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Hierarchical Assembly of a Self-Replicating Spacecraft

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Abstract—**Extraterrestrial fabrication of spacecraft by current best-practice manufacturing methods is complicated by the need to integrate thousands of unique parts, each made using a diversity of processes and raw materials. Reducing this complexity could enable exponential space exploration via self-replicating spacecraft (known as Von Neumann probes). We propose a hierarchical model for machine design, based on 13 reversibly-assembled part types, reducing the complexity of machine self-replication and bridging prior work in the areas of in-situ resource utilization (ISRU) and modular robotics. Analogous to amino acids in biological systems, these parts form a basis set for the electronic and mechanical subsystems of an exploratory spacecraft. In simulation we validate representative subsystem designs and develop a hierarchical architecture for the design of mechanisms, actuation, and electronics. By standardizing and modularizing the parts, we drastically reduce the diversity of the required supply chain as well as the minimum viable payload mass. We estimate that a seed launch could contain approximately 10^5 parts, fit within the envelope of a 3U cubesat, and enable the assembly of over one hundred self-replicating assemblers.**

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1. INTRODUCTION

Motivation

Extraterrestrial fabrication of spacecraft by current best-practice manufacturing methods is complicated by the need to integrate thousands of unique parts, each made using a diversity of processes and raw materials [1]. Reducing the complexity of extraterrestrial fabrication could enable exponential space exploration via self-replicating spacecraft (known as Von Neumann probes).

We propose an approach that discretizes robotic systems at a much finer granularity than prior work in modular robotics and show that complex systems can be assembled from a small set of functional part-types. In our prior work, we have demonstrated the assembly of functional electronic devices from three single-material part-types. Our proposed approach extends this by introducing flexural, actuating, and semiconducting elements. We outline 13 part-types necessary to assemble actuated robotic systems, including an assembler made out of the parts it assembles. In this way, the parts are analogous to amino acids in biological systems—forming a basis set for electronic and mechanical subsystems of a self-replicating spacecraft.

Our assembly system drastically lowers the barrier to in-situ resource utilization (ISRU). Rather than recreating the complex material workflows and processes that exist in terrestrial manufacturing, we show that ISRU efforts can be focused towards the creation of this small set of part-types from which a large diversity of spacecraft can be assembled.

Background

Our work draws on prior studies of space-focused self-replicating systems, modular robotics, and in-space manufacturing.

Many researchers see additive manufacturing as the most promising fabrication technique for space [2]. There has been recent interest in 3D printing as a means of manufacturing spacecraft, and their parts, both on- and off-Earth [3]. This hopefulness, in large part, rests on the ability to print functional devices with a range of materials. While there is a great range of 3D printing techniques, which work with a number of different materials, the processes are still generally restricted to a single material at a time; those that can print with multiple materials simultaneously are typically limited to printing polymers with a narrow range of material properties. While additive manufacturing capabilities will certainly be useful in developing off-Earth manufacturing workflows, they do not span the required material diversity and will need to be complemented with alternate manufacturing and assembly capabilities.

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Modular robotics attempts to alleviate the problem of in-situ fabrication by standardizing parts and enabling a large number of identical modules to be reconfigured to suit a particular application. However, these robots have had little impact outside of the research lab. In their current form, they are not a cost-effective technology for space applications; each constituent module is made highly complex by the need to incorporate power, computation, networking, actuation, and control in a single unit [4]. A branch of modular robotics which focuses on heterogeneous architectures with active agents and passive structural members may be most promising for space applications. These robots move on or relative to a lattice and are able to manipulate and build upon the environment that they move in [5] [6].

The development of in-space manufacturing capabilities and modular robotics architectures are important steps towards self-replicating systems. Research in self-replicating hardware is in early stages and most prior work addresses high-level system design challenges including hierarchy and scale [7] as well as required ISRU capabilities and launch requirements for self-sustaining factories [8]. Other prior work has looked at lower-level implementation details and established methods of creating self-replicating systems with macroscale building blocks. Moses et al. built a universal constructor system, for example, using 18 part-types that is capable of assembling some of its own subsystems [9]. However, the parts have a high-degree of embedded complexity, including conventional actuators and processors, which limits the usefulness of such a system.

With the ability to self-replicate comes the opportunity for a spacecraft, probe, or rover to reconfigure, repair, or adapt itself to its environment. These abilities are desirable for the efficiency and flexibility of space exploration missions. Such missions include evaluating locations on Mars for future human settlement, searching moons within our solar system (including Europa for signs of life), and probing asteroids to test for material composition. Failure or errors can arise from unexpected landing configurations, such as when the Rosetta mission's Philae spacecraft landed incorrectly on an asteroid, resulting in its batteries running out after two days due to being unable to charge them with its solar panels. Numerous attempts have been made or proposed for reconfigurable spacecraft. Ferguson et al. proposed a transforming rover system with basic mechanisms capable of expanding, dividing, and reorienting [10].

In our prior work, we have shown that with two single-material part-types (conducting and insulating), it is possible to route arbitrary electrical traces through three dimensional volumes. Furthermore, with the addition of a resistive part-type, any passive electronic component (capacitors, inductors, and resistors) can be constructed through the geometric placement of parts [11]. More recently, we have developed computer aided workflows and robotics to automate the assembly of these structures [12].

Compared to our prior work using single-material parts, our proposed approach embeds additional functionality within the parts. With N- and P-channel transistor parts, it is possible to assemble logical functions and circuitry. Furthermore, with coil, magnetic, and flexural parts, Lorentz force actuation between parts can be accomplished, enabling prismatic and revolute displacements of the structure.

