Relative Robotic Assembly of Discrete Cellular Structures

PhD Dissertation Proposal, MIT Media Arts and Sciences

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1 Abstract

In this thesis I will present a robotic system for assembly of high-performance, large scale, modular structures. These types of structures have wide interest in fields ranging from infrastructure to aerospace, yet objectives such as efficiency and scalability have increasingly run into limits of conventional material and robot performance. In order to overcome these limits, my work builds on insights into discretely assembled, “digital” materials, and presents simple, mobile robotic platforms which are designed relative to their modular construction medium. This allows unique properties of the material system to propagate back into the design of the robot, which can be leveraged for reliability, scalability, and versatility not attainable with previous processes. I will show how this tightly integrated material/robot system enables programmable engineering systems that exhibit novel metamaterial properties at scale.

The pursuit of “faster, better, cheaper” promised by automation has led to numerous developments applicable to state-of-the-art structural systems, yet tradeoffs remain. For example, high repeatability for deposition and manipulation processes is achieved with stationary machines using fixed motion axes (ie: gantries). However, there are limits of spatial resolution due to hardware dynamics and control bandwidth, and the scale of the manufactured object is limited by a fixed machine spatial envelope. Mobile robots show promise to enable arbitrarily large scale construction, yet the literature shows an apparent tradeoff between robotic cost and the performance and complexity of the resulting artifact. Even with automation, some limits, such as stochastic errors, are inherent to the continuous materials typically used.

Discrete materials assembled from modular parts propose to provide scalability with precision, incremental error detection and correction, and the ability to create larger functional structures, or metamaterials, whose global behavior is governed by local properties of modules and their spatial distribution. This can result in novel, programmable behavior not attained by conventional engineered materials. Previously, these discrete materials have shown record-setting mechanical properties, large-scale reconfigurability, and tailorable heterogeneity for adaptive performance. However, these structures have been assembled manually, which limits their development to full-scale applications and thus our ability to benefit from their desirable properties. Therefore, automating assembly is critical.

At the heart of this thesis is the notion of what I term a “relative robot” which can build something larger and more precise than itself. This requires discrete materials with sub-linear error scaling. With this, it is possible to create discrete systems with novel properties not possible with traditional robots and materials. I plan to show how the modular construction can inform the architecture of simple, low degree of freedom robots, and how properties inherent to the modular construction can enable these robots to compete with conventional stationary robotic platforms in terms of metrics such as throughput, cost, and precision. I will show how planning algorithm design affects robot design, and when it is beneficial to use centralized, distributed, or hybrid planning models. Full-scale demonstration systems will be used to assemble modular structures, which will be characterized to show improvement upon prior art of robotically assembled, modular structures. Finally, I will describe how this approach enables new designs and applications, how these systems can be tuned to surpass critical performance thresholds, and how they compare to traditional approaches in areas such as infrastructure, transportation, and aerospace.

2 Introduction

The inventions of digital logic, computation, and communication by John von Neumann and Claude Shannon in the mid-20th century led to a revolution in the digitizing of information. Today, there is extensive and ubiquitous computing capabilities, allowing, for example, vast amounts of data to be processed for scientific breakthroughs such as black hole imaging [1]. These developments also enabled the first numerically controlled (NC) mill in the 1950s [2], allowing fairly repeatable, automated machining procedures. Since then, myriad processes have been developed to add or remove material with end effectors driven on stiff motion axes by computational control systems, providing efficient means to realize complex geometries at low cost. This fits a number of needs very well, such as rapid prototyping, multi-material printing, and large dynamic range, which are accessible thanks to the proliferation of digital fabrication. Problems arise, however, at finer granularities and higher performance thresholds. Additively manufactured parts can suffer from undesirable anisotropy or stochastic errors caused by the deposition process, resulting in unpredictable behavior or failure. While this may be acceptable for low fidelity applications, the existence of variation between digitally identical parts is seen as a problem for large scale, high performance systems. To address this, one can look at existing models for error reduction.

Shannon's threshold theorem shows that "digital" scalability and performance relies on considering analog signals, such as waveforms, as representations of discrete units of information, such as bits, and using error correction to account for imperfections (noise) and send information perfectly over the imperfect channel. The notion of programming materials, just as information is programmed, has led to the field of digital programmable materials. Here, continuous material systems are discretized into modular parts, providing control at the unit level, as a means to embody attributes found in digital systems such as error correction, scalability, and combinatorial programmability. These discrete materials can demonstrate continuum behavior with novel effective properties.

In engineering, traditional continuum materials are used in demanding applications because their properties are well defined, and statistical models exist for anisotropy, stochasticity, and failure modes. Combined with rational design of geometry at various scales, we are able to build large scale, high performance structures like trusses and towers. But semi-manual construction is not well suited to the dynamic range achievable with CNC fabrication, and similarly, it is impractical to scale up a gantry to the size of a building (or larger) while maintaining high spatial resolution as a function of finite motor position control. There is room for improvement in the ability to efficiently produce scalable, performative structures with locally controllable properties. In response to this, I plan to automate assembly of discrete materials to build functional discrete systems.

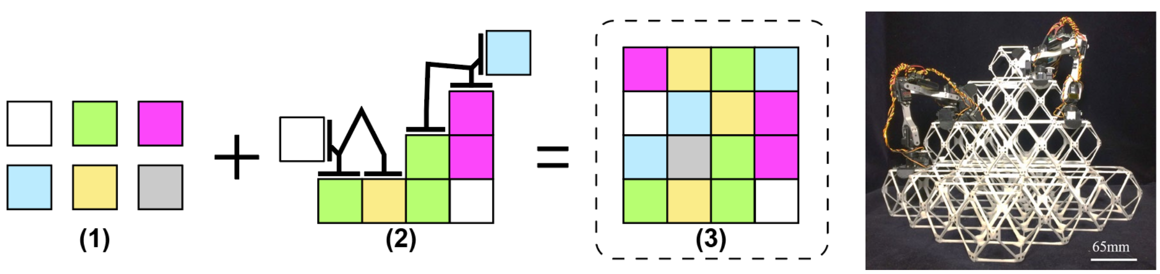


Figure 1: The approach consists of discrete materials (1) assembled by relative robots (2) into functional discrete systems (3).

In this thesis I will describe a novel robotic platform, termed "relative robots", capable of assembling discrete materials into larger, functional discrete systems. I define relative robots as task specific platforms designed relative to a specific spatial/material environment which is leveraged for simplification and implementation. By controlling the tight feedback loop between relative robot and discrete material, one can impart "digital" properties of the material system to the robot, enabling mobile construction of large scale, high performance structures without the inherent scaling problems of stationary platforms. Rather than following the current trend of cost and infrastructure scaling to size and performance, this thesis seeks to invert this conventional manufacturing paradigm. First, I will motivate our approach by discussing the current state of structural system manufacturing, comparing existing material systems and robotic platforms, and identifying applications considered useful and relevant for this thesis. Then I will describe our approach, which consists of the robot-material system and selected applications. Last, I will identify goals, remaining tasks to accomplish these goals, and criteria to evaluate results against current approaches.

3 Background

The notion of discretizing systems has been utilized in engineering for millennia. Monolithic wheels and pyramids gave way to wooden spokes and frames, which further developed into structurally efficient metal truss structures (Figure 2). Similarly, there is a comparable theoretical progression from Hooke's linear stress-strain law in 1678 (describing a bulk material), to Bernoulli and Euler's beam theory in 1744 (describing material and geometry in the form of a structural member), to Maxwell's rules for connectivity and DoF's in space frames in 1890 (describing network of members). There is an increase in hierarchy, and performance, moving up in scale from material, to member, to system. By adding *architecture*, consisting of material and geometry with controlled positions and orientations, the performance of structural systems can improve at increasingly large scales.

The concepts behind scaling *down* architecture can be traced back to observation of hierarchy in natural systems such as wood and bone [3], and more recently to investigations of stochastic polymeric foams, whose cellular structures were studied and manipulated by Lakes to create the first negative Poisson ratio material [4]. Seminal work by Gibson and Ashby was published around the same time [5][6], describing analytically the behavior of cellular materials as a network of beams, whose geometry and connectivity can be controlled to tailor macroscopic behavior, thus enabling design of architected materials. It took several decades before additive manufacturing technologies had advanced sufficiently to enable production of rationally designed, architected cellular materials [7]. Since then, numerous advances have been made, allowing more intricate levels of hierarchy and geometric complexity, increasing precision down to nanometer scale features on centimeter scale parts [8]. However, as many engineering applications operate at scales several orders of magnitude larger than this, how then do we make architected, high performance structural systems at larger scales?

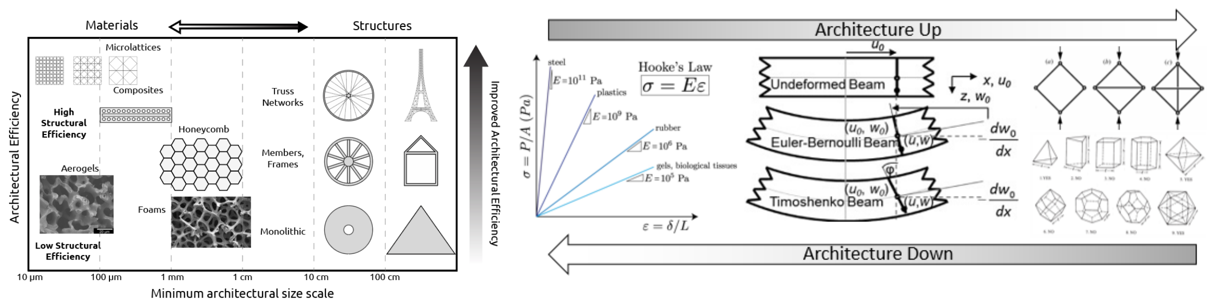


Figure 2: Architecture for performance: structural engineering through material, geometry, and hierarchy.

Before I discuss some state of the art approaches, it is important to mention two critical advances from the last century: mass production and automation. The high repeatability and throughput of mass production today benefit from developments in standardization of parts by Eli Whitney and standardization of procedures by Henry Ford, as embodied in his moving assembly lines. Subsequently, the introduction of the notions of digital signal processing and computation by Claude Shannon and John von Neumann enabled the creation of the first numerically controlled (NC) mill in the 1950s [2], allowing highly repeatable, automated machining procedures. This brings us to today, where automated manufacturing is now ubiquitous, though limitations still exist.

The degree to which automation can be integrated into the production of structural system relies partly on scale. Machines typically have a fixed workspace, defined by the extents of the reach of their motion systems and end effectors. Automobile production is highly automated, from sheet metal forming, to frame assembly and welding, using rows of robotic arms working on moving assembly lines. Here, the effective robot workspace equals roughly the entire car. For larger structures, such as a 70m aircraft, production still relies on a significant amount of manual assembly, and while many aircraft components are robotically manufactured, entire system integration requires scale and complexity that make full automation difficult. Scale also affects what type of material system is employed. Continuous material structures can be made with additive manufacturing up to roughly the meter scale, though as I will explain later, there can be issues with cost, yield and performance. High performance continuous CFRP components tens of meters in length can be made with automated fiber laying machines [9], with associated tooling, autoclave, and part transport being of similar scales. For turbine blades nearing 100m, there are gantries of this scale for milling formwork [10], with manual composite layup. While a robotic tape laying system could certainly be extended to this scale, the overhead and infrastructure required are disproportionately larger than the current demand, and thus impractical. This observation of infrastructure and cost scaling proportionally to size and performance, shown in Figure 3, is a key limitation this thesis seeks to address.

