Ultralight Modular Robotic Building Blocks for the Rapid Deployment of Planetary Outposts

Mustafa Emre Karagozler, Brian Kirby, Wei Jie Lee, Eugene Marinelli,
Tze Chang Ng, Michael Philetus Weller, Seth Copen Goldstein

Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213

gianthecatoms@cs.cmu.edu

Abstract

We examine how modular robots can be used to enable remote robotic construction of planetary and orbital outposts. Each modular robot, called a *catom*, contains sufficient actuation, adhesion, control, and power to allow it to function as part of an ensemble of similar units. We describe the catom design and construction as well as initial experiments carried out to verify the system.

1 Introduction

The President's Space Exploration Initiative calls for NASA to undertake several manned missions to establish outposts on the moon and Mars. NASA's plan calls for sending robotic missions ahead of astronauts to both the moon and Mars to establish automated facilities for gathering in-situ resources such as fuel, water and oxygen. Establishing these facilities before astronauts arrive reduces the amount of material that must be brought from earth and lowers the risk of missions by providing the potential to generate resources to meet unforeseen needs after astronauts have arrived.

These robotic missions will need a variety of structures, including warehouses to accommodate robotic factories, provide storage for the resources they generate, and living spaces both on the surface and in orbit to house the crew when they arrive. Providing lightweight, deployable buildings to send on these missions to bootstrap the on-site manufacturing operations presents a significant design challenge. Structural systems tend to be large and heavy, making them expensive to launch into orbit. The robotic assembly mechanism for these seed structures must be extremely robust as their failure to deploy could jeopordize the entire mission. The building system used to support planetary outposts should also be flexible to allow for the accomodation of unforseen circumstances that could arise in the interval between when a robotic mission is launched and actually arrives on Mars.

We propose here a lightweight construction system to allow the rapid and autonomous deployment of planetary facilities on the moon and Mars, based on modular robotics technologies we are currently developing [**?**]. A robotic factory and a supply of lightweight materials would be shipped from earth with each robotic mission to establish a new planetary outpost. Once on-site the robotic factory would begin constructing modular robotic building blocks from these materials. After a sufficient number of blocks have been generated the site plan for the outpost would be sent to the blocks, and the blocks would autonomously assembly themselves into the required structures. This assembly process is very robust due to the high degree of redundancy of the robotic building blocks, and structures composed of blocks have the capability for self-healing parts of the structure that are damaged by simply replacing the damaged portion of the structure with spare block modules.

This project is an outgrowth of the claytronics project at Carnegie Mellon University. The claytronics project is studying how to build and program massive ensembles of microscale modular robots (called *catoms* for claytronic atoms) to form arbitrary three dimensional objects. Each catom is a self-contained robotic module capable of computing, communicating, cooperative movement and adhesion between neighboring modules, as well as storing and delivering power. The catoms described in this paper are loosely based on, but scaled-up versions of, the microscale catoms being developed for claytronics.

2 Use Scenario

2.1 Advantages of Modular Robotics

One class of modular robots are systems comprised of an ensemble of homogeneous robotic modules. Each individual module is fairly simple and only needs to provide enough actuation, sensing and processing capability to support the functionality of the entrire ensemble [**?**]. Modular robotics technology has several properties that make it ideally suited for space and planetary applications: lightness and compactness, robustness and adaptability and versatility [**?**].

Our ultralight modular robotic building blocks can provide an extremely compact building sytem as there are potentially two stages of expansion. Compactly packaged materials and subassemblies would be assembled into full modules on site; once the modules are assembled they expand from a solid lattice to enclose a volume. The individual modules are built with carbon fiber frames, which provide a great deal of structural support with very little weight.

Modular robotics systems are able to provide highly robust and adaptive performance with large numbers of relatively inexpensively manufactured modules, much like the systems proposed by Brooks for unmanned interplanetary exploration[**?**]. As long as there are sufficient numbers of modules available, failed modules can simply be replaced to allow an ensemble of modules to continue to function properly.

Here we present several specific use scenarios to illustrate the flexibility of our proposed structural system.

2.2 Orbital Space Station

Orbiting space stations allow astronauts to shuttle back and forth from the surface of the planet and catch a ride on an interplanetary vehicle without requiring it to negotiate landing and takeoff, and to provide a safe haven in case of the failure of systems on the surface. Our robotic building blocks could be used to generate space station modules that could expand to accomodate changing numbers of astronauts present, and automatically repair damaged areas. When a robotic mission vehicle arrived at a planet, it could send some modules to the surface, but remain in orbit to provide core life support and communications systems for an orbital space station. An onboard robotic factory would then begin to assemble robotic blocks, which would reconfigure themselves to generate additional modules attached to the original seed to provide space for astronauts and the storage of resources generated on the surface. The walls of each module would be composed of several layeres so that damage could quickly be repaired by spare modules in the outside layers. Once surface manufacturing facilities began to produce resources, the robotic shuttle could bring water and oxygen up from the surface. The inner layers of the modular robotic blocks could then be filled with water to provide a radiation barrier for the crew, and oxygen could be used to generate a breathable atmosphere.