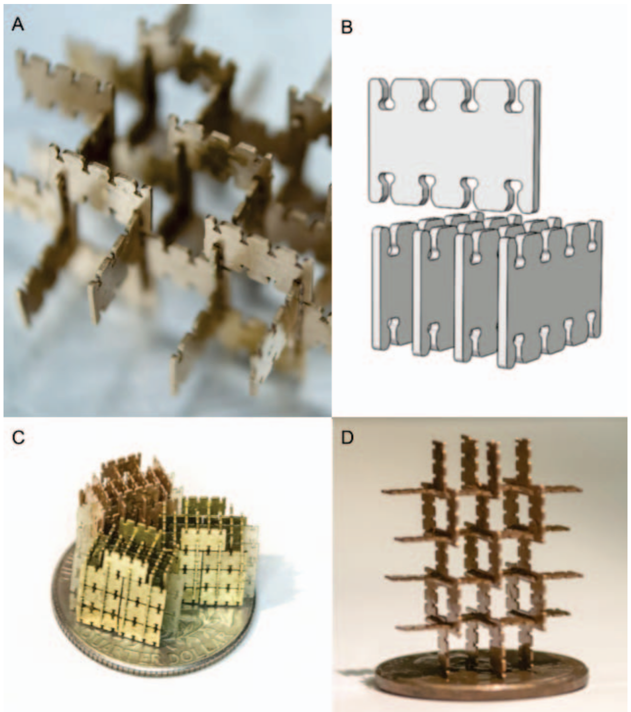

Figure 1. **Examples of various structures assembled from "GIK" [13] parts. (A) and (D) show structures assembled from bronze parts. (C) shows three assembled capacitors and (B) illustrates the interlocking slots that join the parts.**

2. DESIGN ARCHITECTURE

In this section, we detail the architecture of a hierarchically assembled self-replicating spacecraft. First, we describe the assembly architecture and part design that this work is based on. Then, working backwards from the requirements for an assembled assembler, we specify design decisions and constraints for building passive mechanical systems, actuators, and control circuitry from small-scale functional building blocks.

Part-Types

This work rests on the ability to join many discrete parts into three-dimensional structures, like those in Figure 1, through an incremental assembly process. Through the geometrical arrangement of the 13 parts-types enumerated in Figure 2, a diversity of actuated robotic systems can be assembled.

These parts are joined with a common interface, interlocking with neighboring parts to form a regular lattice structure. Primary considerations for the design of the part interfaces include ease of assembly and the ability to transfer mechanical loads and electronic signals to neighboring parts. The parts are designed to be assembled vertically so structures can be built incrementally, one part at a time. They can be easily fabricated at a range of length-scales using a variety of two-dimensional manufacturing processes; these processes include, for example, stamping and laminating, which enable high-throughput production. The simple mechanical interfaces between parts also enable dis-assembly, allowing for reconfigurability and reuse. Furthermore, the interlocking nature of these assemblies allows loads to be distributed

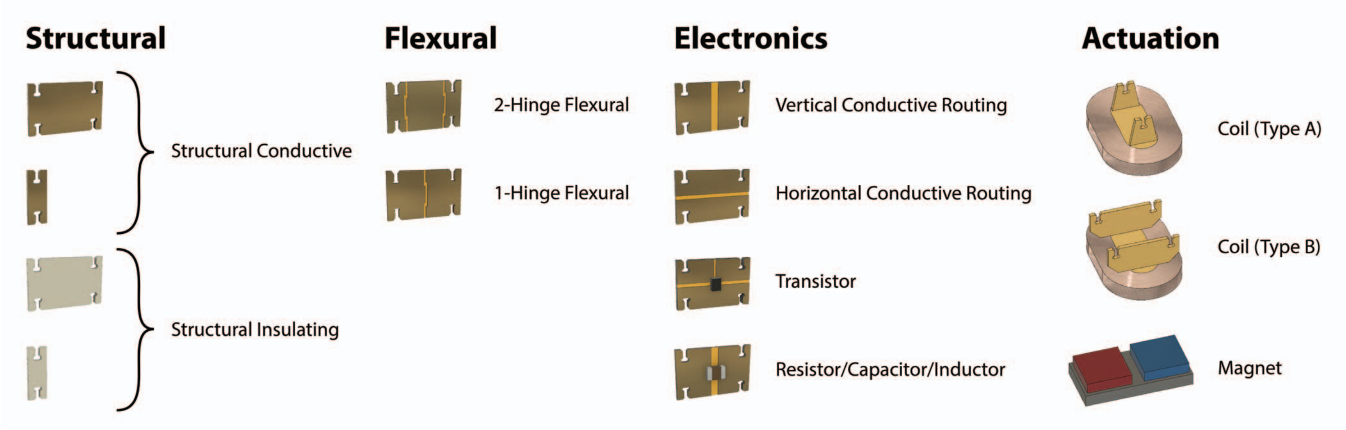

Figure 2. The part set. Thirteen part-types necessary to construct robotic functionality include: (Left to Right) structural parts that insulate and conduct, flexural parts with 1- or 2- degrees of freedom, electronic parts that switch and route signals, and actuation parts including coils and magnets.

through many parallel load-paths and means that the size of the assemblies is not limited by the strength of the individual parts.

These assemblies can be built at a number of different scales. In this work, we focus around the design of assemblies with millimeter scale parts. The parts are approximately 5 mm in their longest dimension with feature sizes on the order of 100 μm. This scale balances the functionality of a single part with the functional density of the assembly (number of parts per cubic volume). Furthermore, at the millimeter scale, electromagnetic actuation is still favorable and the available processes and materials are not as restricted as they are at smaller scales.

