its profile interlocks with that of the previous pile. Additional alignment features include angled rubber pads installed on the jaws of the gripping mechanism, which also enhance the robot's grip on the pile. The mechanical components comprising the gripping mechanism were custom-designed and milled from aluminum stock. The surface of the jaws that comes into contact with the sheet pile is made of steel for enhanced strength. The linear actuators and other chassis elements are made of aluminum channel. A 7.4 V LiPo battery powers the vibratory hammer; a 14.8 V LiPo battery powers the remaining motors. A microcontroller allows the robot to autonomously perform a pile driving sequence. The robot can also be set to a teleoperation mode where individual axes can be commanded independently over a Bluetooth connection, which was useful for testing and development.

The full sequence by which the robot initiates and then extends a structure made of interlocking sheet piles is as follows (Fig. 7; see also Video 1 [15]). (A) The robot locomotes to the desired location to begin constructing a new wall, and retrieves a pile from its hopper. (B) The robot releases the retrieved pile, allowing it to fall to the ground while still contained within the channel formed by the two gripper jaws. (C) The linear actuators raise the chassis such that the robot's gripping mechanism is aligned with the next exposed notch in the pile. (D) The jaws of the gripping mechanism close, engaging with the notch in the pile. The linear actuators then lower the robot chassis 12 cm while the vibratory hammer is activated, driving the pile into the sand. Next, the jaws of the gripping mechanism release the pile, allowing the chassis to be raised again. Steps C–D can be repeated for as many notches as are on the pile. (E) After a pile is driven to the desired depth, the chassis is raised to clear over the top of the driven pile and the robot locomotes forwards ~20cm (roughly the width of one pile). (F) The alignment gripper (red) is closed around the previous pile, causing the chassis to roll slightly forward or back such that the gripping mechanism is properly aligned to allow the next pile to interlock with the previously-driven one. The alignment gripper then releases. (G) Similar to step B, the gripping mechanism retrieves a pile from the hopper and releases it, this time interlocking with the previous pile as it falls to the ground. (H) Steps C–D are repeated for each pile until it is driven to the desired depth. Steps E–G are repeated until the construction is complete, or until the robot's supply of piles is exhausted and it must return to a supple cache to restock. Upon restocking, construction resumes with step F.

The above process is designed to produce low walls where ~15cm of each pile is left exposed above the surface. Such walls may have direct utility as, e.g., check dams, or foundation support atop which to build superstructure. Other infrastructural construction tasks may require sheet piles that protrude a greater distance from the ground.

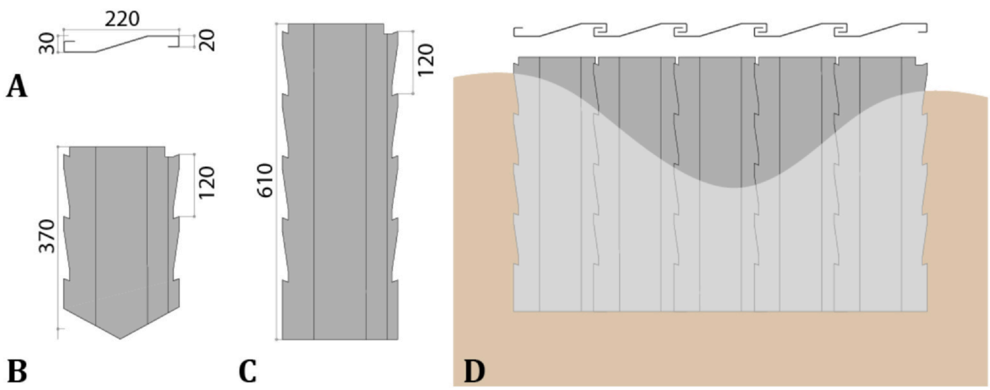

Fig. 6. (A) Top view showing dimensions of the custom sheet pile (mm). (B) Shorter, pointed piles used for outdoor demonstrations. (C) Longer piles used for laboratory experiments. (D) Diagram showing 5 interlocking piles acting as a check dam.

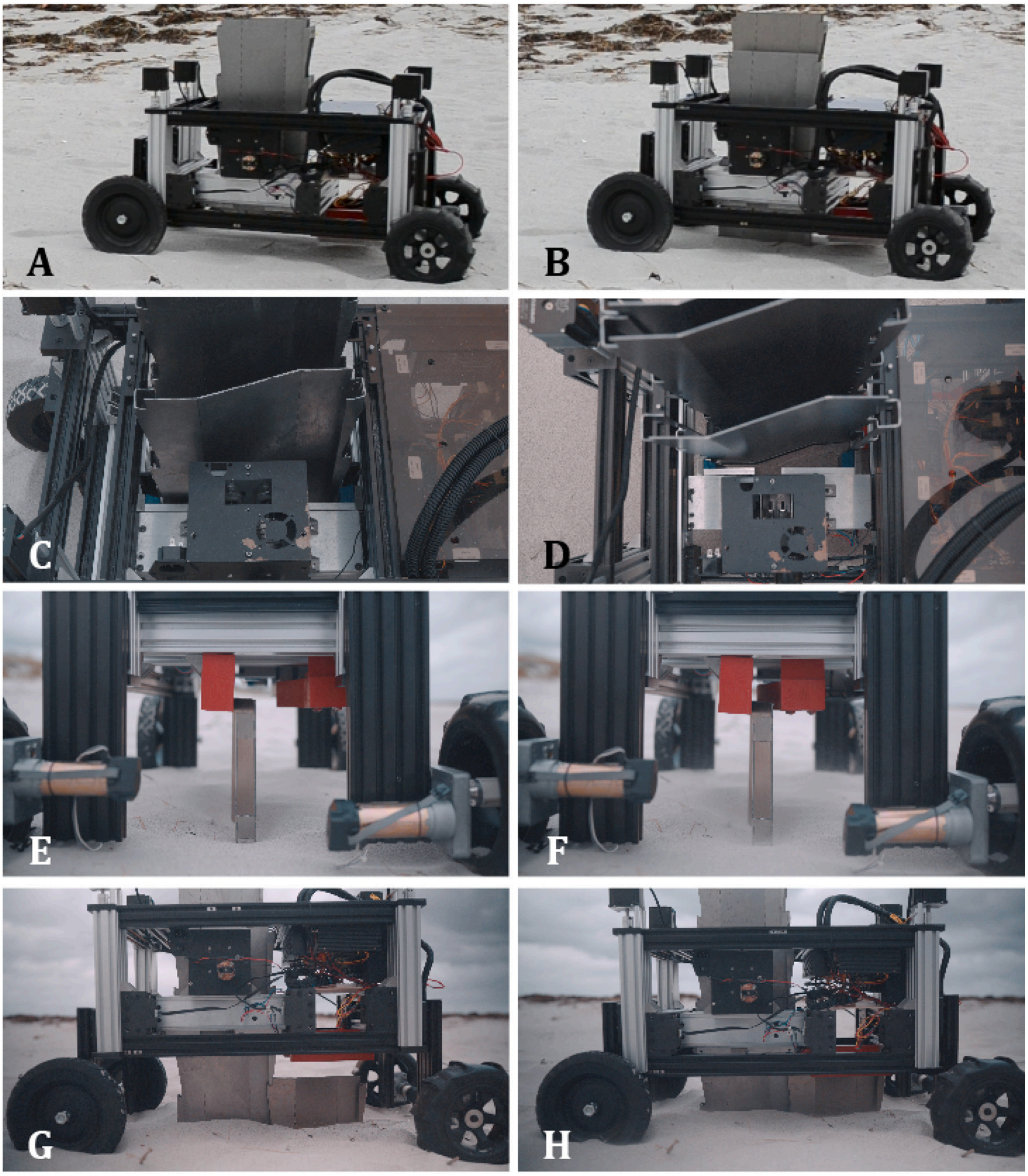

Fig. 7. Process of initiating a sheet pile wall or extending an existing one (details in text).

Romu can be modified to install taller sheet piles, as shown in Fig. 8. This modification features an open-backed chassis, which allows tall piles to be driven and released without interference from the chassis. The sequence by which this is achieved for piles after the first is as follows (Fig. 8). (A) Position the robot in front of the last driven pile, and advance the gripper (shown in red) towards the hopper. (B) Close the gripper jaws (shown in blue) around the next available pile in the hopper, then completely retract the gripper such that the retrieved pile is on the opposite side of the U-shape. (C) Locomote the robot in reverse, such that the interlocking slots are poised to receive each other without collision. (D) Advance the gripper until the interlocking slots of the deployed pile and the previously-driven pile are aligned. Locomote the robot forward until the interlocking slots are firmly in contact, preventing further forward locomotion. Open the gripper jaws, allowing the pile to fall to the soil. Execute cycles of pile driving (as described in Fig. 7C–D) until the pile is driven to the desired depth. After driving to the desired depth, open the gripper jaws and completely retract the gripper. (E) The robot is now free to locomote forward until the recently-driven pile is no longer obstructing the path of the payload gripper to the hopper. Optionally, return to step (A) to repeat the sequence. Since this version of the robot chassis would not need to raise over the height of the driven pile in order to advance forward, piles can be left with any arbitrary amount of their length above ground. Such a feature may be particularly useful in situations where a pile cannot be driven to the intended depth (e.g., because it has hit a rock). Without this modification, such a pile would need to be extracted and the robot would need to advance forward until the pile could be driven to depth, resulting in a gap in the wall. With this modification, the pile could be left in place and pile driving could continue uninterrupted.

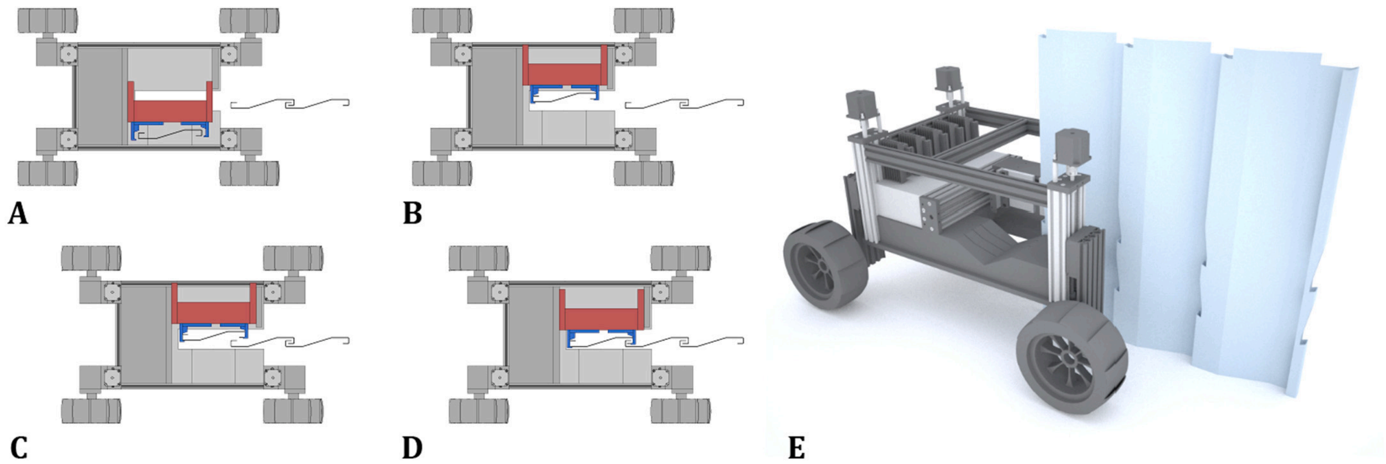

Fig. 8. A variation of Romu where the chassis is open to the rear to accommodate piles of arbitrary height. (A–D) Sequence by which this variation extends an existing wall (details in text). (E) Rendering of robot with wall of tall piles.