2.3 Surface Warehouses

Our robotic blocks could also be used to generate warehouse structures to house surface manufacturing operations and provide a dust free, controlled environment for various manufacturing processes, as well as storage of resources produced by these processes. As new resources are discovered in different areas of the lunar or martian surface, these structures could be quickly taken down and redeployed, allowing robotic missions to respond quickly to information discovered by exploration and efficiently reuse structural components.

2.4 Surface Living Quarters

Living quarters could be erected using blocks prior to the arrival of a crew to decrease the risk of requiring a crew to assemble their own living quarters upon their arrival. A site plan for the living spaces could be generated on site to take geological formations into account, and a series of airtight modules with multilayered walls could be assembled by a group of blocks. Like the orbital station, the interior layer of modules could be filled with water to protect the crew from radiation. As the number of crew members present at the outpost changed, the structure could be reconfigured to accommodate them.

2.5 Architectural Robotics

As proposed by Weller in [**?**] architectural robotic systems composed of modular robotic building blocks could use the space available in surface or orbital crew quarters more efficiently than static structural systems. Instead of having to provide a wide variety of spaces customized for specialized uses such as kitchens and bedrooms, which are only occupied serially at different times of the day, an architectural robotic space could reconfigure itself to provide a large kitchen and dining area at mealtime and then individual bedrooms for crew members in the same space afterwards. In this manner crew quarters built from our robotic blocks could more comfortably accomodate a greater number of crew members in a smaller space while utilizing less structural resources.

2.6 Scaffold for Cross-linked Polymer Resin Bunkers

The block modules could also be used as a scaffold for the creation of more permanent structures. A group of modules could be used to fill a space of the desired shape, and then a release agent could be sprayed onto the structure followed by a cross-linked polymer resin mixed [**?**] with the local soil to create a concrete-like shell. The advantage of this system is that the local soil makes up over 80% of the weight of the final product, so only 20% ofthe weight needs to be transported. Once this shell reached full structural strength, the robotic building blocks could disassemble the scaffold structure and be reused. The concrete-like shell could be covered with soil to provide a more robust and radiation-proof space for either crew housing or long-term storage of resources and equipment.

3 Design Considerations for a Modular Robotic Building Block for Planetary Outposts

Our group has proposed that modular robotic modules should be designed according to the Ensemble Axiom: a single module should provide no more functionality than necessary to generate the desired behavior of the ensemble [**?**]. In this section we discuss some of the factors that the design of our ultralight robotic building block module will need to accomodate to allow a group of blocks to function to generate the structures we proposed in the previous section. We will further discuss the desired properties of an ensemble of robotic blocks and the particular design decisions we have made for the individual block modules in later sections.

3.1 Form Factor

While there are several types of modular robots, lattice type modules are particularly well suited to structural applications. There are several different form factors that have been proposed for lattice type modules, including a rotating sphere, as in Claytronics modules [**?**], and an expanding cube such as Rus and Vona's Crystalline Atom [**?**] and PARC's Telecubes [**?**]. We have chosen to develop a novel hybrid of these two form factors, the cubic rotating module. The advantages of this form factor are that we are able to use an actuation mechanism that is more lightweight and compact than is necessary for expanding cubes, while we need fewer actuators than would be required for a shape with more facets like the catoms. The cubic modules pack tightly into a lattice (with no gaps between modules). This lends itself easily to generating flat surfaces that are typical of buildings. Individual modules have sufficient degrees of freedom to reach any location on the surface of a group of blocks, simplifying reconfiguration planning.

3.2 Actuation

One of our goals it to support reconfiguration of a group of modules into arbitrary structures. This requires that each module have a rich set of movements. There is a tradeoff between the mechanical complexity, actuation forces required, degrees of freedom, and planning complexity. To be able to place a module anywhere on the surface of a group of modules, each module must have actuators capable of at least lifting the module itself, and possibly might have to be able to lift itself and another module or two. In the Claytronics planar prototype, a module can reach any location on the perimeter of a group of modules by rolling just itself across neighboring modules using an array of 24 electromagnets [**?**]. ATRON modules, in contrast, have only one actuator per module, but that actuator must be powerful enough to move two other modules to achieve enough degrees of freedom to be able to place a module in an arbitrary location on the surface of a group of modules [**?**]. Our cubic catom modules are capable of rotating along any edge adjacent to another module. This requires at least 4 actuated flaps per face, but simplifies planning and the mechanical forces needed, as only one module needs to be moved at a time.