Hierarchy

Organizing all of these parts into higher-level systems requires hierarchy and modularity. We describe four levels of hierarchy: parts, modules, subsystems, and systems. These are analogous to primary, secondary, tertiary, and quaternary structure in molecular biology.

Parts are the most basic building blocks making up this system. Each of the 13 part types is a simple, functional primitive (3 actuation, 6 passive-mechanical, 2 conductivity, and 2 electronic). The parts structurally interlock with one another, enabling the construction of higher-level modules and ultimately all of the required functions of the spacecraft.

Modules are assemblies of parts that perform certain operations, such as locomotion, part manipulation, logic, and amplification.

Subsystems encompass the capabilities of the spacecraft. Example subsystem functions include assembly, communication, energy storage, energy capture, computation, structure, and mechanisms.

Systems are compositions of subsystems that form self-contained machines: in this case, the spacecraft itself.

The Assembler

The assembler is the key enabling technology required for a self-replicating spacecraft. The assembler is a machine that is capable, given a feedstock of parts, of assembling a diversity of spacecraft subsystems, including another assembler. To accomplish this, the assembler needs to be capable of assembling (and disassembling) parts as well as locomoting to position parts spatially. To demonstrate self-replication, we need to show that these capabilities (part manipulation and locomotion) can be assembled from discrete parts.

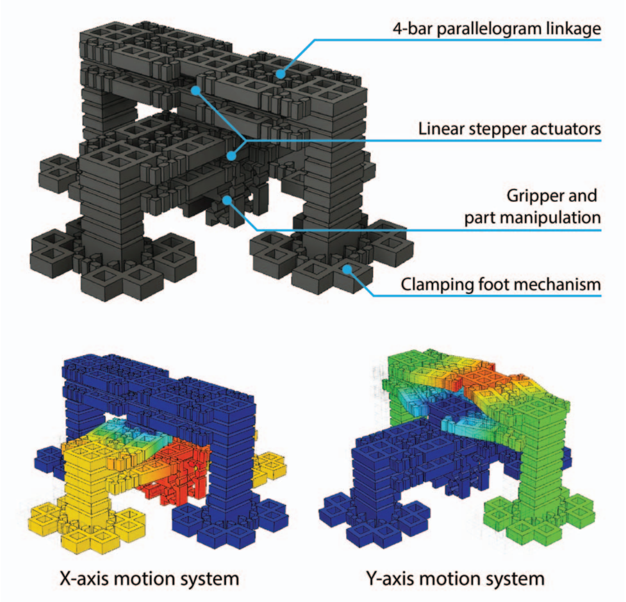

Figure 3. The assembler is assembled from a number of subsystems including linear motion modules, clamping feet mechanisms, and grippers that can manipulate parts. The assembler moves by actuating two of the feet at time.

In this paper, we assume that the self-replicating spacecraft is given a feedstock of parts from which to assemble further spacecraft. To be fully self-replicating, this feedstock of parts would need to be produced using in-situ materials and processes. While the methods which could be used to convert in-situ materials into usable building block parts are not in the scope of this paper, an increasing amount of research is being done in the area of ISRU and points to possible methods for the refinement of metal, polymers, semiconductors, and magnetic materials [14][15][16][17].

Furthermore, we consider a useful self-replicating system to be one in which the dynamic range between the complexity of the parts and the complexity of the assembly is relatively large. Which is to say, there is information and value added through the geometrical arrangement of parts.

We have found that part-manipulation and locomotion can be assembled from just three types of modules: linear motion, part-gripping, and lattice anchoring. A preliminary design of such an assembler is depicted in Figure 3.

Linear Motion: The assembler needs to be able to move by at least one lattice pitch. The precision of the movement only needs to be as good as the error correcting capability of the parts.

Part Gripping: The assembler should be able to move, manipulate, and assemble a raw feedstock of parts.

Lattice Anchoring: During locomotion and assembly processes, the assembler must clamp onto existing lattice geometry.

In turn, these modules can be assembled from functional parts. Using a linear motion stage as a representative example, in this section we will detail the hierarchical design of passive mechanical systems.

3. PASSIVE MECHANICAL SYSTEMS

Design

A classic challenge in mechanism design is the generation of straight-line motion from rigid links and revolute joints. Here, we demonstrate the assembly of a four-bar parallelogram linkage from three passive-mechanical part-types: rigid, single-hinge, and double-hinge. These parts are composed hierarchically to form cells and those cells are composed to form mechanisms, as shown in Figure 4.

We restrict our exploration of the design space to 2.5D structures. Because of the anisotropic nature of the assembled structures, we focus on developing functionality in-plane. Fully three-dimensional quasi-isotropic lattices are possible but not required for assembling the required mechanical functionality for a self-replicating system.

While a straight line mechanism could be constructed with as few as four parts (using rigid and double-hinged parts), and a revolute joint with as few as 3 parts (using rigid and a single-hinged part), these un-reinforced mechanisms do not scale to enable the constraint of long strokes against large off-axis loads; furthermore, un-reinforced flexural hinges like these are especially prone to breaking due to off-axis torsional loads [18].

On the other hand, by building mechanisms out of reinforced motion cells, our assembly architecture can scale to move substantial loads by large displacements. The four-bar parallelogram linkage can be thought of as the composition of three motion cells:

Shear cell: Four double-hinged parts combine to form a cell that can shear along both X and Y axes.