2.3. Performance tests

We conducted laboratory experiments to characterize the pile-driving performance of the robot as a function of the mechanical parameters of its vibratory hammer. For ease of manipulation and consistency of conditions across experiments, we used commercial-grade coarse sand (readily available at most hardware stores) as the substrate. A custom sandbox was constructed to facilitate testing in repeatable laboratory conditions. In order to eliminate inconsistencies in compaction due to driving and removing successive piles in the same vicinity, the sandbox was flipped upside down and shaken after each trial to ensure the sand in the testbed was at a consistent uncompacted state. The sandbox was made to be deeper (48 cm) than the anticipated maximum depth for the experiments (~40cm), giving a buffer to avoid effects from a pile approaching the rigid bottom.

Experiments were designed to measure the impact of varying each of the three key mechanical parameters (bias mass, eccentric mass and hammer speed) on pile driving performance [15]. While varying each parameter, the values for the other two parameters were held constant: bias mass at 24 kg, hammer speed at 2100RPM, and eccentric mass at 240 g (when varying hammer speed) or 120 g (when varying bias mass, to avoid driving more than 40 cm into the sandbox). Five trials were performed for each variant. Pile driving was allowed to continue until one or more of the wheels of the robot were observed to lift off of the ground, indicating that the forces imparted by the robot could no longer overcome the resistance of the sand. The duration of each trial was not recorded, as the speed of pile driving in these experiments is governed by the constant speed at which the linear actuators lower the robot. For each trial the ultimate driven depth of the pile was recorded (Fig. 9), as well as the vertical force required to remove it (Fig. 10). The robot was tethered during lab experiments in order to guarantee a constant supply voltage (the robot was powered by battery for field tests and demonstrations).

The results indicated that over this range of depths, increasing the values of bias mass, eccentric mass or hammer speed each yield roughly linear improvements in ultimate driven depth (Fig. 9). A noticeable exception is that substantially worse performance was observed when setting the hammer speed to 0 RPM (i.e., turning it off). This result shows the advantage of the vibratory hammer compared to downward force alone. The force required to extract driven piles also increased linearly with any of the tested parameters (Fig. 10). Comparing the driven depth of the piles to the force required to extract them (Fig. 11) yields an approximately linear relationship for depths in this range:

$$F = (4.9N/cm)d - 23N$$

where F is the force required to extract the pile (N) and d is the driven depth (cm).

Force plate readings were conducted in order to characterize the hammer performance while varying the governing parameters of bias weight, eccentric weight and hammer frequency. While grasping a sheet pile, the robot was positioned across force plates such that forces transmitted through the sheet pile were isolated to one plate (see Appendix A). We found that the peak downward force exerted by the robot using the vibratory hammer can be up to 80% greater than the

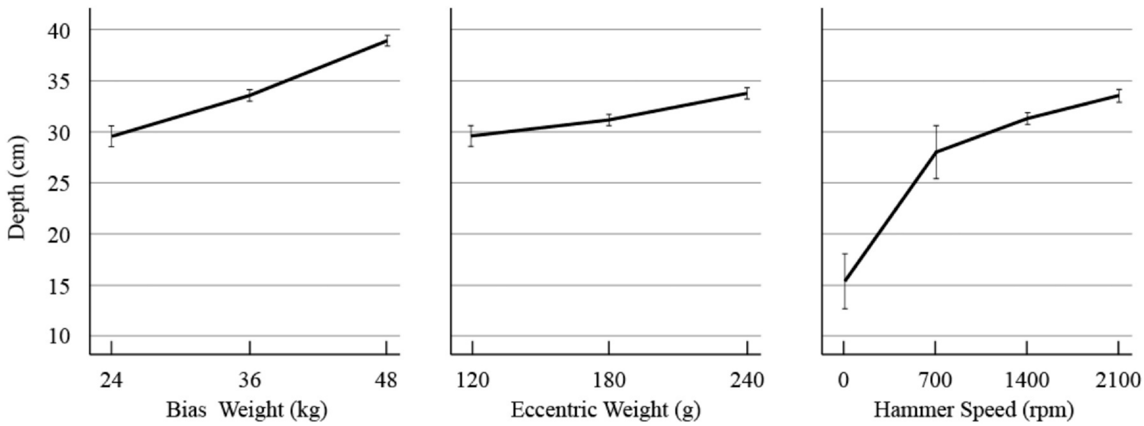

Fig. 9. The ultimate driven depth recorded when varying three factors that influence pile driving performance: bias mass, eccentric mass, and hammer speed. Five trials were performed for each variant.

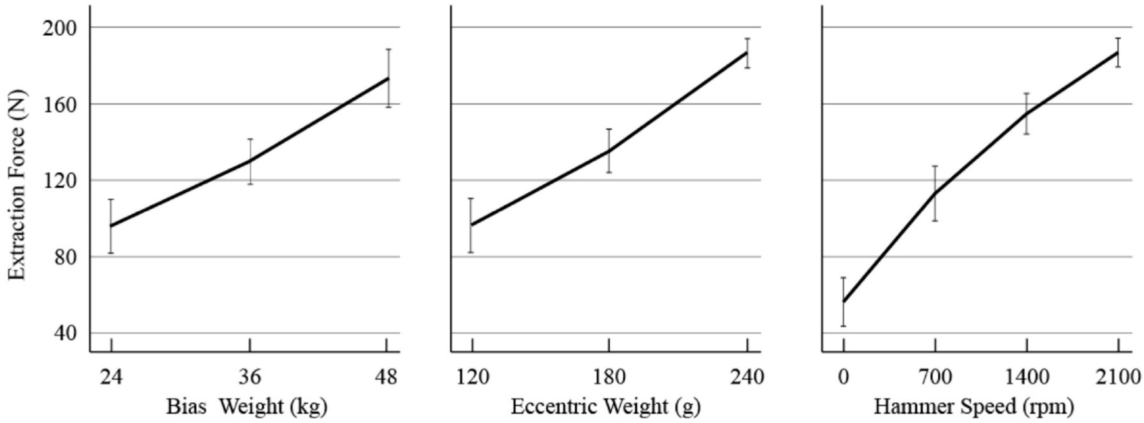

Fig. 10. The vertical force required to remove a driven pile from the sandbox recorded when varying the robot's bias mass, eccentric mass, and hammer speed. Five trials were performed for each variant.

force exerted while at rest (Fig. 12). Peak downward force increases roughly linearly with increased bias weight, eccentric weight and hammer frequency (Fig. 13).

After this characterization of pile driving performance in the lab, field experiments were performed at Revere Beach, Massachusetts (Fig. 7), as a real-world analogue of the sand substrate used in the laboratory experiments. (We suggest that the application of building check dams is likely to be as or more impactful for peatlands and arid regions (Fig. 3) as for sandy terrain; we limited these tests to beaches as the only accessible natural terrain within a reasonable travel distance that was largely free of roots and rocks.) The beach sand was found to be much more compacted than in the tests in the lab sandbox. Using bias mass of 24 kg, eccentric mass of 240 g, hammer speed of 2400RPM, and the same flat-ended piles used in the lab experiments, the robot was only able to drive piles 6–8 cm deep; when instead using piles with a pointed tip (Fig. 6B), the robot was able to drive to depths of 10–12 cm. By increasing the bias mass from 24 kg to 48 kg, the robot was able to drive flat piles to depths of 10–12 cm and pointed piles to depths of 15–18 cm (the piles shown in Fig. 1 were driven several cm further by hand).

2.4. Terrain-scale simulations: Behaviors for sheet pile-driving robots

The kinds of infrastructural or environmental management projects that robots like Romu might be well suited to address, such as desertification and erosion, often require interventions to be applied over very large areas. Historically, watershed stabilization was accomplished with large centralized dams because they were easier to build with available tools. However, many watershed regions would be more effectively managed by a multitude of smaller check dams distributed across the terrain [28]. Such projects are more naturally suited to a collective of smaller robots than to single heavy machines. A distributed swarm of robots at Romu's scale would be able to increase the speed of operations through parallelism and provide larger-scale interventions without unwanted side effects like damage that massive machinery may be prone to causing, particularly in vulnerable environments. Furthermore, teams of robots that operate in large dynamic landscapes (it is not uncommon for dunes in the Sahara to move 100 m per year [29]) could benefit from an approach in which individual robots act independently and in response to site conditions they encounter, rather than a centralized approach relying on constant communication (which may be difficult to maintain in remote, large-scale settings) or assignment of specific tasks based on earlier survey information that may become outdated.

While we demonstrate a single robot in hardware experiments, we have developed a custom simulation platform to evaluate the potential effectiveness of autonomous robots building check dams in various terrains in order to reduce hydraulic erosion. This simulation platform was created using the development platform Unity3D and allows for importing topographic data from the United States Geological Survey, which maintains and distributes a publicly accessible dataset for the entire country (see Appendix B). Terrain samples can then be instantiated with a user-specified number of identical robotic agents, each programmed with the same behavior (Fig. 14A–B). After the simulated robot collective has finished installing an intervention, the platform performs a hydraulic erosion routine on the terrain sample and quantifies the amount of sediment displaced (Fig. 14C–D). Using this platform, we explore whether autonomous robot collectives limited to using only local information are able to place check dams in a way that significantly reduces erosion from a given terrain.

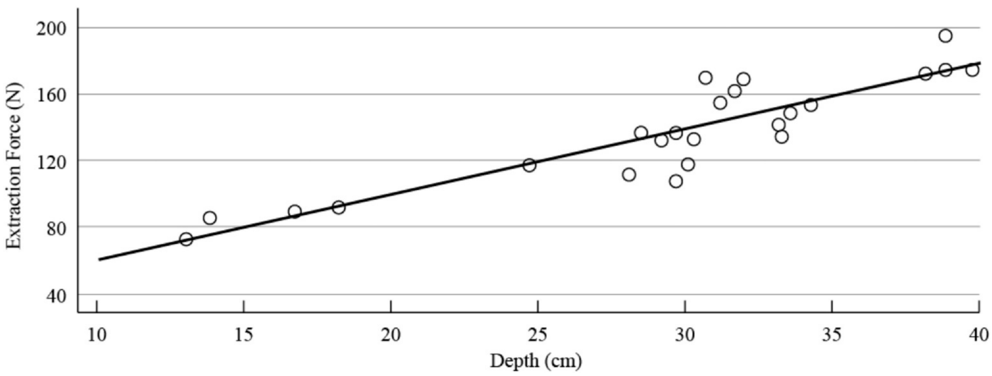

Fig. 11. Over the range of depths that were evaluated, the relationship between a pile's driven depth and the vertical force required to remove it is approximately linear.