3.3 Control / Communication

It is generally necessary to have a mechanism for local communication between neighboring latched modules, as broadcast wireless communications do not work well through dense lattices of modules. Depending on the complexity of the control system modules can either communicate just with their neighbors to discover the local topology, or can have a more complex message routing scheme to allow messages to be sent to any module in the group through local connections. More complex connector hardware, such as a dedicated pair of electrical contacts for communication in each latch, can simplify the routing of messages, but can make latching and unlatching modules more complex. Routing both power and communication through unary connectors makes the control problem more complex but makes latching and unlatching simpler and more robust [**?**].

3.4 Power

As modules are to be remotely deployed, it is important that they are able to route power from a central source to be able to recharge their onboard batteries. We have researched a variety of algorithms for routing power through unary or binary power connectors in [**?**]. While these adaptive power routing algorithms place extra processing and messaging demands on the modules, they can significantly increase the robustness of the entire ensemble by preventing any modules from being starved for power.

3.5 Adhesion

There are a variety of mechanisms that have been proposed to latch modules to their neighbors. They fall generally into two classes: mechanical connectors, like the ATRON module [**?**] and magnetic or electromagnetic connectors such as the Telecubes [**?**] and our catom modules [**?**]. The advantage of mechanical latches is that they tend to be very strong, but they are complex to build and prone to binding under load. Magnetic latches help align connectors during latching but tend to provide less adhesive force. Additionally, permanent latching connectors like the Telecube's can be difficult to control and do not turn all the way off, complicating unlatching, while electromagnetic latches like our catom module's draw power even when sitting still.

We have developed a novel latching system for our robotic building blocks, which relies on electrostatic induction to adhere two flaps to one another. This mechanism has advantages similar to an electromagnetic latch, but draws very little power once latched. We intend to further develop our mechanism to allow the creation of an airtight seal between modules to allow the support of a breathable atmosphere in space and on the lunar and martian surfaces.

3.6 Environmental Constraints

There are a variety of different environmental constraints that our robotic building blocks would have to address depending on whether they are deployed in space or on the lunar or martian surface. We discuss here a few of these constraints that we believe are particularly relevant, although there are many more that would need to be considered.

3.6.1 Radiation

All of the environments we are considering are frequently exposed to dangerous levels of radiation. To protect sensitive manufacturing equipment or members of the crew we intend to allow our modules to be filled with water generated on site to create a radiation barrier.

3.6.2 Air Density

As none of the environments we are considering has an air density suitable for a breathable atmosphere it will be necessary for modules to be able to generate airtight pressurized spaces that can be filled with oxygen and nitrogen generated by surface resource processing.

Air density is also critical for convective cooling of electronics and actuators. Low atmospheric densities could require active cooling of these components.

3.6.3 Gravity

In our experiments that we have performed we have filled our robotic building blocks with helium to simulate very low gravity conditions similar to those encountered in orbit. However more robust actuation mechanisms could be necessary to provide enough power on the martian and lunar surfaces, as although there is gravitational force on Mars, very little lift can be generated by displacing the thin atmosphere with helium. Similarly there is even less gravitational force on the moon, but there is no atmosphere to be displaced.

3.6.4 Wind

As our ultralight robotic building blocks have very little mass and a great deal of surface area, they are somewhat sensitive to wind. Although the Martian surface frequently experiences winds of up to 300 miles per hour the atmosphere is much less dense, and so would exert less force than wind here.

3.6.5 Dust

Lunar and particularly windblown Martian dust can create problems for a variety of mechanisms, including solar cells. Our electrostatic inductive latching flaps could be particularly severely impacted as static forces on the flaps would tend to cause dust to adhere to the surface. We intend to investigate mechanisms to prevent the buildup of dust on the robotic building block's flaps.

4 Related Work

There has been a great deal of research into the feasibility of building lattice type modular robotics systems. Rus and Vona's Crystalline Modules [**?**] and PARC's Telecubes [**?**] demonstrated the potential of expanding lattice type modules. The Crystalline Atom, although it only reconfigured in two dimensions, demonstrated that an ensemble of lattice type modules could be programmed to generate any arbitrary shape, but its mechanical latches had issues with binding and its actuation mechanism was not powerful enough to function in 3D. The Telecubes were a fully 3D crystalline expanding module, and replaced the Crystalline Atoms' mechanical latches with switching permanent magnets, and used a fairly complex and expensive actuation system to produce enough power to lift the weight of the module itself and another module.