This problem is exacerbated for space structures, for which both scale and performance are desirable. Aside from 3D printing of small non-structural, non-critical components on the ISS [11], all space structures are fabricated on the earth then fit into a payload and launched on a rocket—the ISS was built on orbit, module by module, over roughly 15 years. Payloads have mass and volume limits which influence the material selection and geometric complexity of structural systems, sometimes requiring solutions such as unfolding deployable structures, which have parasitic mass and high-risk deployment sequences. Due to the high cost of launches, on-orbit construction is proposed using assembly [12] or fabrication [13]. The former was tested previously with astronauts positioned by robotic arms to perform truss assembly [14]. While effective, this is not scalable due to risk involved with EVA. In the latter, raw material is launched and converted to structural elements *in situ* using various additive processes [15]. While this approach can avoid imparting launch loads onto delicate structural systems, it is unproven how additive manufacturing can produce parts to reliably meet application requirements.

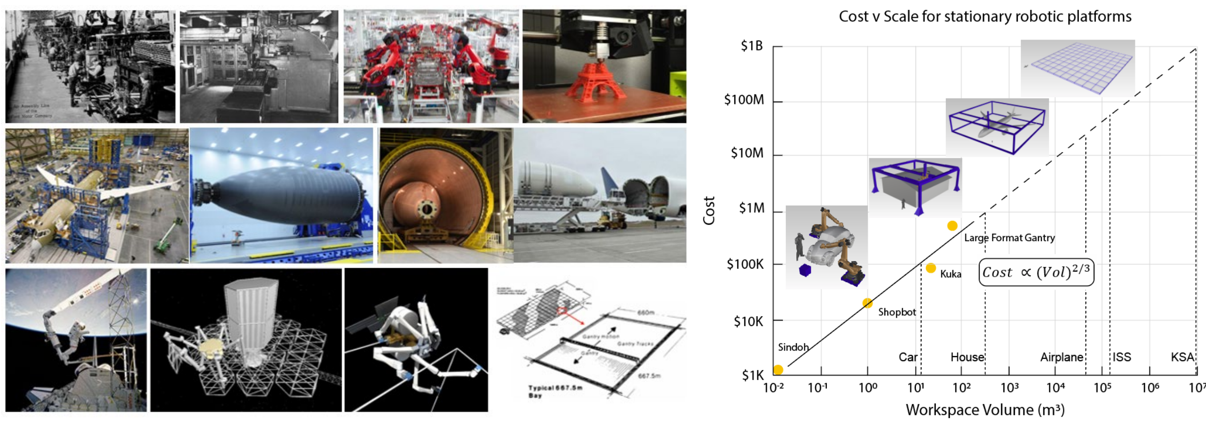


Figure 3: Automation and digital fabrication. Machines scale with the size of the part, with associated cost increase.

Within state of the art additive processes, I identify several key aspects related to the robotic platform and material utilized, including *scale, geometric complexity, performance, and automation.* Many processes for continuous material deposition show a large dynamic range (object size/feature size). Large Area Projection Microstereolithography (LAPμSL) can achieve nanometer (10^{-9} m) scale features on centimeter (10^{-2} m) scale parts, commercial FDM is available up to the meter scale, and several custom large format additive manufacturing platforms extend to nearly 10m, such as room-sized FDM machines [16], and house-sized cementitious deposition gantries [17]. Given the finite precision of affordable digital control systems, these larger scale platforms inevitably tradeoff some precision for scale. In response to this, several mobile robotic approaches seek to extend the boundaries of continuous deposition processes. LiDAR directed, multi-DoF arms with rolling bases can coordinate on cementitious deposition within a given sensing range [18], while a foam-depositing arm mounted to a mobile crane has a large workspace [19], though relocation for extensible construction has not been demonstrated.

At small scales, low-cost geometric complexity enables the creation of novel metamaterials. Hierarchical lattices demonstrate high stiffness at ultralight densities [26] and this has been improved upon by plate lattices [20]. Other strategies seek to parameterize the elasticity tensor by controlling the Young's modulus *E,* Poisson ratio *v* [21], shear modulus *G*, or bulk modulus *B* [27]*.* These can be spatially programmed to invent mechanisms [28] [22], and this cellular level of control results in an exponential number of combinatorial designs for a given system size [23] (attributable to programmable matter theory rather than the specific additive process). In more demanding applications, parts made with layer-based deposition processes can suffer from undesirable anisotropy [24], as well as being susceptible to stochastic error inherent to continuous material [29]. For risk-averse applications, such as 3D printed rocket parts, time and labor intensive non-destructive inspection, such as ultrasonic imaging [25], is required. While continuous material deposition techniques used in additive manufacturing offer promising complexity and efficiency at small scales, performance degrades as you scale up.

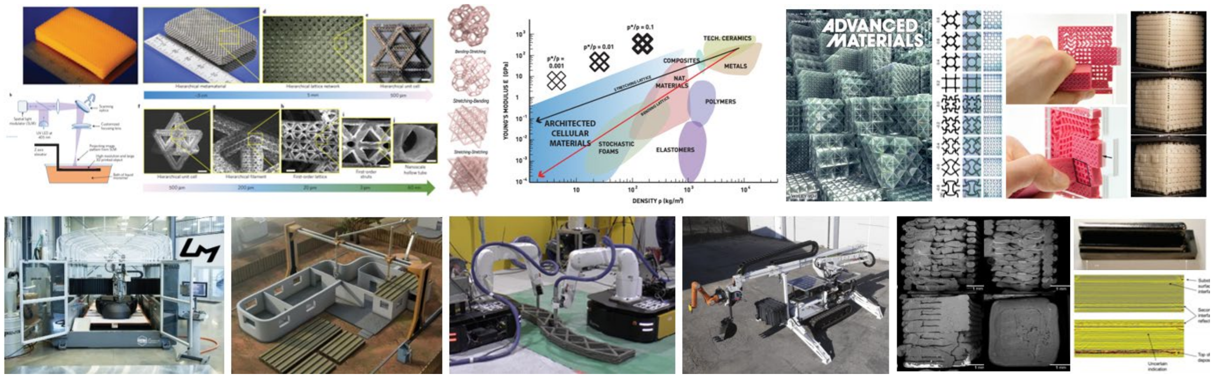


Figure 4: Continuous deposition processes and metamaterials. LAPµSL of truss [8] *and plate* [20] *lattices, tunable Poisson's ratio material* [21]*, programmable functionality for mechanisms* [22] *and machines* [23]*. Large scale stationary* [16][17] *and mobile* [18][19] *deposition systems. Material anisotropy* [24] *and ultrasonic error detection* [25]*.*

Discrete materials seek to provide scalability with precision, incremental error detection and correction, and the ability to create larger functional structures and metamaterials, whose global behavior is governed by local properties of cells or modules and their spatial distribution. To this end, I identify several key aspects of prior art in discretely assembled materials, including *joints*, *geometry*, *material*, and *automation.* To properly predict behavior of discretely assembled macro-structures, joints must meet specific performance requirements. Mechanical connections such as shear clips [30] and friction press-fits [31] have been shown to provide sufficient load transfer or electronic interconnect, respectively, to build metamaterials with nearly ideal mechanical performance. Part geometries vary from space-filling lattices [30] and spheres [32], to 2D and 3D bricks with interlocking features [31][33]. For structural applications, this geometry is critical for high performance, while for electromagnetic applications, preference is given for successful interconnect and subsystem integration [34]. Discrete materials can utilize base materials unavailable to additive manufacturing, such as aligned, continuous filament CFRP [30], and can easily join heterogeneous materials to program spatial functionality [31][35]. Repeatable part production is critical for assumptions about continuum behavior of an assembled material system, as errors in parts above a certain threshold can prevent successful assembly at large scales. Several demonstrations of automated assembly show promise for high throughput manufacturing. Desktop-size gantries place parts individually [31] or in parallel [32], and rely on end effector alignment and elastic averaging of part error for overall precision. Strut and node systems designed for human assembly of trusses [39] have been robotically assembled, but at a slower pace due to challenges of alignment and dexterity [40]. Voxel systems have been assembled manually with a throughput on par with commercial FDM [35], and robotic assembly improves this metric [37], indicating benefits of modularity that will be leveraged in this work.

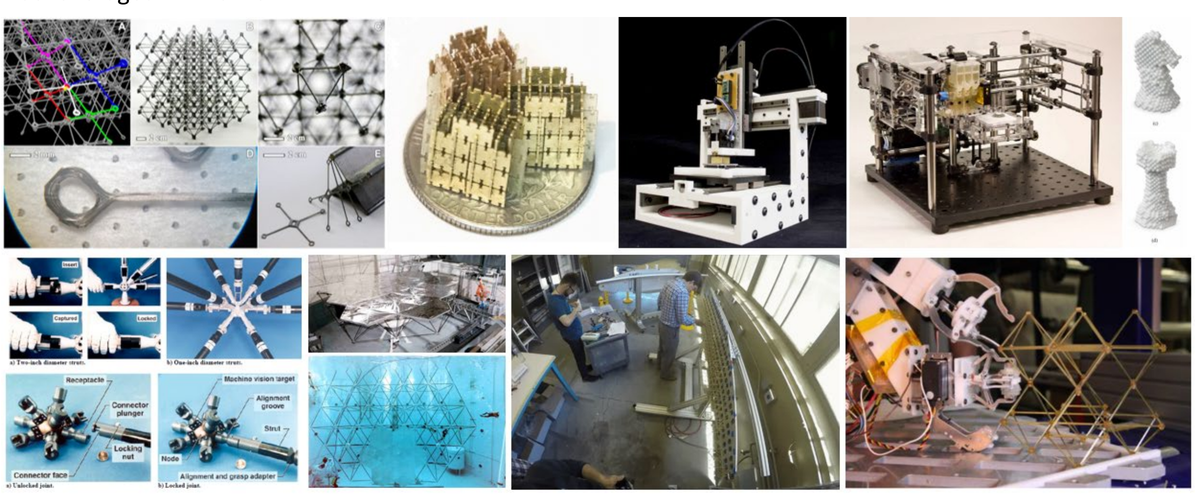


Figure 5: Discrete materials and assembly. Planar lattice elements [30]*, electronic bricks* [31] *and spherical voxels* [32]*, with gantry-style assembly platforms. Robotic and manual assembly of strut-and-node systems* [36] *and voxels* [37][38]*.*

Mobile robots have also been proposed for assembly of various discrete material systems. Key aspects of mobile robotic assembly platforms include *material/structural system*, *locomotion system, sensing system, and control architecture*. Discrete material systems used in mobile robotic assembly tend to be either bricks, which are solid, or struts and nodes, which are sparse. Brick-based systems can take advantage of the higher ratio of contact surface between parts to allow alignment [41] [42], or rely on passive, gravity-based stacking to build 2.5D structures [43] [44]. Struts and nodes require different strategies for assembly [45], or can be grouped as a modular truss unit [46]. Locomotion strategies for mobile assembly robots tend to be either flight, ground-based rolling, or *in situ* climbing. Flight allows robots more spatial access, at the cost of more complex controls to navigate this larger space [43] [45]. Rolling provides stabilization on a ground plane, while requiring the robot to position itself successfully within this more confined space [44] [46]. Crawling, specifically, on the structure, can result in highly customized kinematics, but also allow robots to locally align to the structure [41] [42] [47] [48]. Local sensing, such as IR or contact sensors, gives robots a close feedback loop between parts and themselves [41] [44] [47], but can have a limited error correction range. Global sensing, typically achieved with LiDAR [45] [43], provides control of the entire workspace, but is limited to a finite range, and thus is not arbitrarily scalable. Centralized control manages single [46] or multiple robots [43] [45], and can be more efficient for small-scale systems, but vulnerable to single points of failure. Distributed systems require more autonomy (and thus complexity) for robots [41][42], but can be more robust and scalable.