Revolute Cell: Single-hinged, rigid, and double-hinged parts form a reinforced revolute joint spanning two cells.

Rigid Cell: Four rigid parts combine together to form a rigid cell.

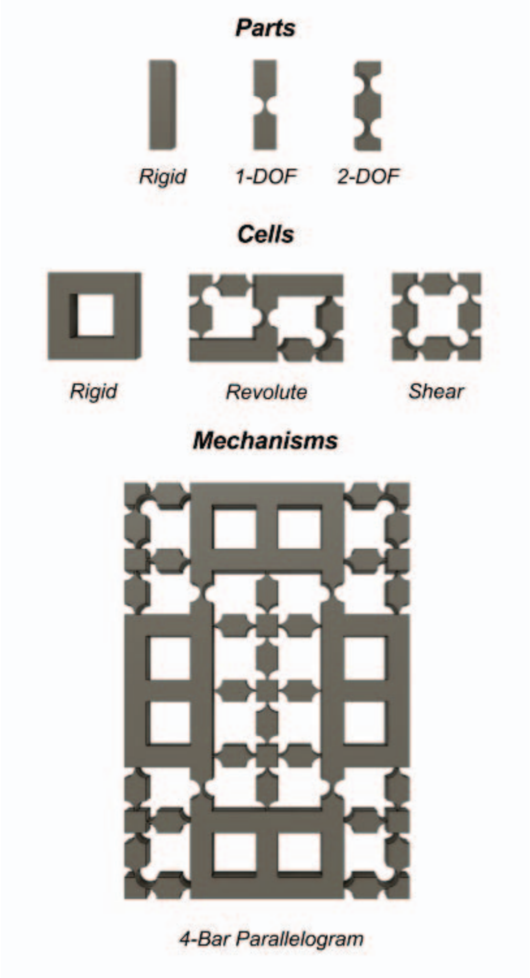

Figure 4. Passive mechanical systems have a natural hierarchy in which mechanisms break into cells and cells into parts.

A single four-bar parallelogram linkage approximates a straight-line motion within small angles of displacement. To achieve true straight line motion, two parallelogram linkages can be stacked on top of one another and superimposed to cancel their cosine errors. Furthermore, a mirror pair can be used to increase the off-axis stiffness of the mechanism. This kind of motion stage assembly is depicted in Figure 6.

Modeling

Using the design of the linear motion stage as a representative example, we will describe the design and simulation of such a device in a custom voxel-based CAD/FEA tool, AMOEBA [19], and show a scaled up physical manifestation of the device.

We represent the discrete parts in a number of ways throughout this paper depending of the level of abstraction warranted by the task. In AMOEBA (Anisotropic Modeling of En-

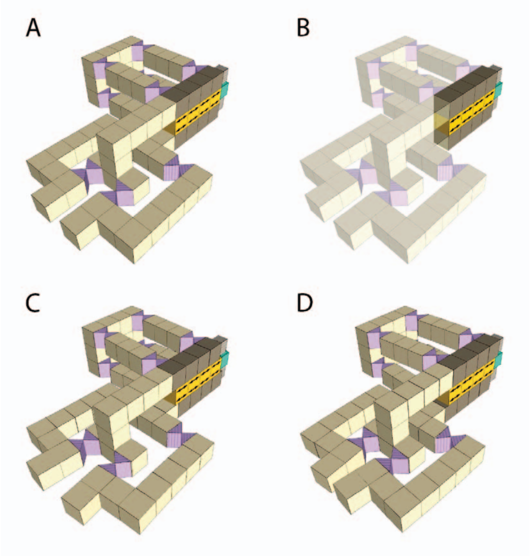

Figure 5. **Gripper mechanism modeled in AMOEBA (A) with electronic circuitry highlighted (B). Full stroke of shear actuators results in opening (C) and closing (D) motion of gripper.**

gineered Bits and Atoms), parts are represented as voxels, which exhibit characteristics of cell-level assemblies. To model the flexural mechanisms, the parts are represented as thick bars with flexural notches. Cells interact with their six face-connected neighbors through elastic interactions. These interactions are modeled using a dynamic spring-damper solver with non-linear handling of large angular deformations. An example mechanism is modeled in Figure 5.

Cells may contain internal degrees of freedom such as bending or shear. In these cases, a cell's stiffness in response to an applied force or moment is modeled anisotropically—stiff in some directions and flexible in others. Dithering of different material properties in adjacent cells is handled by precomputing a composite stiffness and damping constant for the cell-cell interaction.

Cells are defined not only by their mechanical properties, but also by their ability to transmit electronic signals from one face to another, and their active properties in response to a signal. Connected conducting elements within an assembly are precomputed and their electronic state is instantaneously updated at each time step of the simulation. We model actuation in AMOEBA through adjustments to the nominal position of an axial or rotational spring constraint.

Fabrication

To make the parts, we use a smart composite manufacturing (SCM) technique which involves machining (usually with a laser or wire-EDM) individual layers and laminating them together to achieve a functional device [20]. Parts produced in this way can be made in batches, enabling both rapid prototyping and relatively high-throughput production.

Looking at a specific example of this fabrication strategy, the double-hinge part is composed of five layers: two outer brass layers, a central Kapton layer, and two sheet adhesive layers (Pyralux) between them, which bond everything together when heated and pressed. This process is illustrated in Figure 7. The parts make use of castellated hinges [18] to ensure a high precision revolute joint is made. The flexibility of the Kapton enables very large angular displacements without yielding or fatiguing the material. These joints have been shown to be capable of handling many thousands of cycles (and up to millions in the right conditions) before failure [21].