More recently several rotating lattice type modules have been developed, notably the Adaptronics group's ATRON module [**?**] and our catom module [**?**]. ATRON modules only have one motion actuator per module, simplifying each module and leaving room for a robust mechanical latching system. However the limited degrees of freedom of the module make it difficult to plan to reach an arbitrary position. Like the Telecubes, our catom modules have a fairly large number of actuators, but each actuator needs to provide less power as it only needs to rotate one module a small angle. The other innovative feature of our catoms is their unary electromagnetic latching system that allows modules to very quickly latch and unlatch.

There have been several proposals to leverage modular robotics technology for space exploration. Modular robotics researchers at PARC have suggested that the ability to reuse the same components for different applications rather than having to launch a new design into space every time needs change make modular robotics ideal for space applications [**?**]. Shen, Will and Khoshnevis describe a self-assembling structural system for reconfigurable satellites that would obviate the need to launch new structural components into space for every new satellite, as parts from defunct satellites already in orbit could be reused [**?**].

Although we do not discuss the details of our high-level control system to achieve recongfiguration here, our group has developed a distributed, parallelized algorithm to support reconfiguration between arbitrary shapes, based on the random motion of "hole" metamodules in the interior of the ensemble [**?**]. Also relevant is Stoy and Nagpal's 3D, distributed, parallelized control system for rotating lattice type cubes described in [**?**].

5 Proposed Design

Our reconfigurable structural system will be composed of cubic catoms with four triangular actuated flaps on each face. These catoms will be able to rotate around each other by extending a flap to the next face of a neighboring cube and releasing the flap latched to the current face as in Figure **??**.

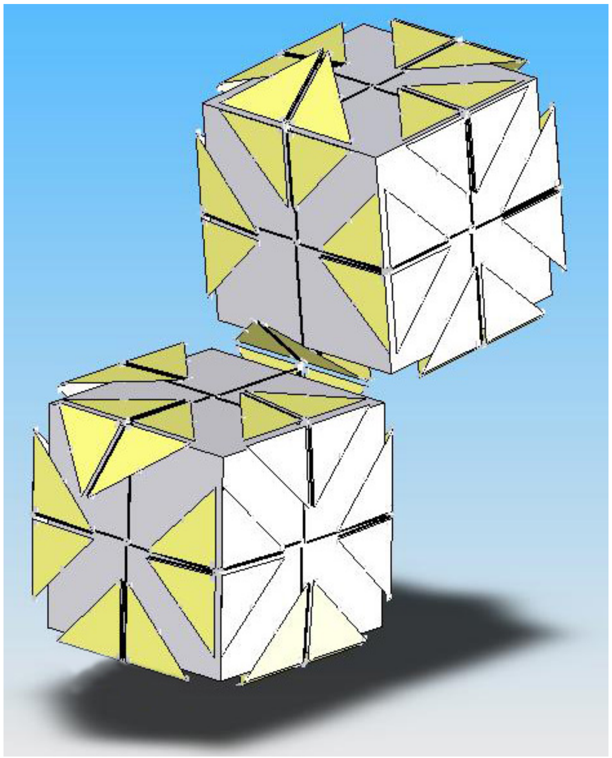


Figure 1: Illustration of one catom rotating around another catom and two of the constructed catoms sitting on top of each other.

The ultimate goal for this system is an adaptive, scalable, and robust control system that coordinates itself in a distributed fashion based on high-level global demands. An earth-based or preprogrammed goal model would be set, and then the catoms would interact locally to construct the model. The software would adapt around local failures and scale from a few modules to thousands or millions without any emergent problems.

For shipping the catoms on interplanetary missions subassemblies consisting of two flaps and the associated internal structure would be tightly packed to conserve space. Upon arrival a robotic factory would assemble these subassemblies into complete catoms. The newly constructed catoms would then be sent directions from the central planner on board the probe to reconfigure into structures as needed to support mission activities. This system would allow an expansion of roughly two orders of magnitude from the space required on the probe vehicle to space enclosed by the system. This efficiency is further compounded by the ability to reuse the structure for other purposes.

5.1 Actuation

Each catom requires 24 moveable flaps for complete mobility. Our current system actuates and controls each flap independently using a composite shape memory alloy (SMA) / spring system shown in Figure **??**. The SMA contracts as it is heated, lifting the flap via a pulley. As it cools, a constant force spring slowly closes the flap and returns the SMA to its initial length. The benefit of this system is that it closely mimics the microscale actuation of a bimorph heater, implying significant flexibility in catom sizing. One downside is that heating the SMA requires a high current power source and substantial wiring. More troubling is that reverse actuation is at the mercy of convective cooling.