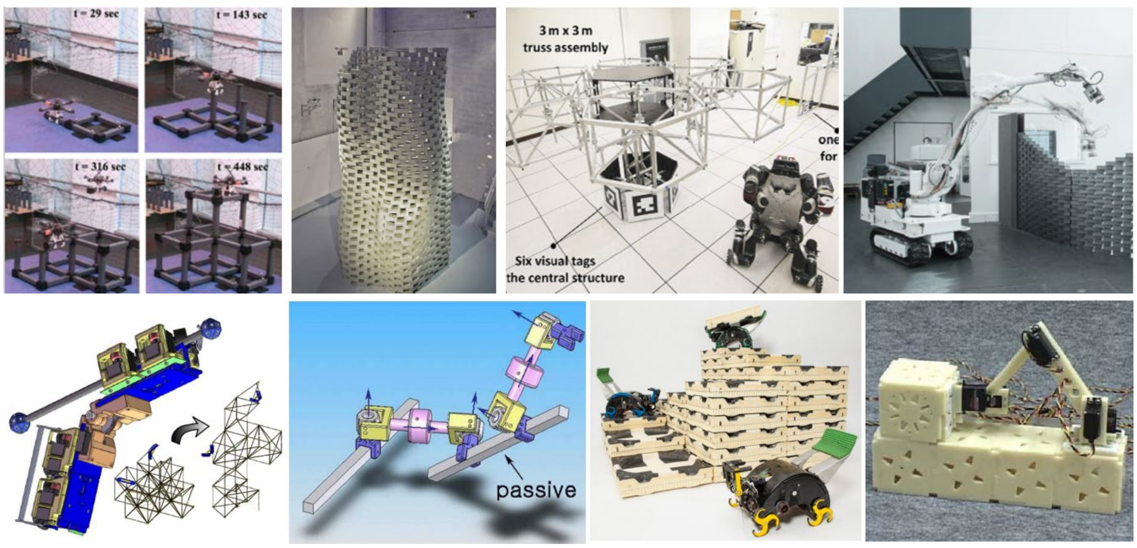


Figure 6: Mobile robotic assembly systems. UAV truss [45] *and brick* [43] *assembly, wheeled robot truss* [46] *and brick* [44] *assembly, structure-traversing truss* [47][48] *and brick robots* [41][42].

Given these approaches, what types of large structural systems are intended to be built? Today, meso- to macro-structures vary widely based on functional requirements. Car structures (chassis and body) tend to be steel or aluminum, cut from sheets, then stamped, folded and welded into a variety of shapes, with a high degree of automation at each step. Automobile performance can be improved with mass reduction and aerodynamic efficiency, but fabrication of complex geometries can require significant development time and cost, limiting near-term implementation. The future of self-driving will likely spur the demand for low-cost vehicles for transport and logistics [49], and thus may require a shift from personal vehicle manufacturing to a more modular and flexible system. At larger scales, aircraft structures have been incrementally refined for decades, relying heavily on high performance metal alloys for performance and ease of construction. More composite material is being gradually integrated, while overcoming myriad cost and manufacturing challenges. Aircraft geometries stray very little from the “tube with wings” motif, primarily due to the heavy reliance on legacy as a basis for cost, safety, and performance risk reduction. However, the performance of non-traditional aircraft has been studied extensively. One such design, the blended wing body (BWB), has been shown to offer significant improvement in fuel efficiency over traditional aircraft [50]. Yet its geometry essentially makes it a non-starter, due to the cost-sensitive and risk-averse nature of the airline industry. Perhaps equally well studied is the use of morphing structures, which allow shape change to optimize performance [51]. To date, very few designs have flown at scale [52].

There exist number of applications within atmospheric infrastructure requiring high performance structures. Airships, which combine lifting gas for buoyant force with propulsion and control surfaces for maneuvering, show promise of low-cost locomotion for logistics and sustainment [53]. To address the issue of gas diffusion, vacuum airships have been studied [54] and proposed [55], but never realized. High altitude long endurance (HALE) aircraft can provide infrastructure for communication, observation, and logistics, and designs look to maximize lifting surface at minimum weight [56], resulting in long span (>50m) structures that pose challenges in both fabrication and implementation in non-cruise flight regimes, such as takeoff. Finally, low altitude (<1km) wind harvesting for energy generation has been demonstrated in industry, such as a tethered 26m span airfoil kite, whose rotors transfer wind energy into electrical energy [57]. Due to the more consistent and higher wind speeds at altitudes around 10km, there are a number of proposals for high altitude wind power (HAWP) [58], which will place significantly greater requirements on these structures. Space structures have widely varying applications and requirements, some of which are outlined in [59]. Proposed solar electric transport vehicles require 300 kW arrays measuring 45m x 11m supported by lightweight, stiff, and volumetrically-efficient truss structures [60]. The James Webb Space Telescope (JWST) is a 6.5m precision segmented reflector with nanometer scale mirror surface precision requirements [61]. In addition, it has to fit within a standard launch shroud, and deploy several complex structural systems, including a tennis-court sized solar shield. The challenges of this scale, performance and complexity has resulted in the schedule doubling (from 10 to 20 years) and increased the budget ten-fold ($1B to $10B), as of this writing. On the other hand, 10-cm scale cubesats cost only thousands of dollars to build and can “piggyback” onto existing launch manifests in place of vehicle balancing ballast. Almost all on-orbit habitats are metallic cylinders, such as modules on the ISS, though recently a 4 meter inflatable fabric habitat module was deployed on orbit [62]. The several-hundred meter habitats (ie: Stanford torus, O’Neill cylinder) envisioned in a report which preceded the Space Shuttle program may be physically possible [63], but currently would be logistically infeasible. More near-term infrastructure plans include lunar and Martian habitats, which may be assembled from shipped parts [64], or made using local resources [65]. These are some of the many applications which would benefit from the performance of discrete materials; the next key step is scaling up production.

Figure 7: High performance structures. (L to R) Ground and air transportation, air and space infrastructure.

4 Questions, Goals

Given this as background, the heart of this thesis is the notion that a relative robot can build something larger and more precise than itself. This requires discrete materials with sub-linear error scaling. With this, one can create discrete systems with novel properties not possible with traditional robots and materials.

Within this, I will need to answer many questions, including, but not limited to, the following:

Table I. Questions

Discrete Materials	***Relative Robots***	***Discrete Systems***
What is the part geometry?	How are robots designed?	What are the applications?
How are parts joined?	How are robots controlled?	How are they constructed?
How are parts manufactured?	How are robots implement?	How are they implemented?
How do I control material behavior?	How do I determine system output?	How do they perform?

In answering these questions, we can outline the goals of this thesis, which are, in order:

1. Relative robots which leverage discrete material properties to achieve scalability and performance at low cost.

2. Discrete materials which are designed for relative robotic assembly into larger, high performance structures.

3. Discrete systems which demonstrate novel properties for applications not attainable with current approaches.

5 Approach, Proposed Work

5.1 Discrete Materials

The core contribution of this topic will be the development of a discrete material geometry and joining system that enables robotic assembly. To date, this has not been sufficiently demonstrated for high performance structures. Here I discuss prior work and current and proposed work within subtopics of geometry, joints, performance, and manufacturing.

Prior Work

First, the research in [66] presented a large scale, reconfigurable discrete lattice system. By utilizing high modulus (E = 130 GPa) CFRP tubes, we achieved the highest reported modulus for ultralight materials (E^* = 15 MPa, ρ^* = 5 kg/m^3). However, small errors in tube length (<0.01*L) contributed to alignment errors when building in 3D, and due to the high stiffness of the struts, misalignments exceeded the error threshold for elastic averaging, demonstrating the importance of this property. In [67], I presented a multi-scale discrete lattice system made of aerospace-grade alloy 316L stainless steel. This work expanded discrete lattices into metals with densities and geometries not possible with current metal additive processes. However, it required non-trivial dexterity for assembly, which is a critical factor in automating the process. In [38], Gregg *et al* presented an injection molded GFRP octahedral voxel, resulting in one of the most advanced discrete material system to date, due to the high repeatability and speed of the manufacturing process. Voxels take 17 seconds to produce and have been shown to have comparable throughput to FDM when assembled manually [35]. In addition, the ease with which large structures were produced enabled development of mobile robotic platforms, described in the next section.

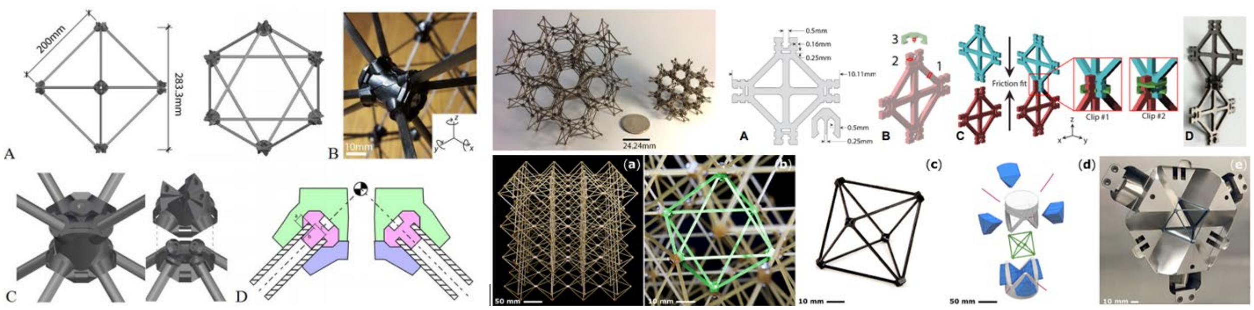


Figure 8: Discrete material system prior work. CFRP [66]*, metal* [67]*, GFRP* [38].