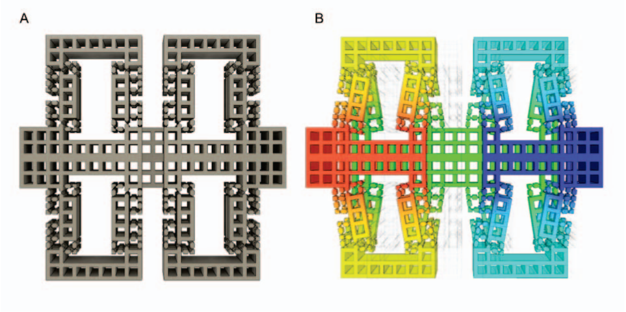

Figure 6. **The deformation of a linear stage made out of the three passive mechanical parts.**

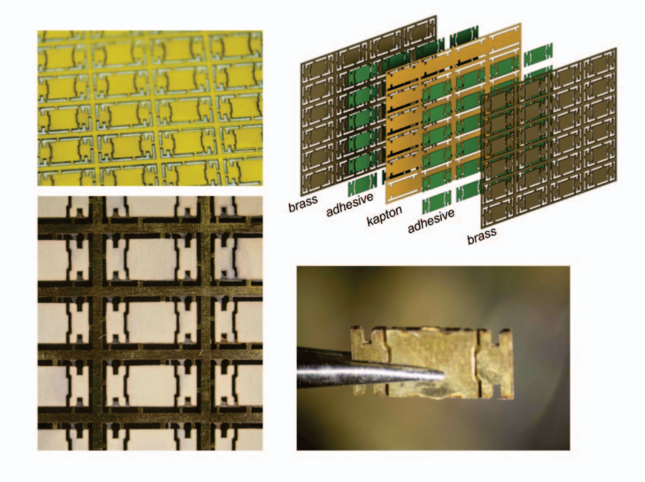

Figure 7. **The fabrication steps involved in manufacturing the double-hinge passive mechanical parts include layer stacking, heat bonding, and singulation from the scaffold.**

Results

Mechanisms made using our assembly approach have many advantages over conventionally machined mechanisms. For one, the flexural hinges are essentially frictionless and contribute minimal damping, allowing for very high-bandwidth actuation. The joints also have much larger angular strokes than monolithic single-material flexures; when properly designed, the flexural hinges can routinely accommodate 180 degrees of rotation.

We assembled a large-scale prototype of the parallelogram mechanism described previously. The same three part-types are used (single-hinge, double-hinge, and rigid) and are made using a laminate process from delrin and paper-reinforced double-sided tape. The assembly, pictured in Figure 8, consists of 48 parts and fits within a footprint of 15 cm by

10 cm. The flexure is able to displace by 50 mm, which is just over twice the lattice pitch. The stroke of the flexure is limited by the geometry of the shear cells; because of the offset imposed by the press-fit slot interfaces, the mechanism cannot shear completely.

We found that buckling of the flexural hinges in compression limited the out of plane bending stiffness of the assembly. This can be remedied by an improved no-buckling geometry which supports the hinge line from both sides so it is never put in compression [20].

4. ACTIVE MECHANICAL SYSTEMS

Given the ability to assemble arbitrary mechanisms, we need actuation components to make them move. A number of feasible actuation methods exist and their choice is scale-dependent. For structures assembled from millimeter scale parts, the most promising candidate actuation methods are piezoelectric and electromagnetic. At a larger scale, piezoelectric actuators cannot produce enough stroke and cannot match the energy density of electromagnetic actuators. Conversely, at smaller scales, electromagnetic actuation becomes unfavorable and electrostatic actuators become a more viable choice [22].

Actuation in an assembled lattice structure can take two forms: actuation within parts and actuation between parts. In this work we have chosen to focus on actuation between parts and specifically detail electromagnetic parts which can be used to assemble planar stepper motors of arbitrary size, shape, and power.

Design

Electromagnetic actuation is accomplished through the geometric arrangement of current-carrying wires in magnetic fields. To this end, three additional part types are required to embed actuation within these mechanisms: two coil parts (with different offsets with respect to the lattice) and a magnetic tile (Figure 9). Motion of the stage is achieved by alternating the direction of current through two offset coil pairs.

Both coil types are wrapped around a iron-less core. While an iron core would increase flux density, it would also produce a large attractive force downward (toward the magnets), potentially causing a corresponding unwanted displacement.

The magnetic tiles are made of a high permeability steel to serve as a flux guide and increase the available flux for force production; their thickness is specified to be just thick enough to avoid saturation. With a 250 μm air gap between the coil and the neodymium magnets, a field of approximately 0.2 T can be achieved. Current flowing through the coils interacts with the Y-component of the magnetic field and produces a translational force in the X-direction.

Modeling

We performed a magnetostatic simulation of our coil and magnetic part-types using the multiphysics package COMSOL (Figure 10). The amount of current that can be sent through the coils is limited by thermodynamics, and specifically the tolerable temperature rise of the magnet wire's insulation. With a 75°C increase in temperature (modeled conservatively assuming conduction through air), the coils are capable of dissipating 100 mW of power, which equates to a current of 0.1 A given our geometry. With 40 AWG wire, we are able to fit 200 turns into each coil, giving a potential force of 60 mN when the coil is centered on the poles of the magnets.