Other designs that we are considering include replacing the SMA / spring composite system with a low current motor with a non-backdrivable, reversible gearbox. This will lower the overall current and wiring requirements and equalize the time durations opening and closing the flap. Additionally, it gives us great torque flexibility, permitting us to sacrifice speed for lifting strength limited only by the mechanical strength of the structure. This will be very

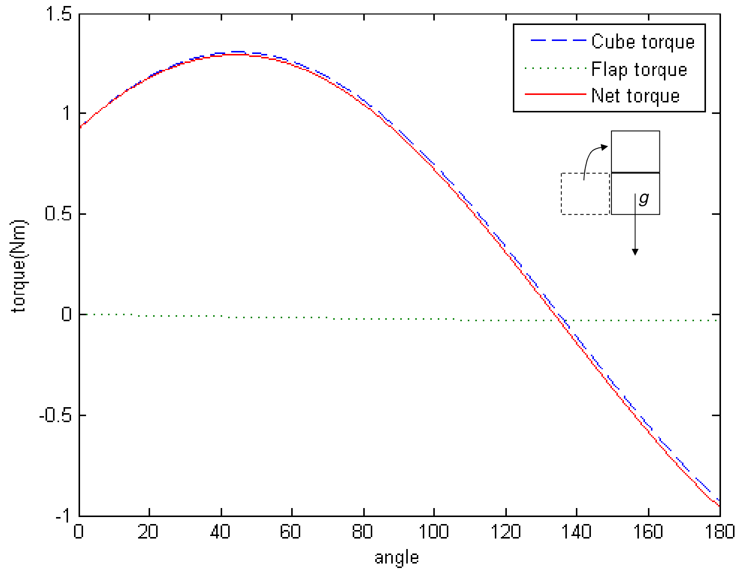


Figure 2: Torque required to lift 10cm, 2kg catoms on Mars. The net torque is the sum of the torque needed to actuate the flap and the torque needed to lift the cube.

helpful in an environment like Mars, where the weight of the robot must be handled by the actuator. This can be seen in Figure **??**.

Another actuation design that we are pursuing is mechanically linking the four flaps on each of the six faces. This means that all four flaps on a face must open together, but also means that we require only six independent actuators. While this constrains some motions, such as moving on a non-catom surface, it still allows full intercatom mobility. This mechanism would be applicable whether we used our SMA/spring composite, gearhead motors, or other system.

5.2 Power

The simplest solution to satisfy the power requirements of catoms would be to individually power each catom by using on board batteries. However, this configuration has many disadvantages when a Martian exploration mission is considered. The main disadvantage is that batteries require recharging/replacement, which increases the costs drastically, and also requires external maintenance staff/machinery. When considering the challenges of such a mission, designing the system in a way that avoids such maintenance is crucial.

Our proposed solution is to make catoms deliver power to each other. In this case, catoms only store a limited amount of power in an internal battery that is enough to move them for a limited time until they establish contact with a group of other catoms, that has a power source. The power source is either a high capacity and stationary battery or a group of specialized catoms that have power scavenging mechanisms such as solar cells. As the contact is established with the group, the catom is powered through this contact, and the internal rechargeable battery is charged.

Catoms make use of electrodes mounted on the flaps to create electrostatic forces that enable them to adhere to each other. An important property of the electrodes is that they provide capacitive coupling between catoms, which allows power transfer through an alternative excitation. In our proposed solution, catoms deliver power to each other using capacitive coupling with alternative currents (AC). The AC power generated at the neighboring catom is then rectified and regulated, and the resulting DC power is used for processing and other electronics (Figure **??**a).

An estimation of the efficiency of power transfer can be made based on the capacitive coupling between catoms. Figure **??**b shows the equivalent circuit of the system, where resistance R represents the input resistance of the rectifying and regulating circuitry (assumed to be purely resistive). The ratio of V_R/V can be considered as a good estimate of efficiency. Then equation **??** is:

$$V_R = \frac{VR}{R + 2/j\omega C}, \quad |V_R| = |V| \frac{R\omega C}{\sqrt{R^2\omega^2C^2 + 4}} \tag{1}$$

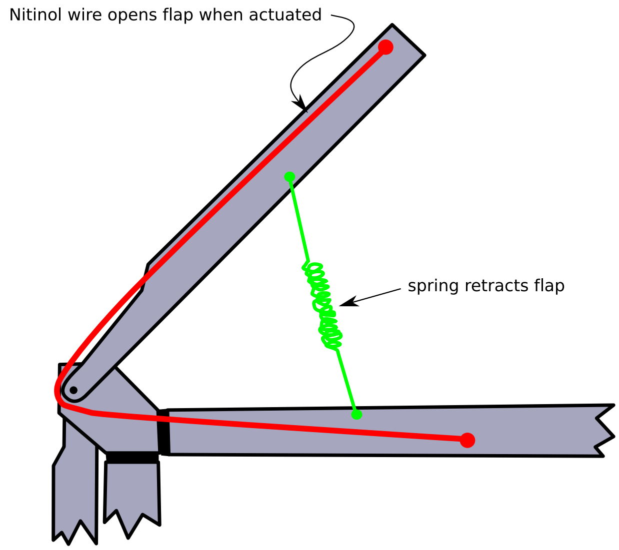


Figure 3: Diagram of flap mechanism with SMA actuator and return spring.