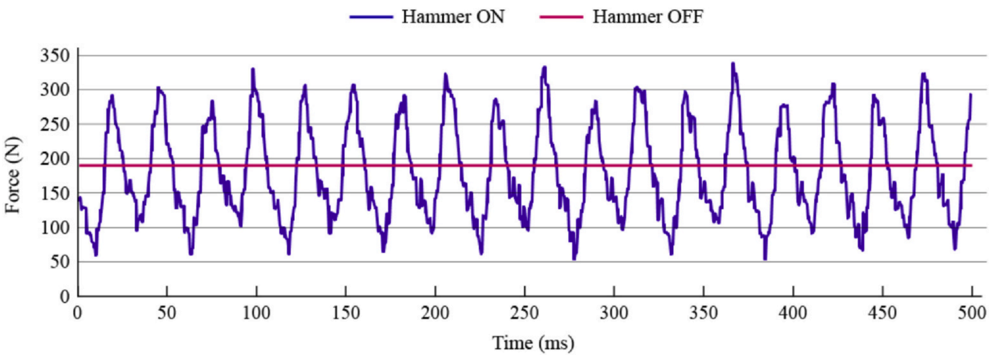

Fig. 12. The downward force exerted by the robot (with and without the vibratory hammer powered on) is illustrated with force plate readings. Readings were sampled at 2000 Hz, and the robot's pile driving parameters were set to a bias mass of 20 kg, eccentric mass of 240 g and a hammer speed of 2400 RPM when powered on. Details about the setup are provided in Appendix A.

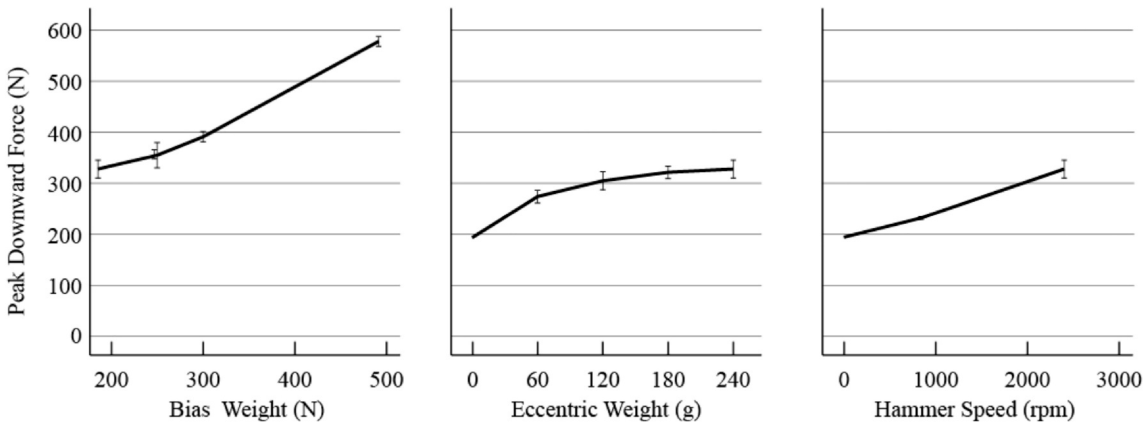

Fig. 13. Force plate readings, sampled at 2000 Hz, showing the average peak downward force exerted by the robot, while varying bias weight, eccentric weight, and hammer speed. These values are determined by averaging the peak downward force for each wave cycle over a 1-s interval of operation.

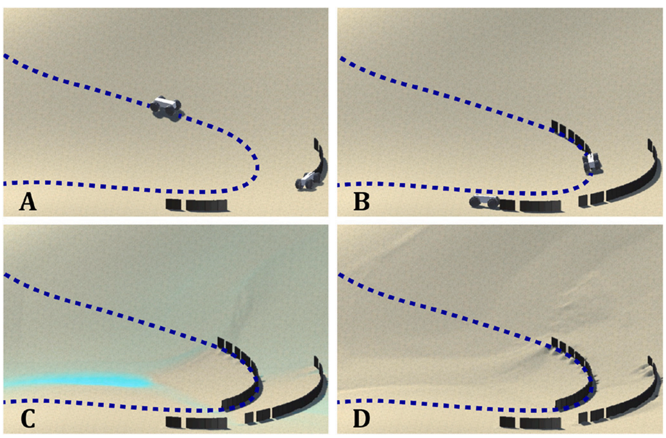

Fig. 14. Snapshots from an example trial conducted within the custom simulation platform. (A) A robot advances forward, adjusting its steering such that it maintains constant elevation, approximating a contour line (dashed blue). (B) The robot installs piles where its radius of curvature is less than 14 m. (C) A hydraulic erosion routine transports water and sediment downhill. (D) Resultant terrain. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Simulations are conducted on three 100m × 100m (1Ha) sample terrains selected from sites in the US, each representative of a different type of landscape where check dams are used: arid regions prone to desertification (Fig. 15A), eroding peatlands (Fig. 15B), and mountaintop sites stripped of natural vegetation (Fig. 15C). Details of the specific terrain samples are provided in Appendix B. Each terrain is subjected to three conditions: (1) no intervention, (2) check dams with locations determined manually in advance, and (3) check dams with locations determined by robots on-the-fly, responding to conditions as they encounter them. Conditions 2 and 3 feature a total of 100 m of check dams installed in each terrain. For condition 2, the predetermined check dam positions for Terrain A are taken from the actual locations on the site of a prior study on the effectiveness of check dams [25]. The predetermined positions for Terrains B and C are placed intuitively using similar guiding principles as found in Terrain A (placing 20 check dams, each 5 m in length, in approximately equal spacing along the apparent concave features of the terrain). For condition 3, 10 identical robots are initialized with random positions and orientations. Robots then locomote across the terrain, maintaining a constant elevation by steering to travel across the slope. As robots effectively trace contour lines along the terrain, they selectively install sheet piles where the contour line has a small radius of curvature (under 14 m). This criterion is expected to have the effect of locating check dams in the concave features of the terrain where water flow and sediment runoff should be greatest. Each robot installs a total of 10 m of sheet piles (taken to be the payload capacity), such that the scale of the total intervention is 100 m, matching that of condition 2. If a robot arrives at an edge of the simulated terrain area, it is replaced at a random location on the opposite edge, from which it continues its contour-following behavior until 10 m of piling has been installed.

Next, a simulated hydraulic erosion routine is performed on the terrain. This erosion simulation is based upon widely published algorithms, especially the method first presented by Musgrave et al. [30]. The routine involves overlaying bitmap layers (500 × 500 resolution in our simulations) that represent terrain height, sediment, and water. Simulations begin by initiating "water" to each pixel of the water bitmap. As water then flows downhill (i.e., moving from its current pixel to neighboring pixels, repeated over many iterations), it acts upon the "sediment" layer, either depositing or eroding sediment according to a predetermined "sediment capacity" constant. Since water is assumed not to flow through a check dam, pixels on opposite sides of a

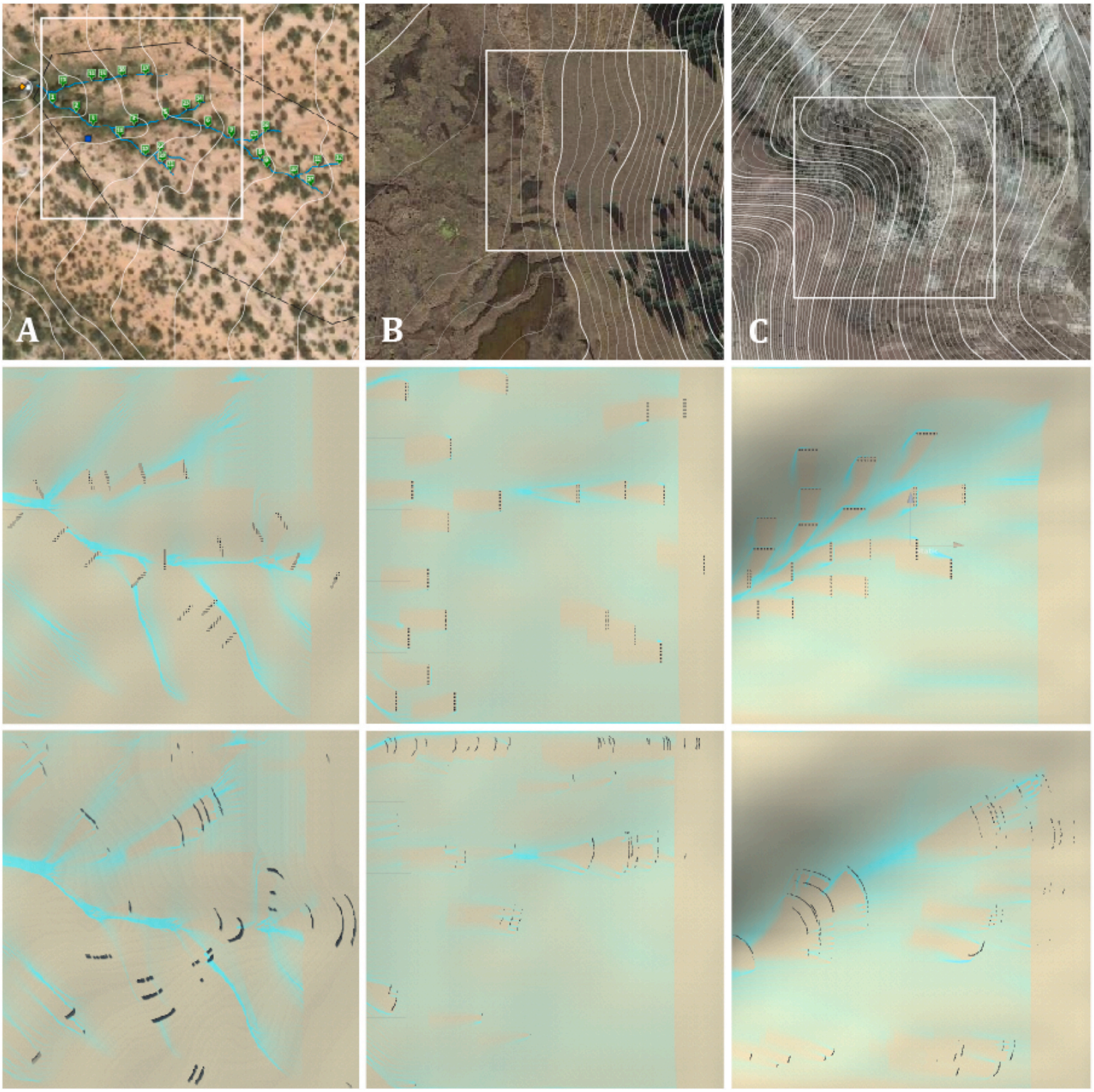

Fig. 15. Erosion simulations on terrains based on GIS data for real landscapes of types where check dams are used: (A) arid regions, (B) eroding peatlands, (C) bare mountaintops (see Appendix B for details). Top row: each 100m × 100m terrain sample and its immediate surroundings. Green markers in (A) are the sites where check dams were placed in this landscape in reality for restoration research purposes [25]. Contour lines are shown at 1 m intervals. Second row: snapshots of trials where check dams were manually placed on the terrain following the example of the existing intervention in (A). Third row: check dams placed by robots responding to conditions they encounter. Water (blue) is seeded to each pixel and flows downhill (right to left) over the course of the erosion simulation; these snapshots were taken approximately 20% of the way through each trial, resulting in the lack of water along the right edge of each image. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sheet pile are not considered neighbors and therefore prevented from exchanging water and sediment, which results in an accumulation of both. Water flows that do not have a downward path diminish according to a preset infiltration factor, depositing sediment to the terrain height map. A more mathematically complete description can be found in prior work [15].