Results

To make sense of this force, we can compare it to the weight of a typical part in our assembly architecture. If we conservatively assume that the part is made of aluminum, each one has mass of approximately 10 mg. The force from a single coil pair, therefore, is enough to lift 460 parts in a 1G environment. A linear motion stage with approximately 1000 moving parts needs just three coil pairs to move against gravity.

In space, the primary form of heat transfer out of the system is radiation. For this reason, the thermal conduction path of heat to an efficient radiator on the skin of the spacecraft would have to be considered. This would likely involve using the core of the coil to conduct heat to the rest of the structure, using conductive parts as conduits for heat exchange.

5. ELECTRONICS

Control and computation are broken down into discrete units and assembled in a similar fashion to the passive and active mechanical systems. In contrast with existing technologies for fabricating integrated circuits, our assembly architecture enables three-dimensional routing of wires and control signals.

Design

In our previous work we demonstrated the assembly of electrical traces and passive electronic components (inductors, capacitors, resistors) from three, single-material part types [12]. With the addition of two more part-types: an N-channel and P-channel MOSFET, it is possible to assemble arbitrary logical circuits.

In order to demonstrate the universality of our logic architecture, we use a NAND gate as a representative example. The NAND operator is functionally complete, meaning that any arbitrary boolean function can be assembled through a combination of NANDs. Figure 11 depicts a NAND gate assembled from 22 conductive and insulating parts as well as N-channel and P-channel MOSFETs.

Fabrication

Transistor parts are fabricated in a laminate process similar to the passive mechanical hinge parts discussed previously. Layers are machined and then stacked and laminated to form a composite sandwich. An internal layer of fiberglass serves as a stiff insulator, ensuring the part is robust to assembly. The patterning of the outer metal layers serves the same role as a printed circuit board in defining conductive regions on the part to which a SOT-883 N-channel or P-channel MOSFET is soldered, as depicted in Figure 11. Though the transistor is currently soldered by hand, there are good methods to scale this production method to make the parts reliably and with high-throughput.

Results

Since each part embodies only a single function, the connectors are comparatively simple: accommodating a single electrical connection for every mechanical interface. In

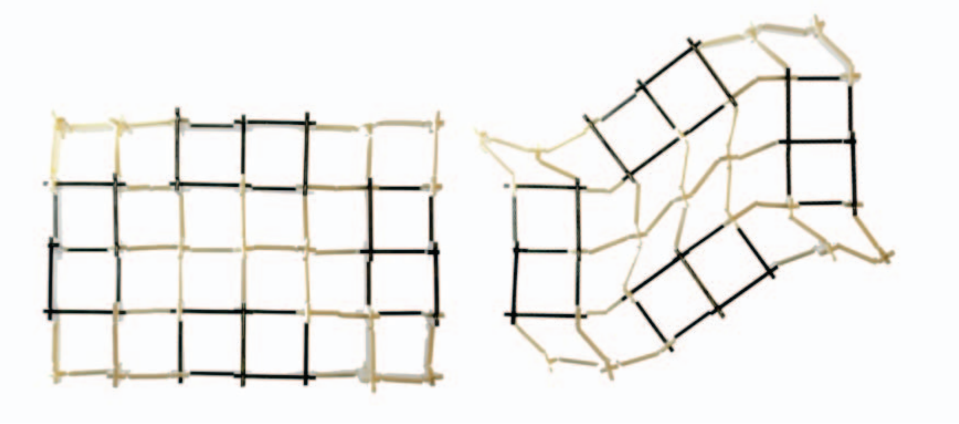

Figure 8. **A physical prototype of a four-bar parallelogram linkage constructed from three scaled-up passive mechanical parts.**

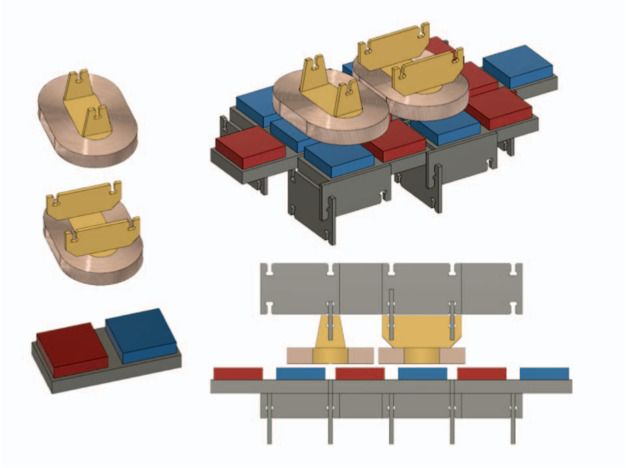

Figure 9. **Three electromagnetic part-types are able to actuate the structures and function as an assemble-able linear stepper motor.**

order to minimize the manufacturing complexity of the parts, the interfaces are simple press-fit slots, which transfer both mechanical forces and electrical currents. To achieve this, the interfacing slots are toleranced to provide a press-fit which cold-works the surface, flattening surface asperities as it is assembled, and leads to improved electrical performance with use. [11]

Fabricated parts have either eight or four press-fit slot interfaces. The number of slots on a part is a design choice that is impacted by the functionality and desired functional density of the module-level application. Mechanical systems decompose more naturally into parts that have four interfaces: two at either end. For many electronic applications, eight interfaces per part allows for a greater functional density and more natural tiling of conductive traces. As long as the pitch of the slots is standardized to the lattice, these parts can be used interchangeably and enable functional density or sparsity to be tuned through assembly.