Current/Proposed Work

In the current approach, the proposed geometry is a Cuboctahedral (Cuboct) unit cell. This produces a lattice which has been shown to have near-linear modulus scaling [38]. A comprehensive summary of the down-selection criteria for this voxel geometry is presented in [68]. To summarize, flat faces, as opposed to vertices, provide more contact area for alignment. Also, the addition of a single voxel provides 4 joined vertices, ensuring proper load transfer, as opposed to the octahedral Cuboct voxel which requires 4 voxels to achieve this condition. The Cuboct cell can be decomposed into 6 identical faces. These faces can be injection molded, possibly with a cost-effective two-part mold. Faces can be riveted to other faces at the vertices to form a voxel. This is an effective, yet pragmatic, geometry for robotically assembled modular structures.

To control the behavior of these materials, I will use a combination of analytical and numerical modeling techniques at various hierarchies and levels of granularity, progressing from macro-scale effective continuum behavior, to local beam behavior, and finally to Hookean material stress behavior. To begin, I perform back of the envelope calculations of effective properties, such as stiffness, using the Gibson-Ashby scaling law: $(E^*/E) \approx b(\rho^*/\rho)^a$, where a is a value based on the lattice geometry. Then, I can use commercial simulation tools (*Oasys, Frame3dd*), which create simplified beam models with linear stiffness matrices significantly smaller than a corresponding system from a conventional meshed FEA [69]. Deflection and load paths can be observed and resulting beam forces can be checked against analytical solutions for Euler approximation of critical column load, $F_{crit} = \pi^2 EI/(k^*L)^2$. Next, in order to validate joint performance, I can create an exemplary unit model for FEA simulations which includes details such as contact surfaces, joint pre-loads, and fully meshed 3D geometries.

Because I define joints as strength-limited, I then check for stress concentrations from a given load case. This load case is then compared back up the hierarchy, to ensure safety margins over critical beam loads and adjust lattice and joint geometries as needed to tailor this highly coupled system. Critical to these assumptions is a highly repeatable part production process.

As shown in [38], injection molding is well-suited for this. However, complex part geometries can result in expensive tooling. One can design a high performance material system with reduced cost through several manufacturing strategies. One strategy is making the geometry two-part moldable and eliminating sliding components such as pulls and shut-offs. 45 degree holes can be achieved with mating features of the cavity and core. Next, I wish to avoid gates in the middle of beams, as this has been found to cause weakened areas. Under large elastic strain, these weak areas will see high stress due to beam deflection and this can result in a strength-limited flexural failure, which is undesirable as a primary failure mode. In addition, gate location affects flow direction, and if flow is continuous from one end of a beam to another, fiber alignment occurs, which is desirable for increased stiffness. Lastly, location and quantity of knit lines are important, as these decrease material strength by roughly half. In our current design, there will always be knit lines in the joint area, so a single gate is chosen to keep these primary knit lines symmetric, while minimizing knit lines within beams.

Remaining tasks for this topic include the development and production of a high fidelity material system which can be robotically assembled. In addition, other performance regimes will be investigated utilizing discretely assembled 3D plate lattices and electromagnetic metamaterials. The proposed joint system will rely on magnets for alignment and a coordinated latching system for structural interconnect. Here, four spring-loaded metal latches can be activated with a single degree of freedom to connect an entire face at once. A gear-like feature engages the opposite latch of the neighboring voxel, thus providing a symmetric joint with reciprocal locking. This allows the joint to be disassembled from the neighboring voxel, which will be critical for reconfiguration. Next steps for this include simulation, prototyping, testing, and design for manufacturing, as well as resulting end effector updates for the robots. I also will look at performance of other discrete material systems. Plate lattices more closely approach the Hashin-Shkirtman bound [70], which is the highest theoretically achievable elastic modulus for an isotropic porous solid [71]. A discretely assembled version will utilize quasi-isotropic CFRP as a base material, which can improve upon plate lattices made with additive manufacturing. Electromagnetic (EM) metamaterials have been demonstrated as lenses [72], cloaks [73], and waveguides [74], typically at near visible to microwave frequencies (THz -GHz) and made with deposition-based processes . I plan to demonstrate proof of concept for a discretely assembled, 3D EM metamaterial consisting of lattice substructure and split ring resonator panels to tailor electric field permittivity ε and magnetic field permeability μ for use at the radio wave frequency (MHz). Lastly, I know that I will utilize heterogeneous structural material systems for programmable anisotropy, however, this will be application specific and will not be a core deliverable of the materials topic.

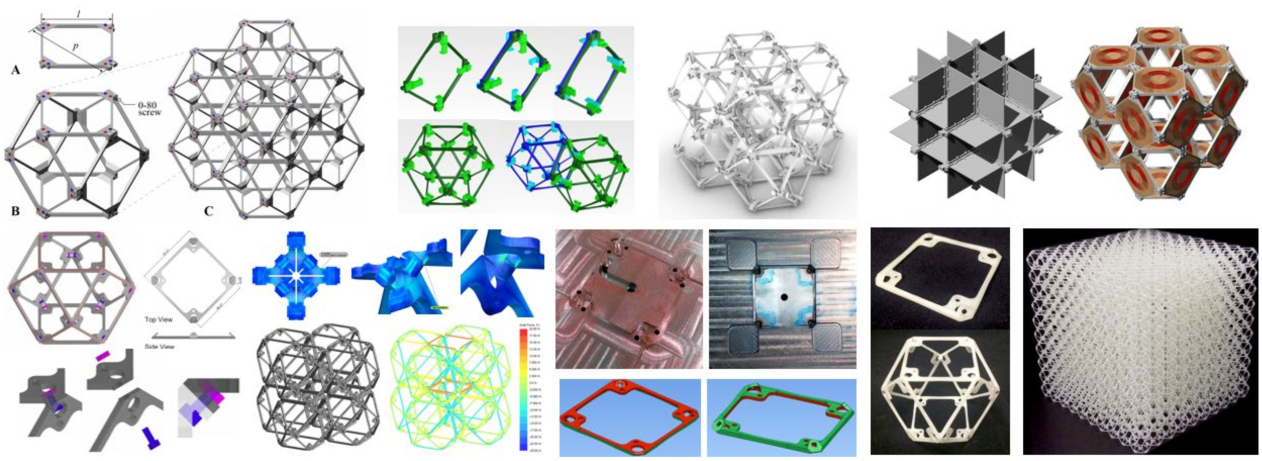


Figure 9: Discrete material system current work. Top (L to R) Cuboct voxel decomposition, robotically assembled latching design, plate lattice and EM discrete materials. Bottom (L to R) Low-cost Cuboct design, simulation of joints and beams, tooling and molding, part production, voxel assembly, and 10x10x10 cube.

5.2 Relative Robotics

The core goal of this topic will be to demonstrate how relative robots can leverage discrete material properties to achieve scalability and performance at low cost. To date, no relative robotic platform has demonstrated assembly of a high performance structural system. Here I will discuss prior art, then current and proposed work of system design, control strategies, and experiments.

Prior Work

Relative robots are a novel contribution to the field of high performance lattice structures. I define relative robots as task specific platforms designed relative to a specific spatial environment which is leveraged for simplification and implementation. Previous examples include TERMES [41] and AMAS [42], both of which use solid brick elements. In our case, robots are designed relative to a periodic lattice structure (Figure 10). One robot, MOJO (Multi Objective JOurneying robot), was designed to crawl through the interior of a lattice to perform exploration and structural health monitoring tasks [75]. The robot fits within a single voxel pitch (3in) and weighs 69g. Its actuation consists of 5 micro servos. Two pairs move top and bottom scissor linkage arms with lattice-specific end effectors for climbing, and one rotates a hip joint to turn. While the robot performed better at climbing in 0g (simulated microgravity on a sub-orbital parabolic flight) than in 1g, its scale presented challenges due to torque density scaling of commercial off the shelf (COTS) motors for overcoming alignment issues.

Another robot was designed to locomote on the exterior of the lattice [76], allowing more room for motors and end effectors. The Bipedal Isotropic Lattice Locomoting Explorer (BILL-E) robot is based on an inchworm architecture and can perform a variety of maneuvers to navigate a full 3D lattice system. Gripping end effectors allow for error correction and alignment, and this platform was used to demonstrate long term, precise travel (3m) based on single-cell (0.076m) step motions which allowed repeated, incremental self-alignment to the lattice. The robot consists of 7 actuators and weighs 520g. This platform serves as the basis of the mobile robotic assembly platform that will be utilized in this thesis.

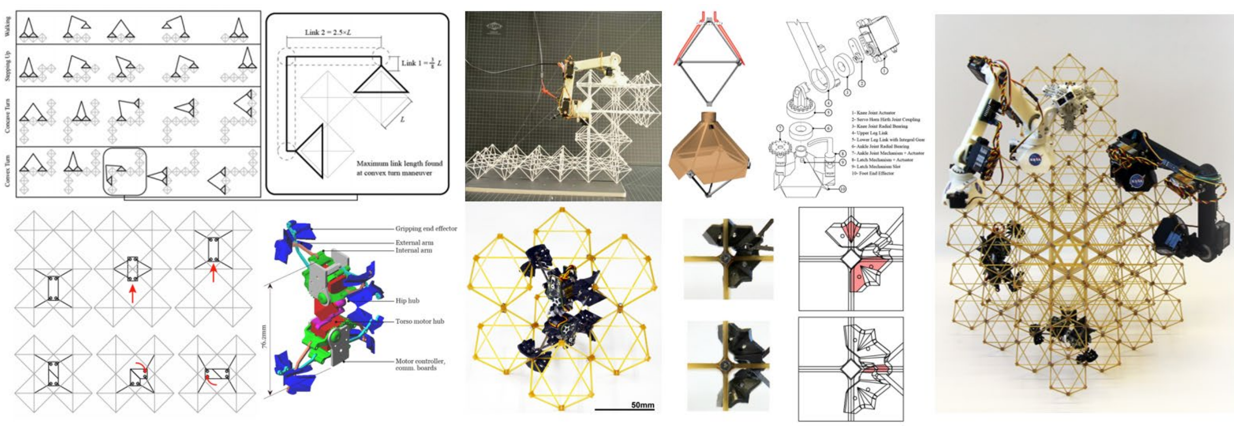


Figure 10: Relative robotics prior work. (Top) BILL-E, for external locomotion and material transport/manipulation [76], (bottom) *MOJO for internal crawling and inspection* [75].

Current/Proposed Work

To summarize, our current centralized control scheme works as follows: CAD models of a given discrete lattice structure can be represented as a 3D bit matrix, or as functional representations (f-reps) in a custom software environment. Next, a build sequence is determined, based on environmental/operational constraints. Depending on single or multi-robot construction, coordination is determined, and path planning for each voxel in the build sequence is sent to the robot. Each path consists of linked primitive moves, such as “step” or “turn 90°”, which are executed based on a robot’s geometry, kinematics, and actuation. Lastly, sensors detect errors during motion execution, and thus can provide feedback to avoid failure. I will now describe these steps in detail.