Table 1 reports the results of five trials for each intervention on each of the three terrains. "Sediment Lost" is a measure of all of the sediment that was carried off of the terrain during the erosion routine. "Sediment Displaced" is calculated by finding the difference in height for each pixel between the start and the end of the erosion routine. Values for all pixels with a negative difference (i.e., pixels that lost elevation) are summed, which gives a measure of sediment that has shifted within the landscape but not eroded away completely. The results show that the effectiveness of the tested interventions varies based on topography. For the gently sloping Terrain A, the check dams placed manually

Table 1
Effects of hydraulic erosion on sediment (m).

	Intervention:	(1) None	(2) Manual	(3) Reactive
A	Sed. Lost	7.6	4.7	5.4 ± 0.6
	Displaced	62.3	54.5	55.1 ± 1.8
B	Sed. Lost	24.7	12.2	16.8 ± 0.3
	Displaced	69.2	62.5	62.3 ± 0.7
C	Sed. Lost	23.7	11.8	10.5 ± 3.6
	Displaced	77.9	72.8	68.3 ± 4.0

(informed by a previous study [25]) retain 38% of the soil that would otherwise be washed away, while check dams placed by robots following contours retain only 28%. A starker contrast is observed in Terrain B (a steeper but uniformly sloping terrain), where manually placed dams retain 51% of soil compared to 32% retained by robots following contours. However, for the steep and concave topography of Terrain C, the contour-following robots place check dams that disrupt the singularly concentrated flow path, yielding no significant difference ($P = 0.46$) at retaining soil (56%) when compared to the manually placed dams (50%). In all trials, a significant amount of sediment is still redistributed within the terrain, however, carried down from higher points to accumulate behind the dams.

3. Post driving and sand fencing

Posts (including stakes, poles, rods or other linear elements) are commonly used in infrastructural construction and land management for a wide range of fencing applications, in addition to providing anchoring support for larger structures. Post driving, the task of sinking non-interlocking discrete linear elements into the ground, is a constituent task of nearly every construction project. However, posts can also form useful structures on their own, e.g., in the form of sand fencing, used as scaffolding to build dunes along coasts. This section presents a modification of Romu for driving posts of multiple shapes and materials in natural environments. Section 3.1 describes the context and motivation for this application, Section 3.2 describes the design and fabrication of novel hardware needed to accomplish this task, and Section 3.3 describes the results of physical tests in realistic environments in order to characterize the effectiveness of the hardware. Section 3.4 describes terrain-scale physical simulations in a wind tunnel used to better understand how different arrangements of robotically installed sand fencing might foster dune building.

3.1. Context and motivation

Post driving is an ancient method of anchoring structures to the earth, and is a critical task for all industries that work with land. Automating post driving could be useful for a wide range of applications, especially in remote areas. Common examples of light-duty post driving include fencing, stakes for tents and other temporary structures, surveying, staking coir logs for erosion control, and other land management tasks. Specific examples are given in Fig. 16. These examples show post driving as a component of construction projects that require additional tasks. Even so, automating these kinds of tasks is important because they would be necessary in any fully autonomous construction project. However, some structures built by post driving are useful independent of auxiliary construction tasks. One such structure is sand fencing, an important intervention for applications like coastal defense or combating desertification, and one that can be composed solely of small driven posts.

Coastal states like Massachusetts are spending an increasing amount of tax dollars on coastal resiliency, especially as sea levels rise, storms become more frequent and the global demand for sand increases. The Massachusetts State's Office of Coastal Zone Management (CZM) promotes the installation of "soft" measures (such as artificial marshes and

Fig. 16. Readily available post types and example applications. (A) Posts used in this study and reported in Table 3, from left to right: rebar, T-post, 3/4in square post, fence slat (flat), fence slat (pointed) and wooden shim. (B) Rebar used to support a small retaining wall. (C) T-posts used for fencing. (D) Wooden posts used for fencing or cordoning.

sand fencing) as opposed to "hard" interventions like seawalls, which transfer the erosive effects of waves to neighboring properties [31]. (The kinds of sheet piling walls described in Section 2 are thus better suited to arid environments or peatlands than to seawalls.)

Sand fencing works by leveraging natural energy to transport sand to desired locations, thereby establishing dunes. Sand fencing mimics the functionality of vegetation such as dune grass, which reduces the velocity and disrupts the laminar flow of the landward winds that pass through it, thereby causing the airborne sand to fall and locally accumulate in both the windward and leeward directions of the fence [32].

While sand fences can be made of porous mesh materials for use in arid regions (Fig. 17C), coastal applications typically consist of one or more rows of wooden slats (Fig. 17A). The dimensions and spacing of this type of sand fencing have been the subject of scientific studies, using both empirical experiments and computational simulations. These studies generally recommend a porosity (ratio of total permeable area to total surface area) of 40–50% for sand fences [34] and suggest that porosity has a greater bearing on the sand fence's effectiveness than its height. Sand fence height has little effect other than to determine the maximum potential elevation of the accumulation, which in practice is rarely achieved [34,35].

The kind of sand fencing typically seen in coastal areas in the United States can be traced back to the Civilian Conservation Corps during the Great Depression. The construction of overly large, heavy-duty sand fences (Fig. 17A) was excessively labor-intensive. However, requiring a great deal of labor was advantageous in the context of the CCC program, for which creating low-skill jobs was a primary objective [36]. Despite its heavy labor requirement, this method has become the

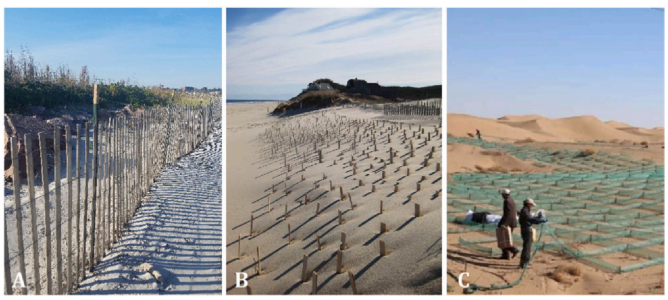

Fig. 17. Examples of sand fences, composed either partly or entirely of posts driven into the ground. (A) Typical sand fencing is installed in a linear or zig-zag pattern along coasts, and consists of large posts driven several feet into the sand, with rolls of 4 ft. slats attached to them. (B) A barrier dune restoration in Truro, MA where heavy posts are not used; instead 14in wooden shims are driven directly into the sand with a mallet. [33]. (C) An example of short sand fencing installed in China's Kubuqi desert in order to reduce dust storms and slow desertification, with mesh fabric anchored by posts.

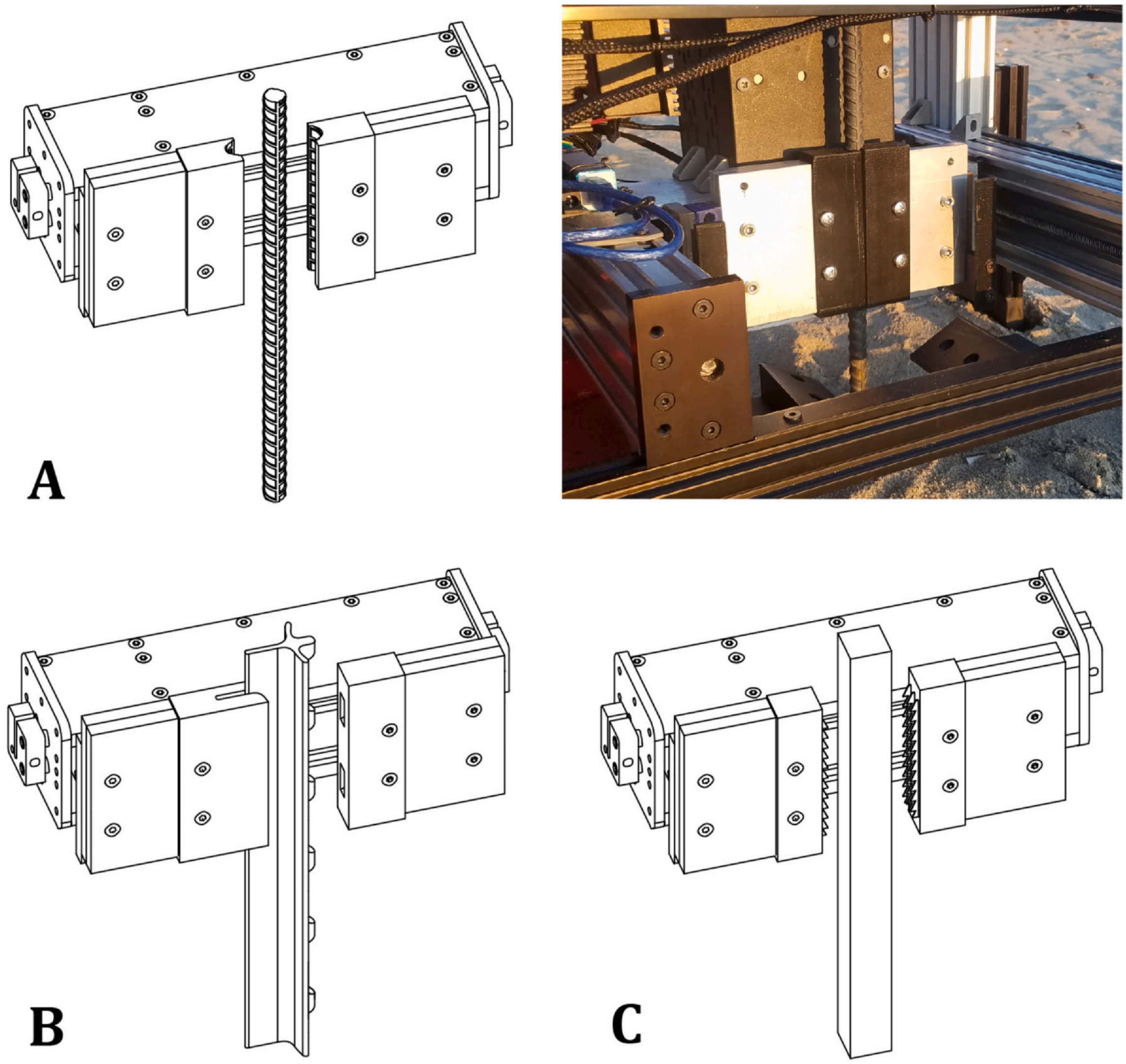

Fig. 18. (A) Detail of gripper design for driving rebar, (B) T-posts, and (C) wooden posts of a range of dimensions. The photograph in (A) shows the gripper in use for field tests, after it has closed around a length of rebar.

default mode of intervention, due in part to its constituent materials becoming readily available. Specifically, rolls of 4 ft-long wooden slats tied together with twisted steel wire were developed for this particular method of sand fencing (Fig. 17A), and became fixtures at coastal hardware and building supply stores. These rolls of slats are nailed to wooden posts that must be driven deep into the ground (the most labor-intensive part of the process) in order to withstand the wind force exerted on the tall slats. While this method can be effective at building dunes in some contexts, it is also used for other purposes like directing pedestrian traffic, which may instill in the public a general misunderstanding of its primary utility. While this primitive method has added some value to coastal protection efforts over the last century, the current increasing strain on coastal infrastructure draws attention to its insufficiency and may provide a motivation to develop new and innovative approaches.