6. MISSION ARCHITECTURE

Based on our modeling, an assembler would likely be composed of approximately two-thousand parts. This number assumes that assembler must be capable of moving in both X and Y directions, using parallelogram flexural linkages like described above. The parts breakdown by subsystem as follows:

Passive Mechanical: Each linkage is composed of 50 parts and a well-constrained linear motion stage can be assembled from eight of these linkages. With two primary motion stages per assembler and 10% overhead, that totals **900 parts**.
Active Mechanical: Every actuated degree of freedom needs, at a minimum, two coils and two magnet parts. To actuate greater loads, more coil pairs are necessary. We estimate that 6 coil pairs would be necessary for each degree of freedom. Those six coil pairs decompose into four parts each with 7 degrees of freedom on the assembler; totalling approximately **200 parts**.
Electronic: In large part, circuitry can be embedded in the mechanical structure by swapping insulating structural parts with conductive ones (at no additional part count). However, each actuator needs logic and switching for power. It is reasonable to assume that there is an equal amount of electronic complexity as mechanical complexity which would total **900 parts**.

We will now assess a potential mission architecture for the Self Replicating System (SRS). We will assume the initial configuration is a 3U cubesat, in which 1U is dedicated to the pre-built assembler, and the remaining 2U are dedicated to parts. We make the following assumptions:

Parts are 5 mm x 3 mm x 0.25 mm, = 3.75 mm^3
Average Density is 2.7 g/cm3
Mass = 10 mg
Assembler = 2000 parts
Assembler mass = 0.02 kg (200 g)

Based on the payload mass and volume limitations of cubesats (1.33 kg and 10 cm x 10 cm x 10 cm) and the mass and volume of a typical parts, we can estimate that we will be mass-limited to a payload of 133,000 parts per 1U, giving us a total of 266,000 parts. This will give us enough parts to build approximately 133 assemblers.

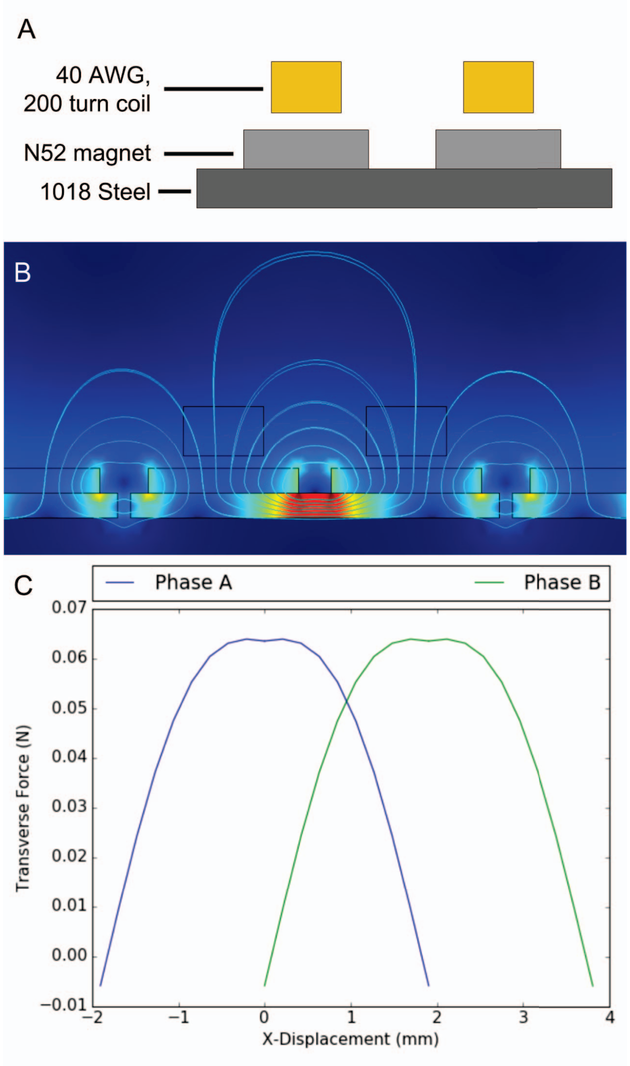

Figure 10. The electromagnetic parts are modeled in COMSOL to evaluate the force output from the coils. (A) illustrates the geometry of the cross section model. The simulation in (B) depicts the magnetic flux density norm within a cross section. The streamlines reveal that the field is largely oriented in the +Y direction within the coil cross-section. (C) Shows the maximum force generated by the coil-field interaction as the coil is displaced from its initial configuration.

We look at two scenarios: one in which the SRS simply creates as many of itself as possible, and the other where a percentage of the parts are allocated to creating spacecraft components, so that an SRS can journey beyond its current location, and have the ability to find new material and exponentially self-replicate. These two scenarios are depicted graphically in Figure 12. We can make some assumptions about the specific components for the spacecraft, but generally speaking we would require the following:

- power generation (solar panels)
- power storage (batteries)
- propulsion (propellant-less)
- body/fairing (entry/descent)
- navigation (star tracker)
- controls (reaction wheels)
- communications (antenna)
- computation (CPU for spacecraft guidance)

Our objective would be to limit the number of parts required to construct this spacecraft to the capacity of a 1U storage unit (133,000 parts). As shown, the spacecraft would be just large enough to fit the SRS (8 cm x 8 cm x 8 cm bounding box).

7. CONCLUSION

In developing a hierarchical architecture for self-replicating spacecraft, we have shown that a diversity of actuated robotic systems can be assembled from just 13 part-types. Our approach reduces the diversity of the supply chain, simplifies extraterrestrial assembly and repair, and enables adaptability to unforeseen conditions. We have shown current work on modeling, part design, and fabrication as well as design methodologies for mechanical and electronic systems assembled from reconfigurable parts.