Within our control strategy, I start with determining build sequence, or the order in which parts will be placed, using two algorithms, one for single robot construction and one for multi-robot construction. Certain assumptions are also imposed, such as the presence of gravity, a single material source, structure connectivity, and the requirement of at least a single neighboring voxel to be empty (based on current placement mechanism). Algorithm 1, for a single robot and part source, starts at the ground plane (*xy*), and for each plane, determines sequence based on Manhattan distance to the source. Here, all paths are precomputed. For single robot construction, the entire path planning happens offline by the centralized system, which is then passed to the robot as a string of commands corresponding to pre-stored motor angle sequences on the robot's microcontroller, which are then executed by the robot.

Algorithm 2 is more amenable to multi-robot construction. Here, within a layer, voxels are ranked based on a distance field to the closest edge. Each voxel has a discrete rank and the robots are forced to follow this rank order, hence building the center of the shape first then successive layers around it, thus preventing deadlock (a situation in which no robot is able to move without causing a collision, or where a part cannot be added). This method can adapt to more robots or part sources, though this requires multi-robot coordination. For multi-robot coordination, heuristics are developed to address scheduling issues and to avoid collisions. "Spatio-temporal scheduling", similar to a strategy described by Murata and Terada [77], is employed to categorize possible errors and determine rules to govern these scenarios. Two cases look at beginning and ending intersections, one looks at construction dependencies, and another looks at mid-path intersection. The central planner takes these into consideration when performing the path search for multiple robots, whose locations are known at each timestep *t* (based on the previously calculated paths). If no such path exists, the robots wait for certain amount of timesteps until a path is cleared. After having determined the build sequence, an individual robot needs a path from a pickup location to a target location, given an existing voxel configuration. A* search with the Manhattan Distance as the heuristic is employed. At each step, the list of possible next steps is determined and the one with the smallest Manhattan Distance to the target is chosen.

Robot system design includes geometry and kinematics, actuation, end effectors, and sensors. The geometry and resulting kinematics of the robot are based on the maneuvers and configurations required to achieve the desired goals of full 3D locomotion, part transport, and part placement [76]. This provides robot link lengths as a function of lattice pitch; from here, inverse kinematics can be used to determine motor angles for positions and motions. Actuation requirements and selection are determined through worst-case calculations and practical considerations such as favoring COTS actuators for rapid development, while sacrificing finer granularity of motor control. In the current robot version, the end effectors for foot attachment and voxel placement are the same. Through coupled design of the robot and voxel, the gripping mechanism is designed to use as many passive and as few active degrees of freedom as possible. Alignment features constrain translation in *x* and *y*, and rotation in *z*. A single actuator rotates a cruciform "key" 45° to create four contact points with customized surfaces on the underside of each beam of the top square face of the voxel. In this way, translation in *z* is constrained, as is rotation in *x* and *y*. The actuation degree of freedom is orthogonal to the loading direction, thus decoupling these functions and requirements. When the key is in the locked position, the stiffness of the gripper is a function of the key's geometric and material properties, as opposed to the torque capacity of the motor. For sensing, the robot needs feedback for locomotion and for assembly, at a minimum. During locomotion, feedback is provided by tactile sensors on opposite corners of each foot. When both sensors are engaged, one can be confident that the foot is correctly placed. An error correcting loop in the motion control level enforces this as a condition to be satisfied prior to locking the newly placed foot and unlocking the other foot to be moved next. Feedback for part placement can be obtained by monitoring torque of the placement motor while pulling on a newly attached voxel. We utilize a custom software environment for control and simulation of single and multi-robot assembly (development lead is Amira Abdel-Rahman, CBA). This will be used to control robots for experiments, as well as to study scaling of large systems (# voxels > 10^5, # of robots > 10^1).

Remaining tasks include experiments and development of a distributed system architecture. Experiments are mandatory for demonstrating that a relative robot can build something larger and more precise than itself. So far, using the described material and robot system, I have completed several experiments, including single-robot assembly of 1D, 2D, and 3D structures, and preliminary multi-robot construction of branching and monolithic structures. For now, experiments will be performed with the centralized architecture. Experiments focus on the goals of scalability and performance. This includes bulding a large scale structure (>10^2 parts), showing parallelized, multi-robot assembly, employing error correction for increased reliability, demonstrating elastic averaging in 1D, 2D, and 3D structures, and performing reconfiguration of ~27 voxels into a 1D beam, 2D plate, and 3D cube.

Finally, literature suggests that distributed systems typically scale up better than centralized, but may require more autonomy and sensing [78]. A distributed control architecture will therefore be important for scaling our proposed system. Prior art includes an approach based on the concept of stigmergy, where agents make decisions based on shared environmental conditions [79]. In this example, robots follow a linear path blueprint for structure assembly and use local rules and sensing to autonomously determine when and if to add a brick [80]. Success relies on gravity-based 2.5D construction to constrain the robot's motion to ±1 brick in *z.* Extension to 3D structures has been studied algorithmically [81], yet never implemented due to current hardware constraints. Given that our robot is capable of full 3D locomotion and (planned) construction, I aim to develop and implement full 3D distributed control and assembly. For this I will *A)* develop distributed algorithms for mobile robotic assembly (leveraging previous efforts on centralized), *B)* determine hardware and software for autonomous sensing in a 3D lattice environment, *C)* build prototypes and perform experiments demonstrating distributed control for full 3D multi-robot assembly. Comparisons between centralized and distributed with the same material-robot system should provide insight to efficacy and tradeoffs.

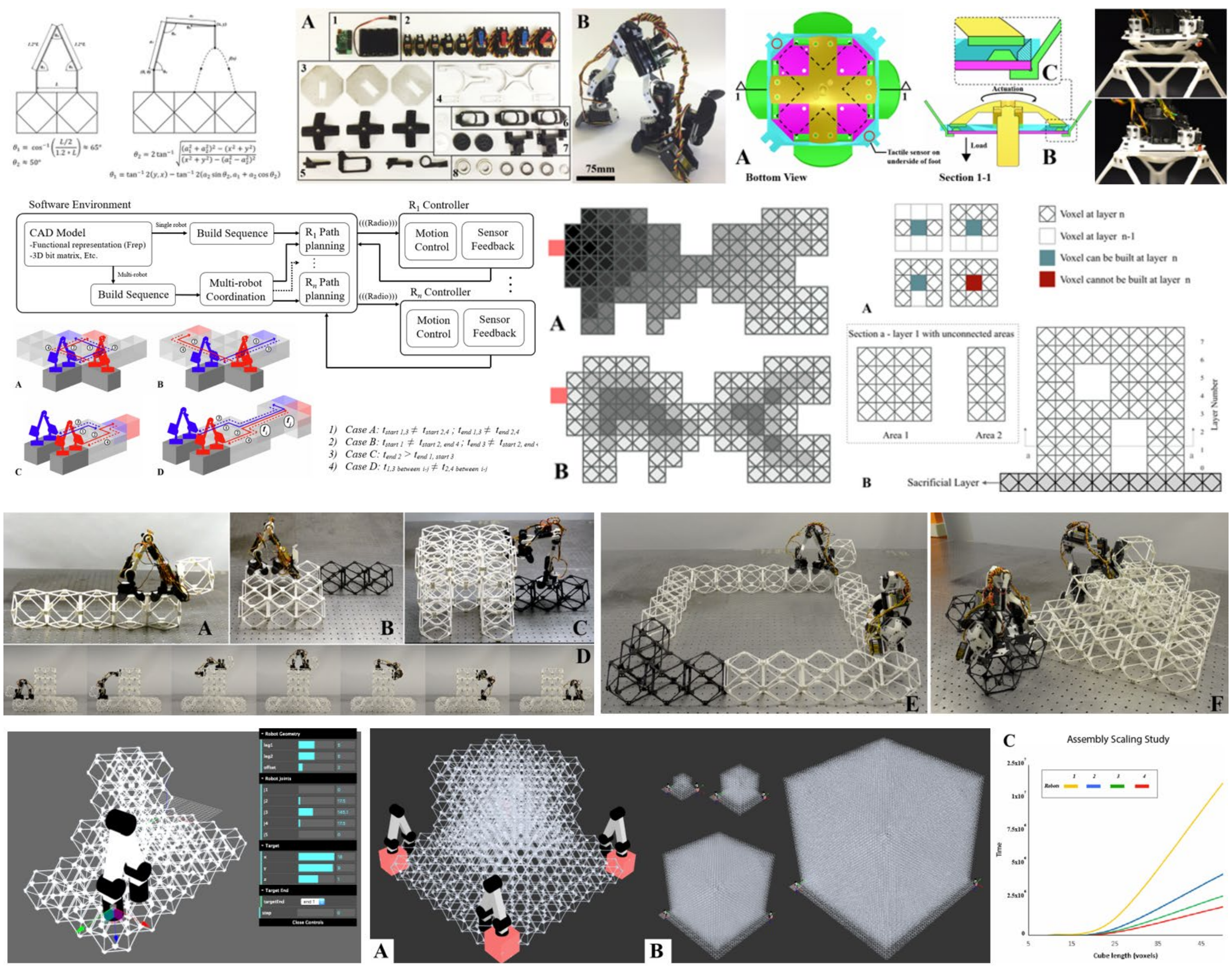


Figure 11: Relative Robotics current work. System Design (Row 1, L to R): Kinematics, actuation, end effectors, sensing. Control Strategies (Row 2, L to R):Centralized architecture, build sequence, coordination, path planning. Assembly testing (Row 3, L to R): 1D, 2D, and 3D construction, global precision using local metrology, multi-robot construction. Software environment (Row 4, L to R): single robot control and motor outputs, multi-robot simulation, large scale simulation and evaluation.

5.3 Discrete Systems

The core goal of this topic will be to demonstrate discrete systems with novel properties for applications not attainable with current approaches. I discuss prior art, then current and proposed work subtopics of scalability, performance, and manufacturability, for transportation and infrastructure applications in land, air and space

Prior Work

In [66], we presented an ultralight CFRP lattice material system which is assembled, disassembled, and reconfigured into a 5m span bridge, a boat, and a shelter. Reconfigurability of a single material system into multiple, high performance structures is desirable in applications where resources are limited, such as exoplanet missions where a single payload of parts can perform multiple functions for a given mission [82]. In [83], we presented a 1m scale discretely assembled aerostructure with programmed anisotropy for application as a morphing wing. Here, heterogeneous lattice geometries are combined to result in a structure that is stiff in bending but compliant in torsion, allowing tip twist actuation and global shape change for roll control with reduced drag. The outer mold line was achieved using highly customized parts, reducing the utility of this particular system for other geometric configurations. In [35], we presented a more scalable and generalizable manufacturing system showing net shape production for a ultralight, morphing aircraft. Here, heterogeneous materials were utilized to tailor passive and active aeroelastic morphing of a 4m aircraft in response to aerodynamic loading during wind tunnel experiments. This scale and behavior are enabled by the discrete material approach. In [84], we presented analysis and simulation of a discretely assembled 40m diameter tetrahedral truss plate with application as an atmospheric decelerator (aerobrake) and a precision segmented reflector (telescope), which are governed by strength and stiffness requirements, respectively. Here, discrete materials are used to offer performance tunability at low cost, while also reducing mass compared to traditional structural approaches.