The dominant mode of sand fence installation since the Great Depression has required a centralized workflow, producing a linear fence using conventional post-pounding equipment. More recent innovations, however, suggest that installing low-profile distributed arrays of posts at more frequent intervals can be more effective at restoring barrier dunes than the dominant method (Fig. 17B). Experiments with smaller-scale sand fence installations, using 14in wooden shims (commonly available in hardware stores) to disrupt the laminar flow of landward wind (Fig. 17B), resulted in accumulation of 10in of sand in ~2 weeks, allowing for another array to be installed atop it at a higher elevation. This process continued until over 20 vertical feet of barrier dune had been restored, a result that would not be easily achieved with the conventional method of sand fencing [33]. Further, such shims can be driven directly into the sand with a mallet, eliminating the need for driving the heavy posts that are typically required to support 4 ft. fences in strong winds [37], resulting in a far less labor-intensive process. This new method would be well-supported by small-scale autonomous robots capable of installing such low-profile arrays.

Further afield, sand fencing has been demonstrated to be effective at halting dust storms and curbing desertification in arid regions. This has been demonstrated most extensively in China, where centralized government has enabled some of the world's most ambitious land restoration projects over the past several decades (Fig. 17C). These interventions have had measurable impact on stabilizing the rate of desertification [38]. Other regions of the world prone to desertification could presumably benefit from such interventions, but lack China's workforce and centralized state planning. Extensive as China's interventions are, they are still limited by a shortage of available labor and the available tools and techniques.

Protecting coastal resiliency, preventing hazardous dust storms, and

Table 2
Soil compressive strength at test sites (*KPa*).

Depth (*cm*)	Dry sand	Wet sand	Soft soil	Hard soil
0	10 ± 0	40 ± 4	67 ± 10	134 ± 17
5	29 ± 0	48 ± 7	96 ± 9	220 ± 14
10	44 ± 11	105 ± 24	172 ± 21	249 ± 10
15	84 ± 8	79 ± 22	211 ± 25	287 ± 21
20	107 ± 16	167 ± 122	220 ± 19	– –
25	121 ± 15	205 ± 135	239 ± 17	– –

reversing desertification are disparate infrastructural objectives sought in very different parts of the world. Yet the desired effects of these interventions could be achieved with the same kind of automated sand fence installation.

3.2. Hardware design

This section builds upon the hardware developments described in Section 2.2, and preserves the key technical achievements of the miniaturization of the vibratory hammer mechanism typically used in heavy equipment, as well as the morphology that delivers a more efficient distribution of mass for driving material into soil. We describe how the gripper used in Section 2 is modified to accommodate a range of readily available building materials, including 14in wooden shims that could be used for sand fencing of the kind outlined above.

Both sheet piles and posts are typically driven from the top rather than from the sides; this method presents a limitation in that it requires a machine that can be positioned at least as high as the material that needs to be driven. As described in Section 2.2, this limitation can be overcome by gripping a sheet pile from the sides, though this requires the design and fabrication of custom sheet piles, as in practice, nearly all commercially available sheet piles are straight linear extrusions that are not conducive to being gripped from the sides. Unlike sheet piles, a number of readily available post materials are fabricated with features that facilitate gripping from the sides. Rather than designing a custom post, a sampling of these commonly driven materials were purchased from a home improvement retailer (Fig. 16A), to explore how the robot could be used for a range of common construction tasks. Steel reinforcing bar (rebar) (Fig. 16B) is commonly used for temporary construction tasks like securing formwork for foundations as well as staking large tents or other structures. Studded T-posts (Fig. 16C) are sturdy steel posts that are commonly used for many types of fencing. The primary utility of the studs is for attaching fencing, but they can also be used to facilitate gripping while being driven into the ground. Wooden posts (Fig. 16D) are commonly used for gardening, light fencing or cordoning. Finally, wooden slats such as 14in cedar shims can be useful for building dunes when driven directly into the sand as described above (Fig. 17B).

In order to accommodate this range of commonly driven materials, three modified grippers were designed and fabricated. Fig. 18A shows a variation designed to grasp 1/2in rebar, while Fig. 18B shows a variation for T-posts. The gripper design in Fig. 18C features serrated steel that can be pressed into wooden posts (including sand fencing slats and shims) with enough force to drive them without slipping. The robot's performance at driving these materials in a variety of terrains is presented in Table 3. The wooden post gripper (Fig. 18C) in particular would be useful for driving wooden shims for the application of sand fencing. A full demonstration of this application would require a modification of the hopper to hold a cache of sand fence shims instead of sheet piles. The recommendation for sand fencing shims is to leave 10in (25 cm) exposed above the surface. This would require either increasing the robot's clearance (e.g., with simple hardware modifications like switching to larger wheels or adding stand-offs), or modifying the chassis to form a U-shaped profile (as seen in Fig. 8) such that any exposed length will not interfere with further locomotion.

3.3. Field performance tests

The performance tests in Section 2 were conducted in a controlled laboratory setting, giving a characterization of the effects of varying the parameters of bias mass, eccentric mass and hammer frequency. However, as the robot is intended to operate in natural environments, this section is concerned solely with field tests.

Four locations for field testing were chosen to represent a wide range of locally available soils in environments where autonomous anchoring could be deemed to have some utility. Each location's soil penetrability (compressive strength) was measured with a penetrometer, which is pressed into the soil while a gauge reports the pressure required to do so. Compressive strength at relevant depths is reported in Table 2. Soil compressive strength is expected to have a negative correlation with driving capacity, though the utility of the vibratory hammer is expected to vary due to soil type. “Dry Sand” refers to a location in the dry supratidal zone of Revere Beach, MA, which represents an ideal candidate terrain for sand fence installation (only the top ~5cm is actually dry, covering damp sand below). “Wet Sand” was tested in the intertidal zone of the same beach. Note that while Revere Beach is a natural beach, it has been renourished several times since the 1950s, most recently in 1991 [39]. Renourishment projects provide only temporary relief, and may be designed to last several years to several decades depending on environmental factors [40]. Renourishment typically entails the placement of tens of centimeters of uncompacted sand on top of the existing beach. Sand in this state would have higher rates of penetrability than would be observed under natural conditions. By selecting a beach that has not recently been renourished, sediment profiles are more indicative of typical natural conditions, including mixed grain size with an abundance of embedded rocks and shells. “Soft Soil” refers to an untrod site on an urban campus, while “Hard Soil” refers to a more heavily trod site nearby. The driving parameters for all field tests in this section were a bias mass of 24 kg, eccentric mass of 240 g and hammer frequency of 2400 RPM. Trials were repeated five times for each variant. The average driven depth for different posts are reported in Table 3. After each trial, the force required to extract the post from the soil is recorded with a hanging scale and reported in Table 4.

Only the rebar went deeper in wet sand than dry sand. This is

Table 3
Driven depth of readily available materials (*cm*).

Post type	Example use		SA (cm^2)	Dry sand	Wet sand	Soft soil	Hard soil
	Application	Min. depth					
Rebar (1/2″)	Landscaping stake	15 [41]	1.3	18.5 ± 2.1	20.3 ± 1.2	21.5 ± 0.9	8.7 ± 1.8
T-post	Silt fence	30 [42]	3.5	12.7 ± 0.8	10.1 ± 0.2	6.8 ± 1.2	3.0 ± 0.4
Square wood (3/4″)	Wattle stake	15 [43]	3.6	12.0 ± 0.6	11.4 ± 0.4	8.7 ± 2.5	3.1 ± 0.4
Fence slat (flat)	Sand fence	8 [44]	1.9	11.9 ± 0.5	10.1 ± 0.3	5.2 ± 1.6	1.9 ± 0.5
Fence slat (pointed)	Sand fence	8 [44]	1.9	12.8 ± 0.5	11.5 ± 0.5	12.4 ± 3.3	3.5 ± 0.9
Wood Shim	Sand fence	8 [33]	0.6–1.9[a]	14.7 ± 0.7	11.3 ± 0.5	13.8 ± 2.4	5.4 ± 0.9

[a] The shim profile tapers along its length.

Table 4
Extraction force required for readily available materials (*N*).

Post type	Dry sand	Wet sand	Soft soil	Hard soil
Rebar (1/2″)	49 ± 4	48 ± 3	130 ± 13	74 ± 19
T-post	26 ± 3	20 ± 4	49 ± 14	14 ± 1
Square wood (3/4″)	17 ± 2	16 ± 1	40 ± 8	7 ± 1
Fence slat (flat)	18 ± 1	15 ± 3	17 ± 7	7 ± 3
Fence slat (pointed)	19 ± 3	15 ± 3	55 ± 24	8 ± 8
Wood Shim	17 ± 2	18 ± 4	56 ± 21	24 ± 4

because of a less penetrable rocky layer that was observed at ~10cm (see Table 2) that prevented the other materials from penetrating further.

All posts feature a tip fashioned to a 45-degree point, which is generally assumed to improve penetrability. Sand fence slats were tested both with and without a pointed tip (Fig. 16A); the point was found to allow for driving considerably deeper in soft soil (138%) and hard soil (84%), though the advantage was much less pronounced in dry sand (8%) and wet sand (14%). Note that the application of sand fencing requires wooden slats or shims to be driven 3–4in (~8–10 cm) into dry sand [33,44], a depth which is easily achieved with the robot in its default, least-weighted state (24 kg bias weight) for all considered materials. Likewise, there are landscaping applications [41] (Fig. 16B) as well as environmental surveying tasks [45,46] that only require rebar to be driven to depths of ~10–20 cm. These use depths are listed in Table 3 under 'Minimum Depth'. In further tests, the robot was outfitted with additional weights, doubling its bias mass from 24 kg to 48 kg. In this state, the robot was able to drive rebar to depths of 30–32 cm in soft soil. This range of depths has been found to be useful for anchoring meteorological stations [47], conducting geological surveys [48], and installing landscape features like staircases [49]. Other use cases may require even greater depths, which could be achieved either by further increasing the bias weight or by increasing the eccentric mass beyond the tested 240 g.

3.4. Terrain-scale characterization: Sand fencing

A considerable number of research studies have investigated sand fences and their influence on sediment transport and erosion, which generally focus on some combination of linear arrays of sand fences [34]. However, in spite of indications that linear arrangements might not be optimal in all cases, only minimal attention has been given to finding effective alternative geometrical arrangements of driven posts in order to maximize sand accumulation [33].

Wind tunnel studies were conducted to determine how a robot such as the one described in this work might drive posts in an arrangement that would be most effective in accumulating sand to build dunes. Specifically, the studies seek to verify literature reports of the effectiveness of rectangular sand fence slats arranged in a random matrix [33,44] as opposed to the conventional method of a linear row of slats spaced to achieve a 50% opacity recommended in literature [34]. The goal of these tests is to maximize sand accumulation for a given amount of raw material (i.e., wooden posts). Many of the use cases that we consider involve building dune elevations of several meters, requiring multiple layers of sand fencing to be installed. For these cases, evenly distributed sand accumulations with gentle slopes are desirable in order to facilitate further locomotion and construction of additional layers.