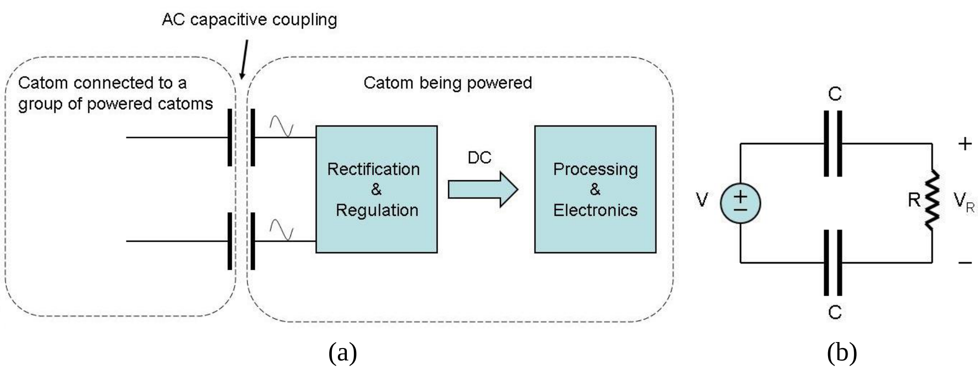


Figure 4: Powering Catoms a) System diagram b) Equivalent circuit.

Equation **??** can be used to determine whether the power transfer can be done efficiently with an AC excitation of reasonable frequency. Assuming $V_R/V = 0.95$, ω and the frequency of the excitation can be estimated. Calculations show that for the proposed electrodes, the capacitance is in the order of $C = 10^{-7}F$, and resistance can be assume as $R = 10^1\Omega$, which results in $f = \omega/2\Pi \cong 1MHz$. The value of frequency of AC excitation can be achieved, thus, reasonably efficient power transfer is possible.

The power requirement of catoms is within in the limits of the amount of power that can be delivered. Moreover, intelligent power routing algorithms can be incorporated to the system, in which a catom can be powered by multiple neighboring catoms at the same time, or catoms can be positioned accordingly to allow more power to a certain part of whole catom ensemble [**?**].

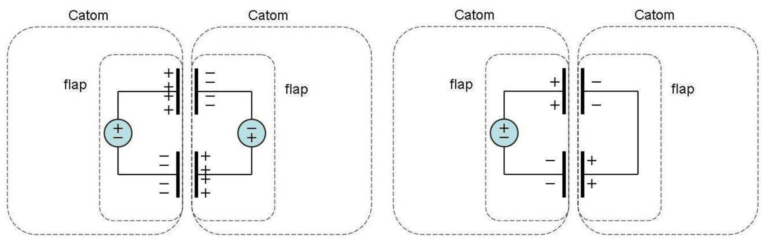
5.3 Adhesion

In our system, catoms make use of electrodes mounted on the flaps to create electrostatic forces that enable them to adhere to each other. With the use of actuation mechanisms explained, catoms move out their flaps which snap into each other's flaps. As the flaps come together, electrostatic forces created latch the flaps.

Some of the advantages of using electrostatics as adhesion mechanism are controllability, low power consumption, high force output. At steady state, the power consumption of this mechanism is minimal, as only leakage currents cause power loss. The charges are easily accumulated by a high voltage amplifier. Our calculations show that the electrostatic forces created are high enough for this application.

There are two isolated electrodes on each flap of catom, which are coated by a dielectric material (mylar). The Dielectric prevents electrical contact between flaps, thus, when a voltage difference is applied to electrodes, accumulated charges create electrostatic forces. The adjacent flap also has two electrodes, which are charged oppositely, so oppositely charged electrodes align as the flaps come together.

Figure **??**.a shows a diagram of the adhesion mechanism. In this case, both electrodes in corresponding catoms are actuated, whereas in Figure **??**.b, only one flap is actuated, while the other is short circuited. In this case the force created is less, but might be still enough in certain applications.