Next steps include integrating passive mechanical, actuation, and electronic systems to build higher-level robotic modules such as the discretely assembled linear stepper motors and gripping mechanisms discussed in previous sections. Additionally, future work will need to further investigate the characteristics of the press-fit joint interfaces. This includes, for example, vibration testing and extreme temperature cycling. Furthermore, the structures detailed in this work are anisotropic; investigating the addition of cross-linking parts in the z-plane could enable the assembly of more isotropic structures with higher functional densities.

ACKNOWLEDGMENTS

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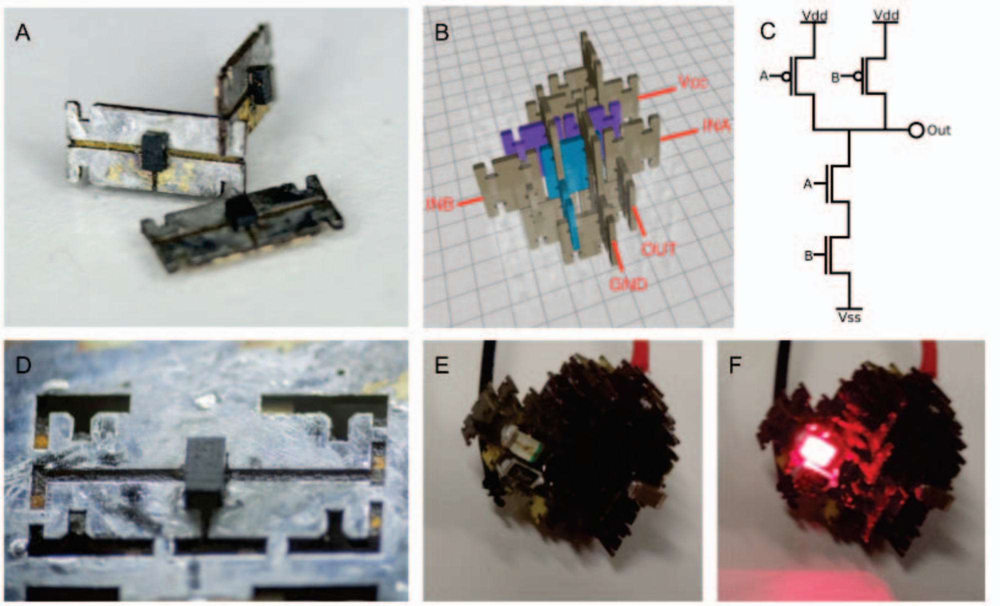

Figure 11. Various discretely assembled electronic structures and parts. (A) and (D) show transistor "GIK" parts which are used to assemble NAND gates shown in (B) and (C). (E) and (F) show a discretely assembled circuit which uses conventional surface mount parts to blink an LED.

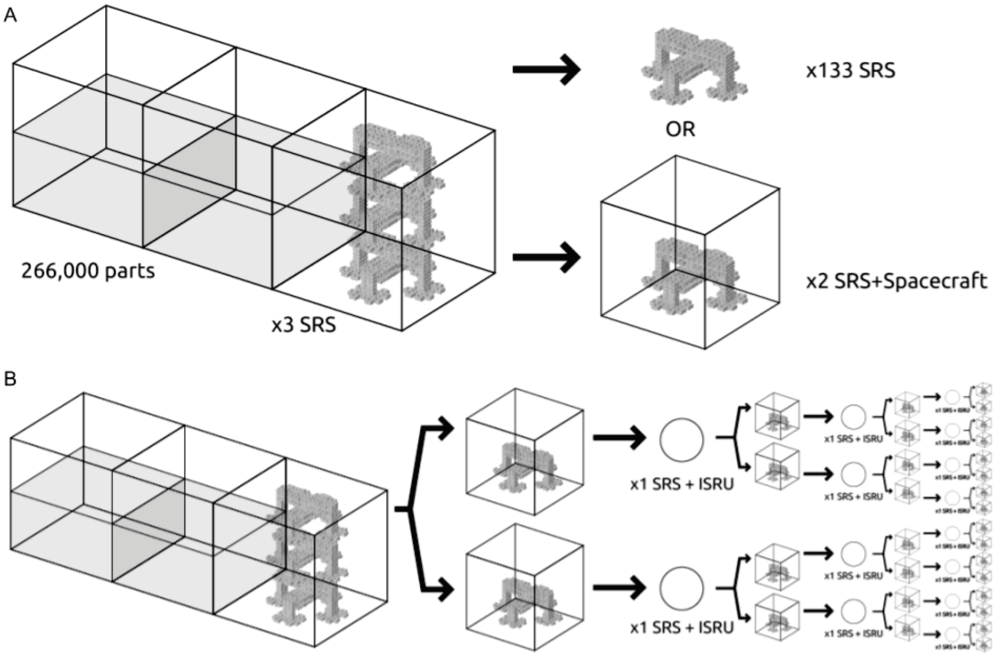

Figure 12. Assemblers can be packaged and deployed from a cubesat with room for enough extra parts to assemble many more systems. (A) shows a scenario in which a 1U full of assemblers is used to assemble 133 self-replicating systems from 2U's full of parts. (B) shows a scenario in which a percentage of those parts are allocated to spacecraft systems to enable travel through space.

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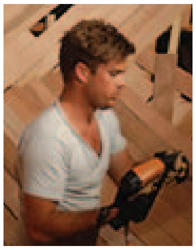

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