4. Materials and methods

The experimental setup for the wind tunnel tests is presented in Fig. 19, and consists of a sand deposition bed (A), a test zone (B) and an overflow zone (C). The experiments are taken to be at ~1:10 scale, such that interventions composed of posts with a 3 mm width roughly correspond to the 3 cm width of the sand fencing slats (Fig. 17B) that were reported in Table 3. The wind tunnel experiments were carried out with dry, loose sand of grain size 0.1 to 0.5 mm and a consistent, laminarized flow of air (234.4 m^3/h) to determine the amount of sand that is deposited within different regions for random vs. linear arrangements of slats. Each trial begins with all three sections of the wind tunnel empty of sand. Sand is then placed in the center of the deposition bed (Fig. 19A) in 50 g increments while the air continues to flow, waiting for each deposition to be blown clear before placing the next, until a total of 1000 g of sand has been added.

Many important aspects of the natural environment cannot be accurately captured by such a scale model test; sand depositions are influenced by tides and longshore (parallel to the shoreline) currents, winds are not constant in one direction, and the natural distribution of sand grain sizes cannot be recreated at a small scale. In certain cases restoration ecologists may use scale model studies to predict the effect that different fences may have on sand movement and accumulation [50], but these are unlikely to replace the more common practice of installing a small fraction of a proposed intervention on site at full scale. While the latter strategy provides a high-fidelity forecast of the effect of the intervention, it does not lend itself to extensive studies on the effects of different geometrical arrangements. Our scale model study is intended to provide an indication of how effective different geometrical post arrangements might be in future field deployments, rather than a quantitative model for any particular natural location.

A control trial was conducted without any posts in the test area to verify that the airflow was of a sufficient velocity to fully clear the test area of sand. As a point of comparison, some initial trials were conducted with both a solid fence and a porous mesh fence (50% porosity with circular openings), each 35 mm in height. Solid and mesh fences are not recommended for use in coastal regions because they impede the natural movement of dunes and are more disruptive of shorebird and turtle habitats than wooden slat fencing [37]. The solid fence collected an average of 316 ± 6*g* in the test area and 64 ± 6*g* in the overflow zone, while the mesh fence collected 329 ± 20*g* in the test area and 83 ± 11*g* in the overflow zone. These fences blocked the flow of wind, resulting in accumulated sand almost entirely on the windward side (see gray lines in Fig. 22).

Prior studies have suggested a suitable height for wooden slat sand fences to be ~50cm [34], but also reported that fence height has little impact on the rate of sand accumulation, and is relevant only in terms of the intended height of the dune [32]. In order to verify this finding, an initial study compared a single row of posts of 50 mm height with a row of posts of 35 mm height. As fence height was not the focus of this study, these trials were conducted with only a single replicate each. These tests revealed comparable sand accumulation for the two heights: the 50 mm posts accumulated 289 g in the test area and 118 g in the overflow zone, compared to 295 g in the test area and 115 g in the overflow zone for the 35 mm posts. Subsequent tests used 35 mm tall posts, corresponding to the 14in wood shims that were recommended in the literature for coastal dune building [33].

Our primary experimental setup consisted of posts arranged in four configurations presented in Fig. 20, each consisting of 13 posts. The single-row arrangement is spaced to adhere to the recommended ~50% opacity [34], while the spacing of the random matrix configurations range from ~10 mm to ~30 mm between posts. Five trials were performed for each variant and new random configurations were generated for each repetition. Following each trial, the shape and height of the sand deposition on the windward and leeward zones of the sand fence were recorded with side-view photographs, and the sand collected in the test area (B) and overflow zone (C) was weighed and reported in Table 5. The profile of sand accumulation for each tested sand fence configuration is illustrated in Fig. 22.

5. Results

The studies showed that the shape and amount of sand deposition is

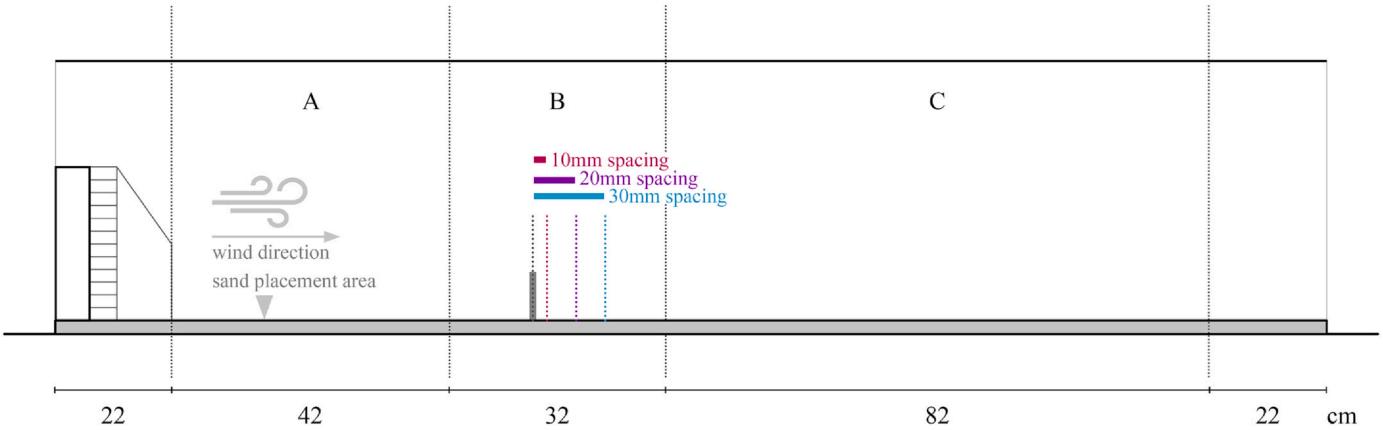

Fig. 19. The wind tunnel has a length of 200 cm, a depth of 70 cm and a height of 40 cm and consists of a sand deposition bed (A), a test area (B) and an overflow zone (C). Posts in various configurations are installed in zone B. Colored bars indicate the widths of the post matrices (shown in top view in Fig. 20).

considerably affected by the arrangement of the sand fencing (Fig. 21). The more widely spaced post arrangements resulted in broader accumulations within the test area, as well as more sand deposited in the overflow zone.

The dune shape resulting from the single row of posts was more limited locally than with the random post matrices, forming a steeper incline in the immediate vicinity of the sand fence. Such an incline could complicate later rounds of post installation (robot locomotion on a steeper sandy slope may be more challenging), as would be needed for large-scale dune building. The total amount of sand accumulated by the 10 mm random matrix was comparable to the amount accumulated by the single row of posts ($P = 0.7$), though it was distributed over a slightly wider area (Fig. 22). The sand collected by the random matrix with 30 mm spacing formed a more evenly distributed accumulation (which is desirable from the standpoint of supporting additional sand collection), though the total accumulated amount was significantly less than that of the single row of posts ($P < 0.01$).

When depositing a total of 1000 g of sand, none of the post arrangements accumulated more than 15 mm of dune elevation (Fig. 22).

Table 5
Deposited mass of sand (*g*).

Post arrangement	Test area (B)	Overflow Zone (C)	Overall
Random matrix:			
10 mm spacing	294 ± 34	127 ± 6	421 ± 37
20 mm spacing	249 ± 29	142 ± 10	392 ± 33
30 mm spacing	227 ± 16	145 ± 19	372 ± 22
Single row	303 ± 16	109 ± 6	414 ± 14

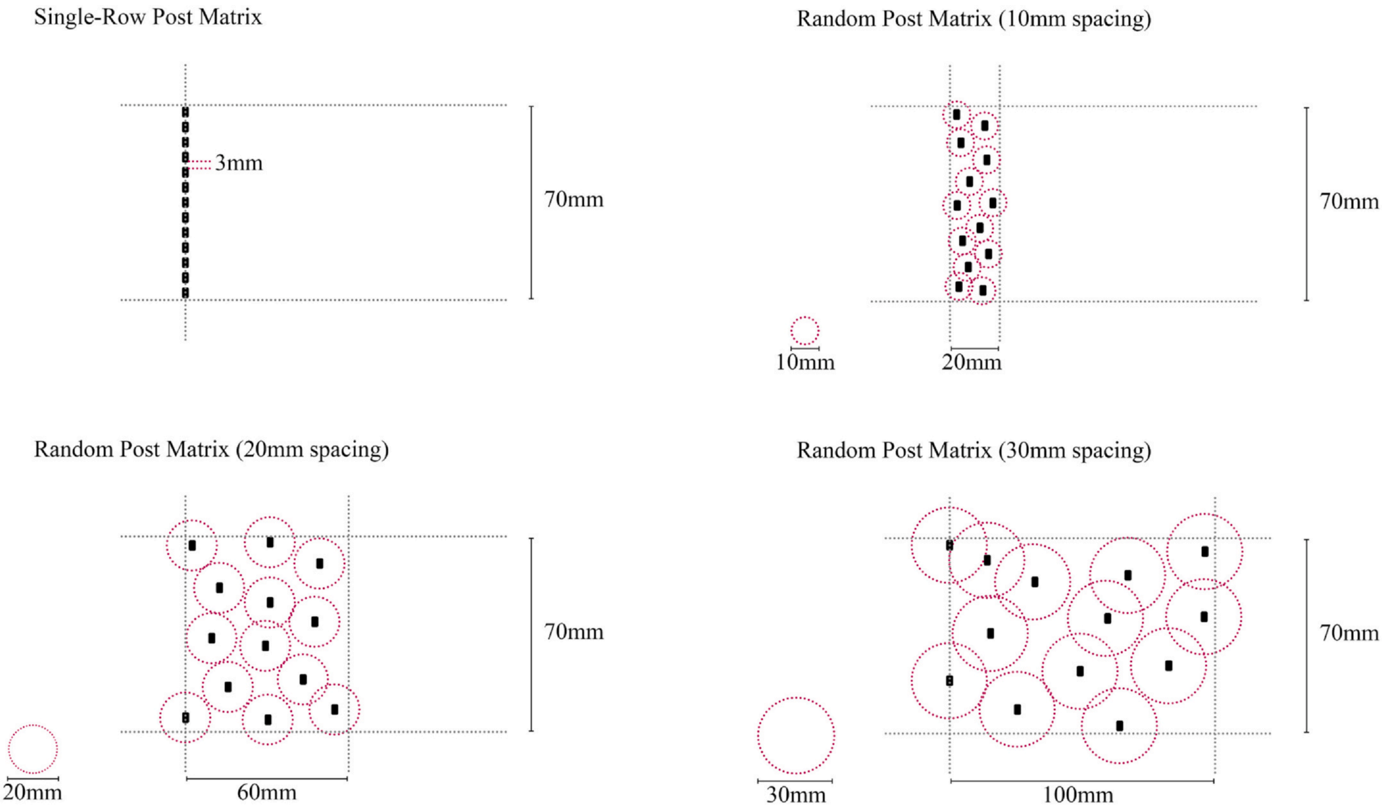

Fig. 20. Top view of the tested post configurations: single-row arrangement and random matrix configuration with 10 mm, 20 mm and 30 mm spacing.