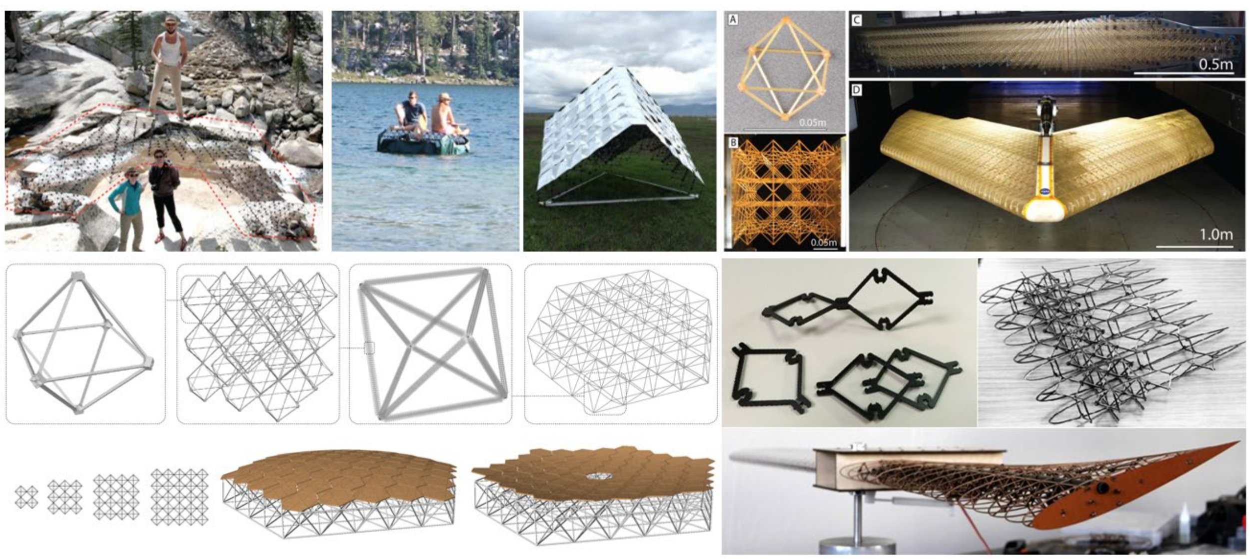


Figure 12: Discrete Systems prior work. Discretely assembled bridge [66]*, morphing wing* [83]*, BWB* [35]*, Space Structures* [85].

Current/Proposed Work

Ground transportation: Here I look at applying high manufacturability ultralight cellular materials to make a Supermileage vehicle in collaboration with an industry partner. The strategy employed here is quite similar to [35], where a discrete material system is mass produced to build a high performance structure, then is fit with a finite set of interface parts and skin elements to form an outer mold line. The overall geometry is a balance between aerodynamics and manufacturability and approximates a NACA profile using only 1:1, 2:1, and 4:1 slopes. The performance of the vehicle is driven by mass and first natural mode, which were set at <20kg and >30 Hz, respectively. After the outer mold line is determined, I use scaling laws to predict various effective densities and stiffnesses based on molded parts made of 33% glass fiber reinforced nylon. Using continuum assumptions, I am able to quickly assess performance of various lattice densities, ranging from 10 to 50 kg/m^3, and show ~30 kg/m^3 is a good solution, for a resulting mass of 15kg and first natural mode of 50 Hz. This behavior can then be verified against a full lattice beam simulation. For quick reduction to practice, blind rivets are selected as the fastening hardware. This allows single-sided access and requires one fastener piece per joint. The final vehicle will consist of 1000 voxels (6000 individual molded faces), 24,000 rivets, and will be 3m long. Aluminum plates with hole patterns to match the lattice will be fabricated to integrate motor/drivetrain, wheels, and seat. The structure is currently in production and is expected to race in June 2019.

Air transportation: Here I look at applying tailorable cellular materials to make morphing aerostructures for use in commercial aircraft control flaps. Chordwise airfoil morphing can be used to control trailing edge geometry for improving lift to drag ratio, or for roll control authority, with potential for improvement in fuel efficiency [86]. The trailing edge is a triangular cross section, 300mm deep, 80mm high, and 8m long. Objectives for this project include a low-cost, scalable manufacturing method which can utilize high performance CFRP and comparing distributed and centralized actuation systems. The method employed here is similar to [83], where a uniform lattice geometry is modified to fit into an airfoil section, and then decomposed into intersecting planes (*x, y, z)*, which are then waterjet cut from quasi-isotropic CFRP sheet. Press fit joints between members constrain 5 of 6 DoF, with the last degree being taken up by a zip tie. The proposed skin system is discretized chordwise into strips that overlap slightly, from leading to trailing edge. These strips span a single lattice pitch in the chordwise direction and are fixed to the lattice with shoulder bolts which screw into custom threaded components that sit atop the lattice nodes. These bolts pass through chordwise slots in the trailing edge-side of each strip, constraining in the direction normal to the strip surface, but allowing it to slide relative to the bolt, thus allowing outer mold line chord length to change passively while maintaining a continuous aerodynamic surface. Morphing is achieved using a pair of cables that attach at one end to a lattice node at the trailing edge, and at the other end is fixed to a drum/spool mounted to a motor. Thus, with a single degree of actuation, the trailing edge tip can be deflected up or down through clockwise or counterclockwise rotation of the drum. This applies a tensile force in one of the cables, pulling the tip towards the leading edge, and slightly up/down, which, due to the lattice geometry, results in a global shape change of the lattice substructure, as shown below. A proof of concept prototype has been built using Delrin for the lattice material and high torque COTS servo motors for distributed actuation. The future work for this application includes fabricating a high-fidelity CFRP version and actuation selection. This will be a wind-tunnel ready model, date and location TBD (expected Fall 2019).

Atmospheric infrastructure: Here I look at applying high performance cellular materials to a make a vacuum airship. A vacuum balloon is a structure which weighs less than the air it encloses when evacuated, yet stiff enough to withstand the external pressure load without buckling. Assuming a thin shell geometry ($R/t > 10$), I can derive the structural requirements of a material used to make this shell based on the density of air and equations for sphere buckling. For a sphere of outer radius R, with shell thickness t, material elastic modulus E and Poission's ratio v, the critical buckling pressure is $P_{cr} = 0.8E/\sqrt{1-v^2} \cdot (t/R)^2$. To achieve net buoyancy, the mass of the air in the sphere (m_a= 1.125 $kg/m^3 \cdot 4/3\pi \cdot R^3$), must be less than mass of the structure ($m_s = \rho_s \cdot 4\pi t R^2$). Assuming a pressure P=1 *atm* (0.1 MPa) and v =0.3, combining these equations results in a minimum value for our material E/ρ^2 > 7.25e5 Pa/(kg/m^3)^2. A commercially available high modulus carbon fiber epoxy with a Young's Modulus E = 450 GPa and density ρ = 1522 kg/m^3 has a value of E/ρ^2 > 1.94e5 *Pa/(kg/m^3)^2* [54], which is less than 1/3 of the required value. I propose a discrete cellular material made from Ultra High Modulus CFRP tubes with E = 282 GPa and ρ = 1596 kg/m^3. While this is a comparatively worse material, it is commercially available in multi-layer, high stiffness tubes, which can be used to make an ultralight, ultra-high modulus lattice. At an effective density ρ^*= 10 kg/m^3, and assuming linear scaling lattice geometry, this could achieve a theoretical effective stiffness E^* = 0.5 GPa, resulting in a performance metric E^*/ρ^{*2} = 5e6 *Pa/(kg/m^3)^2*, putting it nearly an order of magnitude above the required value. Quasi-static and dynamic stability must be verified. The future work for this application includes designing, simulating, prototyping, and testing joints and skin, as well as determining a minimum diameter for building a partial scale system prototype.

Space infrastructure: Here I look to leverage the scalability of discrete materials and relative robots to investigate a notional kilometer-scale space structure. I will focus on aspects of construction dynamics, scalable algorithmic strategies, and logistical optimization. The quasi-static and modal behavior of a kilometer-scale space truss is described analytically in [87], using a simplified model of the structure as a large, flat plate. A relatively under-developed aspect is the dynamic behavior of such a robot-structure system mid-build. Theoretical approaches for decoupling on-orbit robot and structure dynamics are presented in [88], but in this case, robots are assumed to be able to propel themselves in free space on orbit, and structural elements are assumed to be long, flexible beams. In our case, robots are always attached to the structure, and assembly units are small. Regardless, these mobile robots, which have non-trivial mass compared to the units, can cause excitations while performing locomotion or assembly tasks. In collaboration with colleagues at NASA Ames, we will experimentally characterize the natural frequencies of a cantilever beam under 1g and investigate how a mobile robot can cause destructive and constructive modal excitations, the latter of which could be utilized to benefit the performance of the structure, given periodic actuation routines.

Algorithmically, a distributed system will scale more favorably [78], but simple gradient or source/sink approaches may be sub-optimal. In addition, the computational requirements for very large system compilation should not be ignored, and recent work has shown that significant improvement over basic search-based compilers for mobile robotic assembly can be obtained [89]. Here, a constraint satisfaction problem approach is shown to scale nearly linearly for number of part *n* up to 10^6, where runtime in seconds is $t \approx n * 10^{-4}$. They also show improvement of transition probability based on distance fields for a 30x time improvement for multi robot team building a structure with order 10^2 parts. In our case, a full 3D isotropic strategy will be developed, which will seek to expand algorithmic approaches for sparse (as opposed to monolithic) structures with hierarchy. Finally, for large structures, a single, stationary part depot presents several issues. One is bottleneck of robots picking up parts, and while this can be addressed with queuing [45], for large numbers of robots, this will be highly inefficient. Another issue is that the number of steps (*s*) increase as the square of the number of voxels (*n)*, where *s = n(n+1)/2*, so for large values of *n*, $s \propto n^2$. To improve upon this, I can investigate mobile part depots. Balance between robot and depot saturation will be studied. Resource management (ie: when a new payload of parts arrive, how to determine how they are distributed to depots) may result in hierarchical transportation networks, where maximum area is covered by a branching system of material supply flows which minimize energy waste [90] as it relates to a system of active, energy-consuming robots [91]. These systems will be investigated and simulated in collaboration with CBA and NASA colleagues.