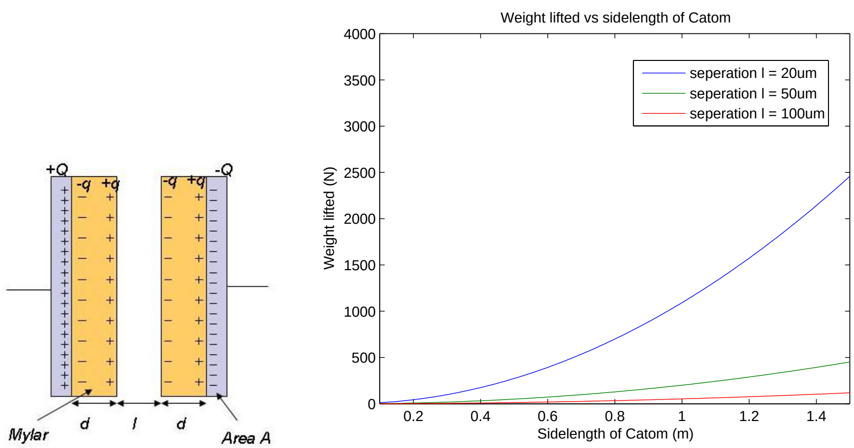


(a) (b)

Figure 5: Electrostatic forces: a) electrodes on both flaps are actuated b) only one electrode is actuated, creating less force.

The electrodes come together forming couples that could be modeled as parallel plate capacitors shown in Figure **??**a, where there is a coating of dielectric (mylar) on each electrode, and a certain amount of separation between electrodes. The electrostatic force created in the case shown in Figure **??**a can be calculated as in equation **??** below:

$$F = \frac{A\epsilon_0 V^2}{(l + 2d/\epsilon)^2} \tag{2}$$



(a) (b)

Figure 6: a) Electrodes come together to form parallel plate capacitors b) The electrostatic force created wrt the catom side length.

The strength electrostatic forces created is the limiting factor for the amount of weight that could be lifted by a catom, without loosing contact with the neighbor catom. As the forces depend heavily on the area of electrodes, it is important to know how much weight could be lifted when the catoms are scaled down to different sizes. Figure **??**b shows the theoretical forces that would be created, with respect to different catom side lengths. The calculation assumes that the total area of a flap is one forth of the single face area of the catom.

The separation between electrodes plays an important role in the force created. Still, it is clear that the amount of forces created are well above the Catom weight range, thus electrostatic adhesion is promising for this application.

6 Experimental Verification of a Prototype Module

6.1 Actuation

6.1.1 Prototyping the mechanical system

Most of our early prototypes were developed using glue, balsa wood and plastic parts printed with a fused deposition modeler. This allowed us to quickly test out designs as well as estimate the overall rigidity of the structure. Once we were satisfied with the design, we adapted it to work with carbon fiber box beams. This gave us increased rigidity and robustness, as well as simplicity of assembly over complex balsa support structures.

Our flap actuation relied on a multipart system shown in Figure **??**. Our flaps attach rigidly to the frame using a hinge. Attached to the flap is a bundle of SMA which, when heated, contracts to pull the flap open. A continuous force spring (similar to an ordinary tape measure), also attached between the frame and flap, provides the torque necessary to stretch the SMA as it cools and return the flap back to its original position. It attaches to each using a zip-tied friction collar, both of which may be moved along the lengths of each beam to vary the amount of torque it generates. The original system was originally intended to open to 45 degrees, however, we found that in practice it could open to almost 150, which increased the movements available to the cubes.

To construct the electrostatic plates, we wanted a material as light as possible that was electrically conductive on one side but isolated on the other. We chose aluminized Mylar, which has a high breakdown voltage and is available in 2 and 4 micron thickness sheets. After testing both, we settled on the 4 micron sheet as it was easier to manipulate and was less prone to damage during handling. Thicker materials were also available, but increasing the dielectric quickly led to diminishing returns in electrostatic force.

To counteract the weight of the frame and flaps, each catom had a large internal balloon filled with helium. These were constructed using a nylon sheet with a heat sealable plastic on one side and metal on the other. Multiple sheets were placed on top of one another with the heat sealable sides facing each other, and by using a hot iron the edges were sealed. By using eight 4m long, 1m wide sheets of material, we were able to construct roughly square balloons with sides approximately 1.9m long. When filled with helium it counteracts 5.6kg in earth gravity.

To assemble a catom, we first attached the uninflated balloon to the bare frame by taping it to the center of each face. We then added approximately 800g of lead shot to the center of each face, to act as ballast and prevent the balloon from lifting the frame as it inflates. After the balloon was inflated, we added electronics and flap hardware, and reduced the ballast to compensate. Since we only attached four flaps to our two prototypes, the majority of the weight on the catom was ballast.

6.2 Problems encountered

During construction of the catoms, many details arose that had to be dealt with. While this is to be expected in any project, two categories of problems were serious enough to warrant considering significantly modifying the basic design.

6.2.1 Inertia

Our experiments revealed that inertia has a bigger factor than we had considered. Though our robots weigh under 50 grams, the effective mass was closer to 6 kilograms with the center of mass almost 1 meter from the rotation point. Our initial hinge design was completely unable to cope with such torques and the catoms would twist and roll off axis due to minute imbalances or wind currents. Adding additional hinges alleviated those problems, though our spring return system still had to contend with ponderously slow payloads.