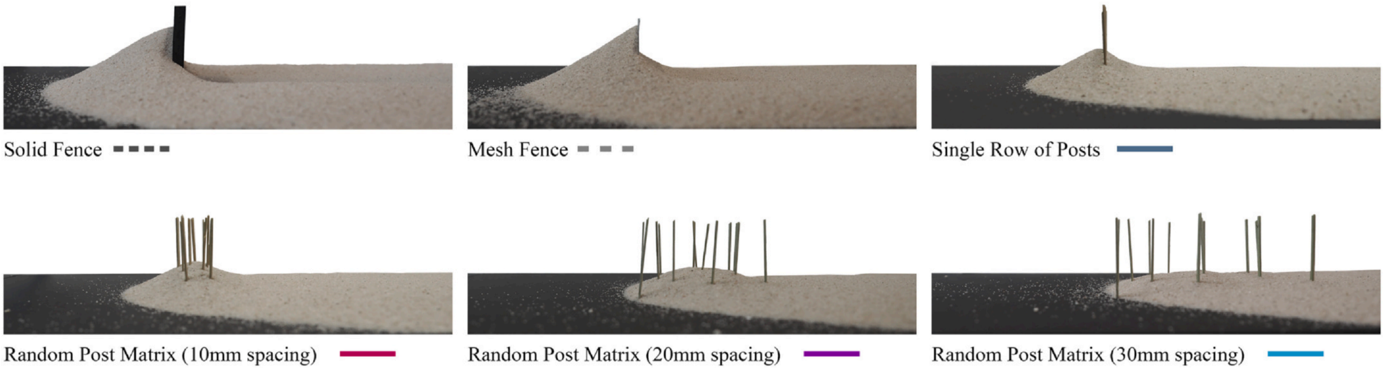

Fig. 21. Photographs of typical sand accumulations with the tested post arrangements. Line style and color shown for each condition refers to the graph in Fig. 22.

The lower height of the accumulations formed by posts arranged in a 30 mm random matrix means that more of the posts remain exposed, suggesting that if allowed to collect sand indefinitely, the same 13 posts arranged in this fashion could ultimately collect a greater quantity of sand than if they were arranged in a single row. To test this conjecture, a single exploratory trial adding a larger amount of sand to the wind tunnel was conducted. First, with a single row of 13 posts, sand was added as previously described until the posts became completely buried and therefore unable to directly affect the flow further. This occurred after the deposition of 4000 g of sand; 1449 g was collected in the test area. Next, a 30 mm random matrix was installed, and the same amount (4000 g) of sand was deposited. This arrangement collected only slightly less sand (1420 g), while the posts still had ~50% of their length exposed and thus available to capture additional sand. This result indicates that a given number of posts arranged in a wider random matrix should be able to capture more sand over a longer period of time than when arranged in a linear row.

The results indicate that different slat configurations and their capacity to accumulate sand and build dunes depends on their arrangement and spacing. A linear arrangement quickly accumulates a large amount of sand locally, but does not as effectively facilitate further build-up to restore beach elevations. The random post matrix leads to a more evenly distributed dune formation over a broader area, which would facilitate the addition of multiple layers of sand fences to reach elevations of several meters as typical of barrier dunes. The results of the differently spaced matrices indicate that posts in a closely-spaced arrangement yield accumulations comparable to that of a linear fence, whereas widely-spaced arrangements do not accumulate sand as quickly. The geometry of the accumulations in our scale model tests qualitatively matches that reported in previous field studies [33,44]. Local restoration ecologists should be involved in any planning for such interventions, as appropriate spacing will likely vary between sites, and different restoration goals (e.g., intended dune height, potential impacts on local flora and fauna, etc.) will likely require different arrangements.

6. Conclusions

The primary contributions presented in this paper include novel hardware design, performance evaluations in both lab and outdoor environments, and terrain-scale characterizations using computer simulations and physical scale model tests. Section 2 described typical applications for the use of sheet piling and presented the design of Romu, a robot capable of driving interlocking piles into soil in order to build a continuous sheet piling wall without human intervention. Unlike conventional methods of driving piles, this robot is capable of using up to 100% of its body weight for driving piles. Conventional equipment requires driving from the top, such that the workspace of the pile driving equipment must be at least as tall as the pile it drives. Romu, on the other hand, grips piles from the sides and is therefore theoretically capable of driving piles of any arbitrary length. Pile driving is accomplished with the use of a miniaturized vibratory hammer (a tool commonly used for large-scale pile driving).

Section 3 presented hardware designed to drive posts instead of piles, still leveraging the unique ability to drive material by gripping from the sides and thereby allowing posts of any arbitrary height to be driven. While sheet piles do not come readily available to consumers, many types of posts do, and are often used in small residential construction, landscaping or gardening tasks, in addition to large-scale infrastructural projects. Rather than needing to design a custom post, it

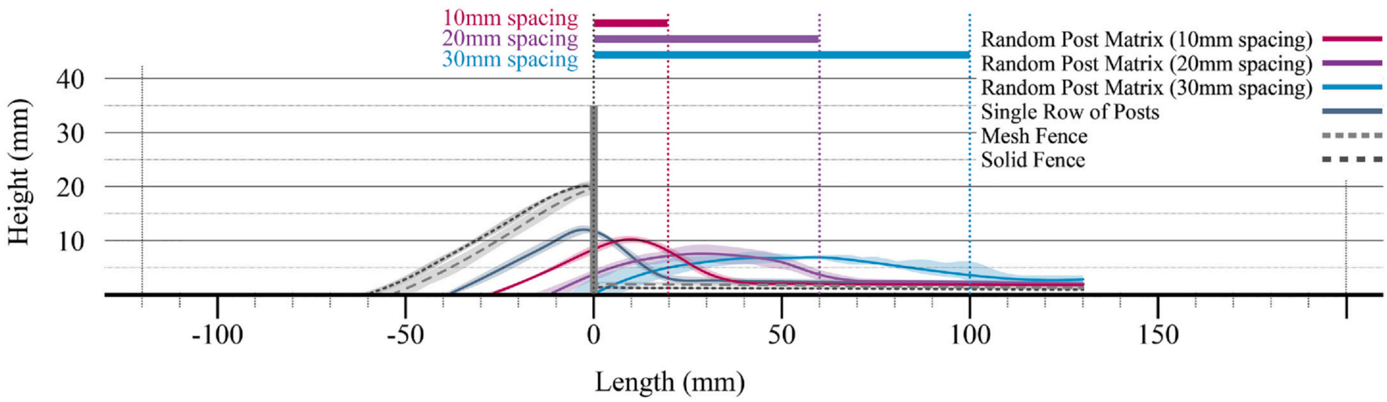

Fig. 22. Comparison of the sand accumulations with the tested post matrices: single-row arrangement (solid gray); random matrix with 10 mm (red), 20 mm (purple), or 30 mm (blue) spacing; porous mesh (gray, dashed) and solid fence (gray, dotted). Shaded regions indicate the minimum and maximum observed accumulation height profiles over 5 replicates. Colored bars at top indicate the widths of the post matrices (shown in top view in Fig. 20). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

was found that many readily-available building supplies like rebar and T-posts already exhibit features that can facilitate gripping from the sides. This property was embraced with the design of three new gripping mechanisms, customized to grasp steel rebar, T-posts, and wooden posts of a range of dimensions. These grippers were capable of repeatably grasping the posts at different heights and driving them into soil without slipping. The demonstrated ability to adapt the fundamental hardware contributions of small-scale vibratory excitation, side-gripping and efficient mass distribution to a variety of land management interventions and soil types suggests that this basic morphology could be further adapted to other applications and terrains.

The performance of the vibratory hammer was characterized with force plate sampling, lab tests and field tests. Force plate measurements revealed the relative influence of the three parameters of (1) bias weight, (2) eccentric weight and (3) hammer frequency. Increasing any of these parameters has the effect of increasing the maximum downward force, though hardware constraints prevented testing eccentric weights and hammer speeds greater than the reported values. The ability to increase these parameters would expand the range of possible use cases (to include, e.g., driving T-posts to depths greater than 20 cm for fencing applications). A future redesign of the vibratory hammer will take this into account. Lab tests (Section 2.3) considered these same three parameters while driving sheet piles into a sandbox. The results of these tests confirmed that increasing any of these three parameters increases the ultimate driven depth of the pile, approximately linearly over the range tested. Finally, field tests (Section 3.3) demonstrated the robot's ability to drive readily available posts into different types of soil, suggesting these mechanical techniques may be broadly useful towards automating a range of common sustainable land management and construction tasks.

One of the challenges of land management automation is the difficulty of predicting the effectiveness of full-scale deployments, so computer simulations and small-scale physical experiments were employed to gain a better understanding. In simulations, the effectiveness of check dams placed by robots following contours (installing check dams where surface curvature is high) was compared to manually placed check dams. It was found that the manually placed check dams performed ~10–20% better for 2 of the 3 terrains, while it performed comparably for a third terrain. While these results suggest the potential value of having robots act in response to conditions encountered on site, without the need for careful preplanning and precise execution, neither of these strategies were particularly optimized. In future work we will develop both manual and autonomous placement strategies to better understand the affordances of each. For the application of sand fencing, computer simulations are notoriously limited when it comes to modeling saltation and deposition that characterizes sand movement in tidal zones. Therefore, wind tunnel tests were used to study the impact of various configurations of sand fencing and their ability to accumulate sand and build dunes. The results suggest that placing sand fencing in single rows can be more effective for quickly building small dunes, while the results of posts arranged in random matrix arrays support past field work that showed an effective approach for multi-layer installations needed to restore ~20ft of dune elevation [33].

Future work will include a new hammer design allowing for greater eccentric mass, which will increase the maximum pile-driving depth while maintaining a relatively low bias weight. Other hardware parameters should be tuned to task- and terrain-specific requirements based on the findings presented here; for example, a suitable bias weight should be great enough to facilitate effective downward force, but small enough to enable locomotion on sandy terrain. Future work will also include multi-robot field deployments using differential GPS for localization. While the ~10–15 m accuracy of conventional GPS would not be sufficient for most construction tasks, Differential GPS is a technique that can achieve millimeter-level accuracy by comparing a rover's GPS reading to that of a base station in a fixed location. In a full-scale demonstration, the supply cache of piles or posts would serve as the base station as well as the origin point for navigation. We believe that such full-scale demonstrations are needed to better understand the design parameters, power requirements and material considerations for full life-cycle analysis of multi-robot systems in challenging outdoor environments.

While automated anchoring has been largely overlooked, we have demonstrated steps towards its realization and believe it would be an integral component of a fully autonomous construction project. Achieving a fully autonomous complete construction system would require substantial advances in autonomy and coordination of site preparation, anchoring and superstructure assembly. Furthermore, it is not obvious that the current set of building materials and heavy machinery that have been developed to facilitate human participation in construction will optimally support increasing automation, as opposed to developing new tools and techniques expressly for autonomous construction.