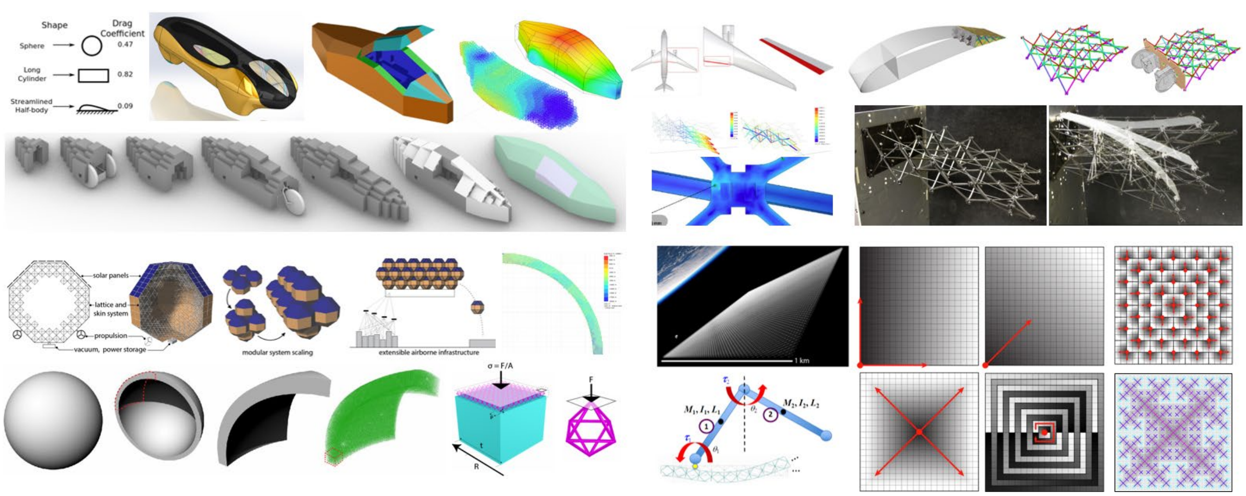


Figure 13: Discrete systems current/proposed work. (Clockwise from top left) Supermileage vehicle, morphing aerostructure, kilometer solar array, vacuum airship.

6 Evaluation

Within each topic, I have a number of qualitative and quantitative performance criteria I wish to achieve. Comparison to state of the art using normalized metrics will provide insight to the utility of this approach.

Evaluation criteria are the following:

1. Efficacy of relative robotic assembly
2. Functionality of discrete material systems
3. Comparative performance of discrete system applications.

Our discrete material system can be quantified in terms of mechanical properties, such as effective stiffness, strength, and density, which are determined empirically with traditional coupon testing, and compare to analytical and numerical results, for linear and non-linear behavior. Failure modes will be studied and quantified for effective strength properties. Effective density must include hardware/fastener mass, which is considered parasitic, in that it does not entirely contribute to effective stiffness, so its inclusion lowers effective specific stiffness (E^*/ρ^*). I can quantify manufacturing properties such as cost, throughput, and embodied energy. Cost can be calculated per unit volume and mass of effective structure (composed of many parts). Throughput includes molding and pre-robot assembly time. Currently voxels are manually assembled, though this could be automated in future research.

For relative robots, first, I can quantify single and multi-robot assembly frequency and compare this to other mobile robotic assembly platforms. Then, I can compare mass and volumetric throughput of robotic assembly to continuous processes such as FDM, SLM, and Polyjet printing. Next, I wish to show that a locally precise robot can build a globally precise structure. I will have single and multiple robots build branching structures that converge some distance away from their shared origin, where this convergence relies on elastic averaging. Analytically, Hiller showed that a stacking pyramid of n voxels with a random standard deviation σ would result in a structure with a theoretical dimensional precision $\varepsilon \approx \sigma\sqrt{n/14.7}$. Both Popescu [92] and Gregg [84] show that increasing the cross section of an $n \times n$ beam will decrease beam length error and beam tip deflection. This has not been demonstrated for large, sparse structures, where elastic averaging and high specific stiffness appear to be orthogonal objectives. For dynamic range, I plan to show large scale assembly of a >10^2 voxel structure. At smaller scales, I will show reconfiguration, from a base set of parts to a 1D, 2D and 3D structure. Finally, I plan to present normalized data supporting selection of stationary vs relative robotic assembly at multiple scales, addressing aspects such as quantification of robotic complexity and resulting cost. This will include control complexity (spatial resolution * # DoF), cost per mass and volume of task and workspace, and actuation and dynamics for high throughput assembly.

For discrete systems, application-specific metrics are important. For ground transportation, I can look at aspects related to motive efficiency, such as specific resistance, for example. This metric, first presented by Gabrielli and von Karman [94], relates mass and speed to power. Lightweight, aerodynamic vehicles can be demonstrated to offer improvement over traditional approaches. For adaptive aircraft, I plan to demonstrate maneuver control authority, as well as quantifying projected large scale system performance. Experimental control over values such as *L/D* at various angles of attack (AoA), with normalization by actuation torque requirements (τ) and combined system mass (m) will allow analysis of extension to larger scales, as well as comparison to other approaches [52][86]. For atmospheric infrastructure, I can quantify performance-related aspects such as net buoyancy (F_B) as a function of airship diameter (d), as well as stiffness of the lattice as it relates to the square of the density (E^*/ρ^2). Additional subsystems such as power budget (in: solar, out: vacuum maintenance, propulsion) and navigation will be addressed pending a collaborative study with industry partners. For space structures, I can compare to prior art in terms of throughput and structural performance. Previous NASA studies include on-orbit EVA assembly testing [14] [96], ground-based simulated EVA assembly [39], and ground-based robotic assembly [40]. Algorithmically, I plan to show assembly performance across a number of scales, selecting previous studies with quantified output metrics to compare with. Structural performance of actual flight hardware is well documented [97], and this can be used to compare to our experimental results and high-performance projections. Lastly, in [98], Gregg *et al* present a study on the benefits a modular, reconfigurable material system can offer for space applications. In particular, it is shown that significant mass penalties result from having to withstand launch acceleration ($m \propto \sqrt{a}$) and modal excitation ($m \propto \omega_1^2$). This is the basis for the argument of flat-packing a structure for on-orbit assembly that I will develop for notional missions.

Table I. Robotic Assembly Demonstration Goals

Goal	***Property***	***Details***
Scalability	Extensibility	$>10^2$ parts
Coordination	Parallelization	> 1 robots (centralized, then distributed)
Error detection/correction	Incrementality	Locomotion, part placement, repair
Local/global precision	Elastic averaging	1D, 2D, and 3D branching structures
Reconfiguration	Contiguity requirements [78]	27x1 1D beam → 5x5(+2) 2D plate → 3x3x3 3D cube

Table II. Robotic System Evaluation Criteria

Criteria	***Metric***	***Notes***
Control Complexity	(Joint Spatial Resolution * # DoF) / Resolvable Unit Vol.	Minimal, "1-Bit" relative robot will be designed
Task/workspace cost	\$/kg, \$/m^3, computational cost/yield	We expect stationary to outperform at small scales
Actuation and dynamics	*τ, power, EI, ω*	Study to include scaling up gantry to km scale.

Table III. Discrete Material Evaluation Criteria

Goal	***Value***	***Details***
Effective Stiffness Scaling	$E \propto \rho^{<2}$	For robotically assembled material
Effective Strength Scaling	$\sigma \propto \rho^{1.5}$	For robotically assembled material
Manufacturability	\$/kg, \$/m^3	Compare to state of the art materials

Table IV. Discrete System Parameters

Application	***Property***	***Scale (m)***	***Altitude (km)***	***Fidelity (1-10)***	***Metric***
Supermileage Vehicle	Manufacturability	10^0	10^0	Full-scale test (10)	*Mpg, mass, cost*
Morphing flap	Tunability	10^4	10^1	Partial-scale test (7)	*L/D, mass, cost*
Vacuum Airship	Performance	10^5	10^1	Prototype (5)	F_B*, mass, cost*
Kilometer solar array	Scalability	10^6	10^3	Study (3)	*ω, mass, volume, cost*

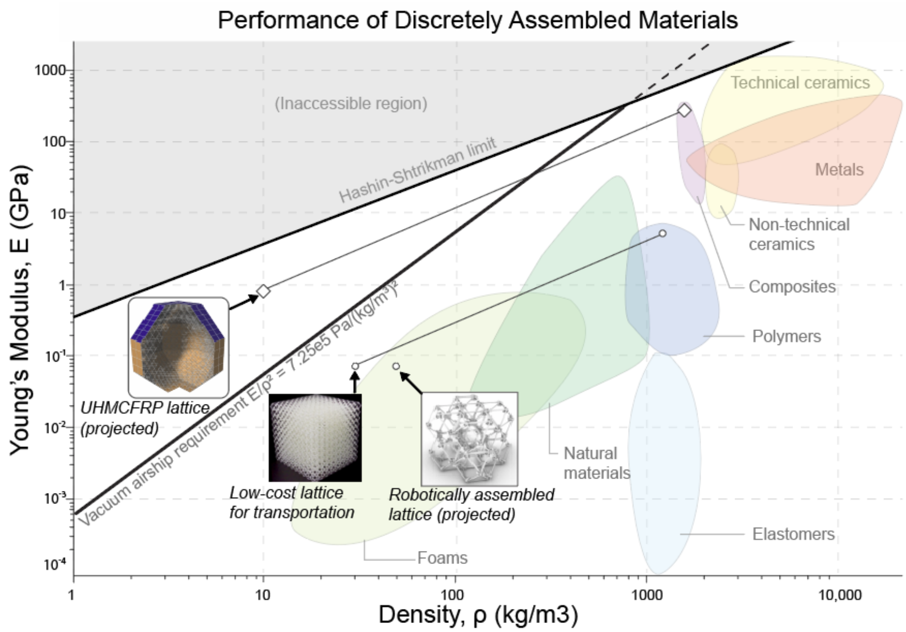


Figure 14: Projected discrete material properties for robotic assembly, low-cost transportation, and LTA buoyancy. Objectives include accessing novel material property space and defining performance of robotically assembled materials.

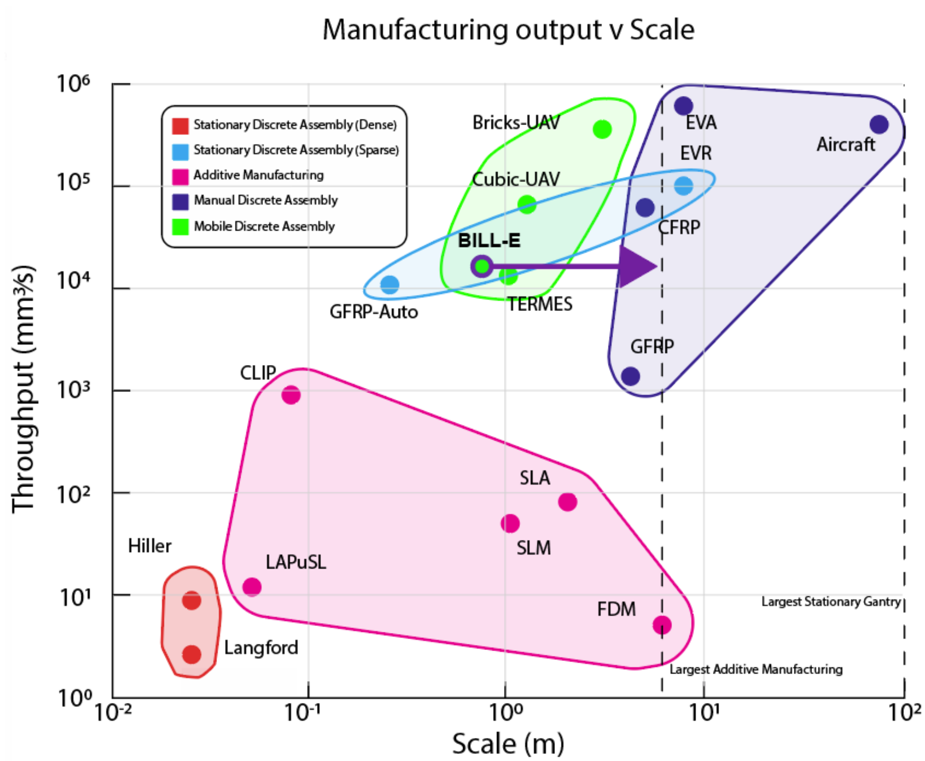


Figure 15: Current and projected robotic throughput and scale, with direction of projected performance indicated. The goal is to maintain high volumetric throughput at larger scales to compete with state of the art assembly.