This paper has demonstrated a limited range of construction tasks that could be facilitated by such new tools. As widespread adoption of new technologies takes time, further consideration should be given to which construction tasks should be prioritized for automation. The autonomous installation of check dams such as those presented in Section 2 might have the greatest impact in regions prone to desertification where human presence is challenging. For such an application, Romu might need to be redesigned to incorporate, e.g., a U-shaped chassis to allow for driving piles of arbitrary heights, a hopper capable of carrying more than three sheet piles, piles made of a biodegradable material, wheels designed for such terrain, a self-charging system, and a localization and navigation system that has been optimized for that kind of landscape. While sand fencing applications such as those presented in Section 3 show considerable promise, land along coasts is often composed of small parcels, which presents a barrier to large-scale automation. Exceptions include barrier islands off of the Louisiana coast, which are critical for tempering storm surges yet are under constant threat of eroding away. These mostly vacant islands are maintained by the government, which regularly funds multi-million dollar dredging operations as well as the installation of many miles of sand fencing. The scale and remoteness of these projects makes them candidates for autonomous solutions that could, e.g., install and maintain sand fencing on abandoned islands, thereby extending the longevity of the island before it needs to be renourished with sand acquired from dredging operations. However, federal regulations require use of traditional sand fencing products and installation methods, precluding opportunities for innovation.

While structures like check dams or sand fences can be built by pile driving alone, posts and piles are most typically employed as constituent pieces of more complex construction projects. An important direction for future work will be cooperation with other types of robots capable of executing other construction tasks. An initial demonstration might consider robotically-driven sheet piles as retaining walls, holding back soil on one side of a sheet piling wall while an excavator robot removes soil on the other. Other demonstrations could consider driven posts as a foundation for the subsequent construction of a superstructure (sheet piles are not commonly used for this purpose). In order to drive piles capable of supporting design loads typical in commercial construction, the robot's bias weight and eccentric weight would likely need to be considerably increased. The discrete posts would then need to be connected by a pile cap (a structure that evenly distributes superstructure loads to piles). While pile caps are most often made of cast-in-place concrete, a similar effect can be achieved by connecting the piles with capping beams, which may be more readily achieved by robotic manipulators.

This work supports a general theme of, when possible, using natural forces and processes to achieve desired ends. In the two applications we consider, check dams harness the same erosive forces that create incising gullies to fill them and redirect water flows, while sand fences harness wind energy to accumulate sand in desired locations. These interventions can be seen as part of a larger trend of leveraging natural energy sources to facilitate infrastructure projects that would otherwise be too costly or labor-intensive to execute. An example is the Zandmotor (Sand motor) project, which uses tidal currents to supply the energy needed to redistribute a massive amount of sand along the Dutch coast [51], and is being replicated elsewhere [52]. We believe that precise interventions performed by distributed task-specific autonomous robots could be an enabling addition to this trend and an essential tool in the persistent struggle to mitigate or even reverse the adverse effects incurred by climate change. We hope to inspire civil engineers, ecologists and other infrastructure professionals to conceptualize and propose future autonomous interventions in pursuit of this goal.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Evelyn Simak 2008.

Fig. 3: (A-B) V. Polyakov ©2014; (C) Dehradun Watershed Management Directorate ©2014; (D-E) Moors for the Future Partnership ©2005; (F) Nilex Inc. ©2014.

Fig. 17 (A) N. Melenbrink ©2019; (B) G. Peabody ©2015; (D) Hightop Inc. ©2019.

Appendix A. Force plate setup

An array of force plates was used to characterize the forces transmitted by the vibratory hammer to the sheet pile (Fig. A.1), as reported in Section 2.3. These force plates are permanently installed in the configuration shown and cannot be moved, so isolating the force due to the sheet pile alone was not possible. In order to avoid confounding damping effects, the wheels are removed, allowing the rigid base of the linear actuator to rest directly on the force plate.

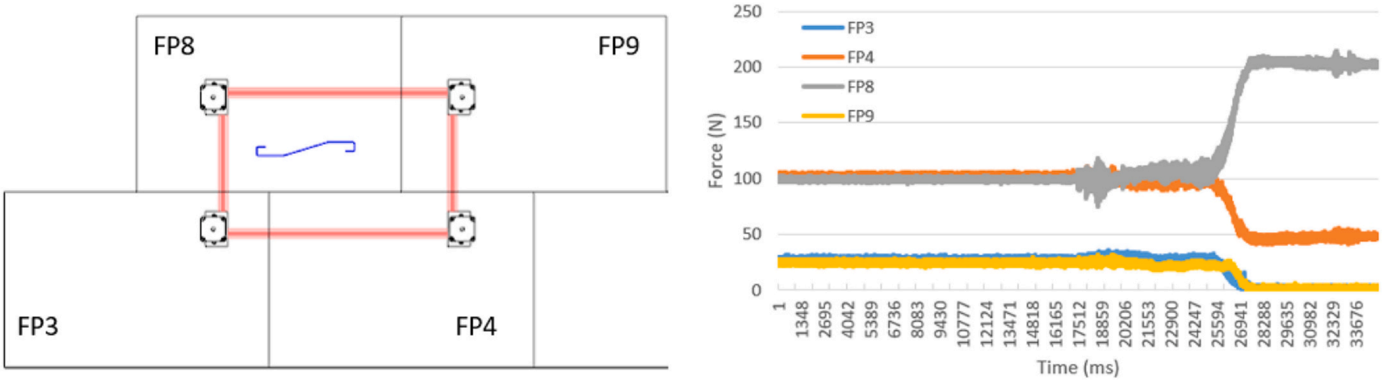

Fig. A.1. (A) Romu positioned on an array of force plates. (B) Force plate readings as the robot lowers a pile to make contact with the ground.

The sequence shown in the plot in Fig. A.1B begins with a sheet pile tightly held in the gripper, but with all four linear actuators equally extended such that the pile does not touch the plate. In this configuration, FP4 and FP8 each support ~40% of the weight of the robot, while the remaining ~20% is split equally between FP3 and FP9. The linear actuators are then retracted until they are higher than the bottom edge of the sheet pile, transferring some amount of the load from each such that the sheet pile presses firmly against FP8 and carries approximately 80% of the weight of the robot, with the remaining 20% supported by the opposite linear actuator (FP4). The force plate readings reported in Figs. 12 and 13 give the values measured by FP8 after the transient period shown (later than ~27 s in this plot).

As different bias weights are attached to the robot, the balance of the load between FP8 and FP4 may shift. This would also be observed during normal operation; the ideal robot morphology is one where the pile is gripped directly at the center of mass.

Appendix B. Terrain data processing

Simulations are conducted on terrains sampled from landscapes of types where check dams are commonly used. Elevation data is acquired through the United States Geological Survey's National Map (https://viewer.nationalmap.gov/basic/), using their 1/3 arc-second Digital Elevation Model, with sampling points at ~10m intervals. Satellite imagery is taken from Google Earth.

Terrain A is an arid region in the Santa Rita Experimental Range in Tucson, AZ (shown in Fig. 3A–B), Terrain B is taken from peatlands in Colorado, and Terrain C is taken from the Mount Haggin region, Montana, which requires extensive restoration after the logging industry left the mountaintops vulnerable to erosion.

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8 Appendix 1: Research Data

The supporting Research Data are hosted on the ICD server and organized according to the Articles contained in the Dissertation.

8.1 Article A

The directory for Article A contains all figures and Latex source files used in the publication. Unlike the other articles, Article A is a review paper, and therefore does not feature original experiments, CAD files or quantitative analysis.

8.2 Article B

The directory for Article B contains an Arduino folder (Article B/Arduino), which contains the microcontroller code used for capacitive force sensing applications. This code is not dependent on any external libraries and will compile for any version of Arduino and compatible microcontroller. The data recorded from this code is contained in (Article B/Data).

Unity3D was used to develop a simulation environment, which was subsequently used to conduct experimental that simulate building activity of a multi-robot collective. First, an environment was developed for node-and-strut construction in 2 dimensions (Article B/Unity3D/Robot2D). This was initially developed in version 5.5.2f1, but has been upgraded to 2018.4.11f1.

This initial environment was later adapted to support 3D block-based assemblies instead of 2D node-and-strut construction (Article B/Unity3D/Blocks3D). This was initially developed in version 5.5.2f1, but has been upgraded to 2018.4.11f1.

The directory for Article B contains all figures and InDesign files used in the publication.

8.3 Article C

The Data folder for Article C (Article C/Data) contains the force plate reading data (Article B/Data/MCL), results of lab and field experiments, and the terrain data used for simulations (Article B/Data/terrains).

Terrain data was acquired through the United States Geological Survey's National Map (https://viewer.nationalmap.gov/basic/), using their 1/3 arc-second Digital Elevation Model, with sampling points at 10m intervals. Satellite imagery is taken from Google Earth. Terrain A is an arid region in the Santa Rita Experimental Range in Tucson, AZ, Terrain B is taken from peatlands in Colorado, and Terrain C is taken from the Mount Haggin region, Montana.

The Models folder contains the CAD files that comprise Romu, the pile driving robot. The Figures folder for Article C contains all figures and Latex source files used in the publication.

8.4 Dissertation

The Dissertation folder contains data from demonstrations that were not included in the the previously published articles.

The Data folder (Dissertation/Data) contains the force sensor data from the anchoring node experiment. The Models folder contains the CAD files for the anchoring node, as well as CAD files used to generate the illustrations throughout the Dissertation document. The Figures folder contains all images and vector graphics files used to create them.

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Image Credits

Figure 1.2: (A) Eliza Grinell 2013 Harvard SEAS, (B) R. Hollis [Public Domain] 2019 USFWS (C) R. Weber 2018 ITECH Stuttgart.
Figure 1.5: Archival patent images (US Patent Nos. 1184705, 126990, 224626, 249832, 200753) are publicly accessible from https://patentscope.wipo.int/
All other images are the creation of the author.

Abstract

Since the First Industrial Revolution, the construction and maintenance of buildings and infrastructure has been characterized by a reliance upon heavy equipment, which has shaped how designers and engineers conceive of their agency in the built environment. However, 21st century advances in hardware and control systems allow for distributed and autonomous hardware solutions, enabling a paradigm shift in the co-design of machines and the interventions they deliver. However, in order to overcome the inertia of the mature technologies developed around heavy equipment, an entirely new suite of sensors, actuators and algorithms needs to be developed.

This thesis will present an argument for small-scale distributed robotics for construction automation, and will demonstrate that this approach can utilize practical materials to build useful structures in unpredictable environments. This argument is supported by an extensive literature review focused on the technological requirements for unsupervised (fully autonomous) robotic construction, and identifies gaps between academic and industry research that remain unfilled. Among these overlooked areas are (1) the need for embedded sensing in construction materials, and for co-designing robot hardware in coordination with novel construction robots, and (2) the need for an autonomous solution to providing foundation support. These two needs are explored through the representative example tasks of truss assembly and pile driving, respectively. Each task is demonstrated in prototypical hardware, with an emphasis on realistic materials and scenarios not dependent on human preparation. Each task is explored in simulation as multi-agent deployments. Finally, a summarizing demonstration illustrates how these two research findings might be leveraged in coordination to advance autonomy in an example construction scenario.

Cover image:
Vision for future work involving distributed robotics for on-site automation.
Nathan Melenbrink, Institute for Computational Design and Construction, 2021

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