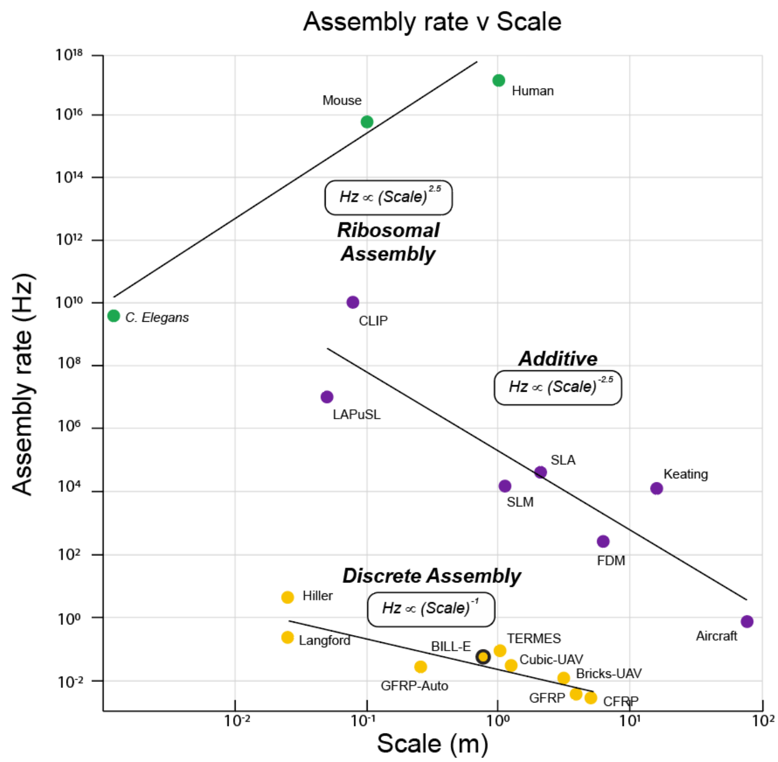


Figure 16: Assembly rate v Scale. The positive slope of biological growth is attributable to recursion. While this thesis will not address recursion, I will demonstrate increased scale and throughput through parallelization.

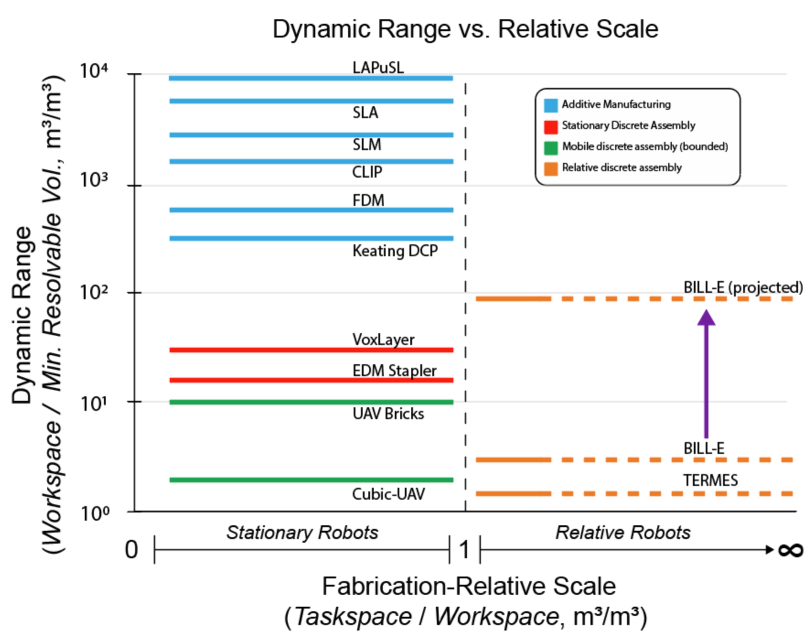
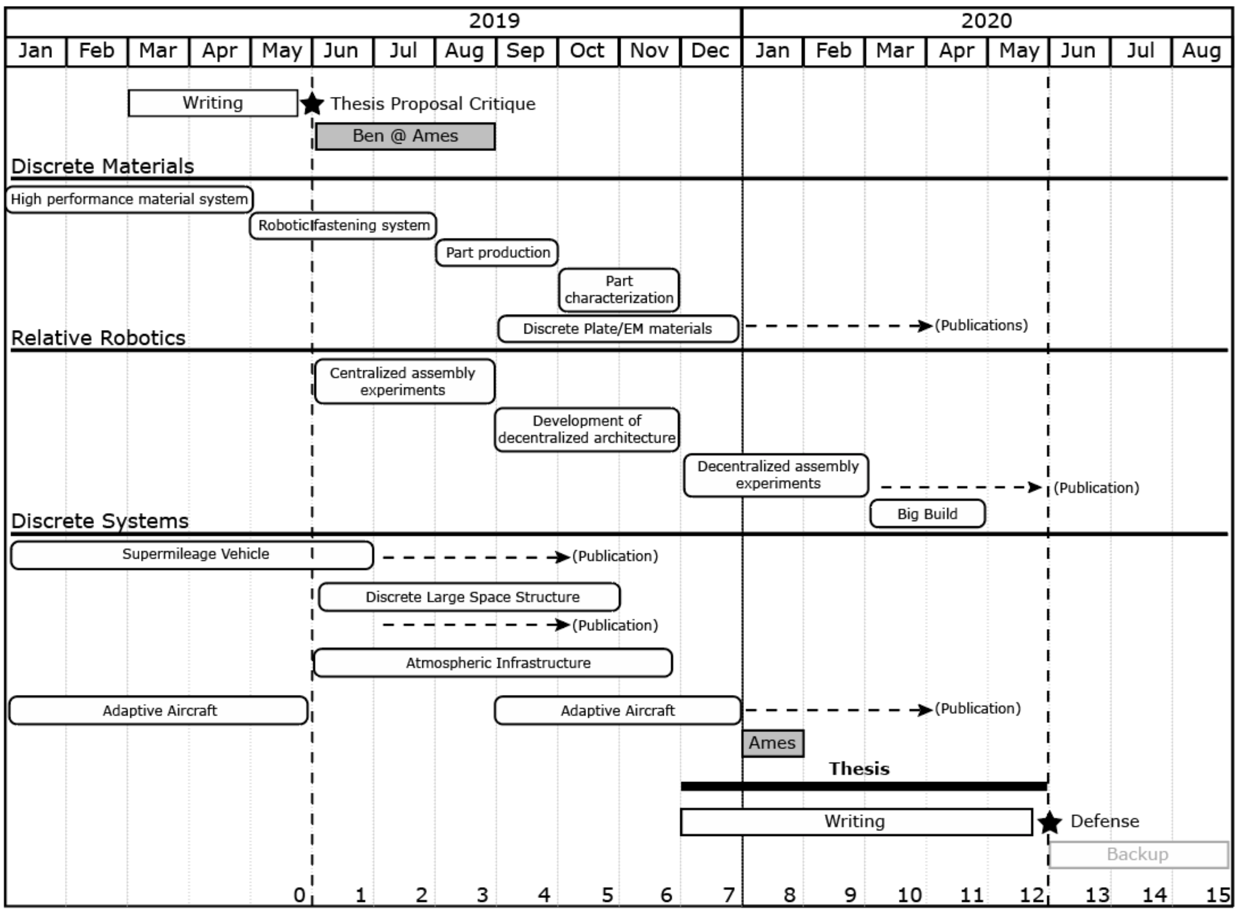


Figure 17: Stationary platforms have large dynamic range, but limited workspace. Relative robots can occupy an unoccupied part of parameter space for robotic fabrication.

7 Timeline

Table IV. Summary of Remaining Tasks

Discrete Materials		*Relative Robots*		*Discrete Systems*	
Task	***Completion***	***Task***	***Completion***	***Task***	***Completion***
Robotic Fastening System	July 2019	Centralized Assembly Experiments	Sep 2019	Supermileage Vehicle	June 2019
Part production	Sep 2019	Decentralized Architecture	Nov 2019	Space Structure Study	Oct 2019
Part characterization	Dec 2019	Decentralized Experiments	Feb 2020	Atmospheric Infrastructure	Nov 2019
Plate/EM Materials	Jan 2020	Big Build	Mar 2020	Adaptive Aircraft Testing	Dec 2019



8 Resources

This thesis will utilize many of machines and tools presently available at CBA. Discrete material prototyping can be done with a variety of 3D printing methods (FDM, Polyjet), and high fidelity material systems will be fabricated using our OMAX waterjet (CFRP) or manufactured at scale with injection molding (Protolabs). Joints, assemblies, and structures can be load tested quasi-statically using our Instron machines. Material system behavior will be simulated using commercial FEA packages (Oasys, Abaqus/COMSOL). For Relative robots, actuators, sensors, and electronics hardware can be purchased from commercial vendors. Robot structures, mechanism, and end effectors will be fabricated in-house using 3D printing, milling and laser cutting machines, with the option to outsource for batch production. Experiments can be performed in our lab, unless larger space is required (ie: E15 atrium). Large scale simulations (> 10^3 voxels) can be performed on our high performance computing station. Discrete systems may require different testing infrastructure depending on their scale and level of maturity. Both the ground and air transportation will be tested, the former in Japan on a racetrack, and the latter in a wind tunnel (likely in Germany). Depending on the scale of the air infrastructure prototype, collaboration with an outside aerospace company may result in an off-site location for construction and testing (ie: warehouse). Space infrastructure concepts may be tested at small scales, for example, integrating COTS solar arrays.

Publications

Feasibility study of a kilometer solar array using discrete lattice materials and distributed mobile robots, B. Jenett, C. Gregg, K. Cheung, *IAC 2019*, (abstract accepted).

Discretely assembled 3D plate-lattice structures, B. Jenett, C. Gregg, K. Cheung, *IASS 2019*, (abstract accepted).

Material-Robot System for Assembly of Discrete Cellular Structures, B. Jenett, A, Abdel-Rahman, K. Cheung, N. Gershenfeld, *IROS RA-L*, (currently under review).

Elastic Shape Morphing of Ultralight Structures by Programmable Assembly, N. Cramer, D. Cellucci, O. Formoso, C. Gregg, B. Jenett, J. Kim, M. Lendraitis, S. Swei, G. Trinh, K. Trinh, K. Cheung, *Smart Materials and Structures*, (2019). https://iopscience.iop.org/article/10.1088/1361-665X/ab0ea2

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