Additionally, the large amount of ballast also caused significant problems with structural stability as the balloon deflated over time. The frame was not designed to handle such weight, and the bottom face especially would tend to sag unless the balloon was inflated and supporting the ballast. Balancing the weight to prevent bias in rotation also required a significant amount of time. We originally considered partially inflating the balloons for testing with fewer than the full set of flaps, but the helium would pool at the top of the balloon, causing strange inertial problems as the catoms rotated and the helium moved. By inflating the balloon completely the balloon would press out equally upon the entire frame, equalizing the effect of the helium.

Inertia also had a larger effect on the movement of the flaps and cubes. We expected to be able to open the flaps, adhere them, and then allow the springs to return them to the closed position. However, since the catom has a much higher moment of inertia, the flaps will move before a catom will begin moving. This will generally cause one of the flaps to hyperextend beyond its ability to close itself. These situations can be seen in Figures **??**c and **??**d, as the angle opens above 100 and 45, respectively.

Some basic analysis indicates that inertia became such an issue because the cube is hollow with all of the mass on its surface. This creates a moment that is an order of magnitude above that of a cube of equal mass but even density. Additionally, as we increased the cube's length from 1m to 1.9m most of the forces remained roughly the same, but the moment of inertia did not.

For an object as large and of such a mass as our catoms, the moment of inertia can not be disregarded. Major improvements in our design would be to center most of the mass, as a design with a lower moment of inertia is much more tractable, even if we do not use helium counterballast at all, or at a reduced rate. For many of the environments that we are considering, weightlessness will either not be possible or not derived from a central helium counterballast. In these cases centralised mass becomes even more feasible.

6.2.2 Flap system

When experimenting with the prototypes we would frequently adjust the lever arm of the constant force spring to vary the torque. If the flap failed to close, we would increase the torque, and if the SMA was unable to open the flap, we would decrease it. Unfortunately, this tended to vary with the flap's orientation in gravity, and an adjustment that works in one configuration may not work in another. This is shown in Figure **??**—certain orientations provided unacceptable torque.

Our SMA also ended up being very difficult to control, Due to an unfortunate choice of flap offset angles during the mechanical design phase. Since our only input variable is the rate of heating the SMA undergoes (and not the rate of cooling), preventing runaway instability in the region of increasing torque with increasing angle is a serious issue.

Rather than tackle such a system with an electronic controller, we have examined how to simplify the system at the mechanical level. Figure **??** shows a system with a refactored offset angle. This system maintains a declining torque for all angles, allowing stable control throughout the entire range without resorting to complex controllers. This allowed us to also fix our spring torque problems with regards to different orientations.

Another serious consideration is whether or not to continue the use of SMA as an actuation mechanism or whether to replace it with a more traditional motor and gear system. The SMA is lighter, easier to transport, and potentially more remotely manufacturable than a precision gearbox. However, it uses a great deal more energy, and has a limited stroke length in which to do mechanical work. A motor would allow us to reduce our power and increase our torque immensely, limited only by the time we are willing to wait for each actuation and the limits of mechanical strength of the system. To pursue this design, we would reduce the number of independent actuators to 6, one per face controlling all four flaps simultaneously. A simple method would be to use a single geared, non-backdrivable motor per face, connected to all four flaps via a cable drive. This would give a very even torque relative to angle, making control extremely simple.

6.2.3 Torque system analysis

The figures show the change in torques generated by different components of the system, namely the SMA, the spring, and the weight of the flap, with respect to the angle between the flap and the frame. As described in the legend of the figure, one curve represents the net torque generated by the spring and the weight of the flap, another curve represents the torque generated by the SMA in order the lift the flap and the third curve represents the deformation torque needed to stretch the SMA. For the system to work, the spring and flap torque curve needs to be in between the other two curves so that the SMA will be able to lift the flap and the spring will be able to pull it back after the SMA cools down.

For three cases, net torque generated by the spring and the weight of the flap becomes lower than the deformation torque needed by the SMA after certain angle. Therefore, when the angle between the flap and the frame goes beyond that angle, the spring will not be able to generate enough torque to close the flap. For one case, the net torque generated by the spring and the weight of the flap becomes lower than the deformation torque needed by the SMA at small angle. Therefore, the spring will not be able to completely close the flap (the flap is closed when there is zero angle between the flap and frame).

For the initial experiment, we tested case related to Figure **??**c, with the operational angle from 0 degrees to 90 degrees. From Figure **??**c, the spring and flap torque curve is always in between the other two curves at the range of 0 degrees to 90 degrees. Therefore, we did not encounter any problem with the initial experiment. However, during our

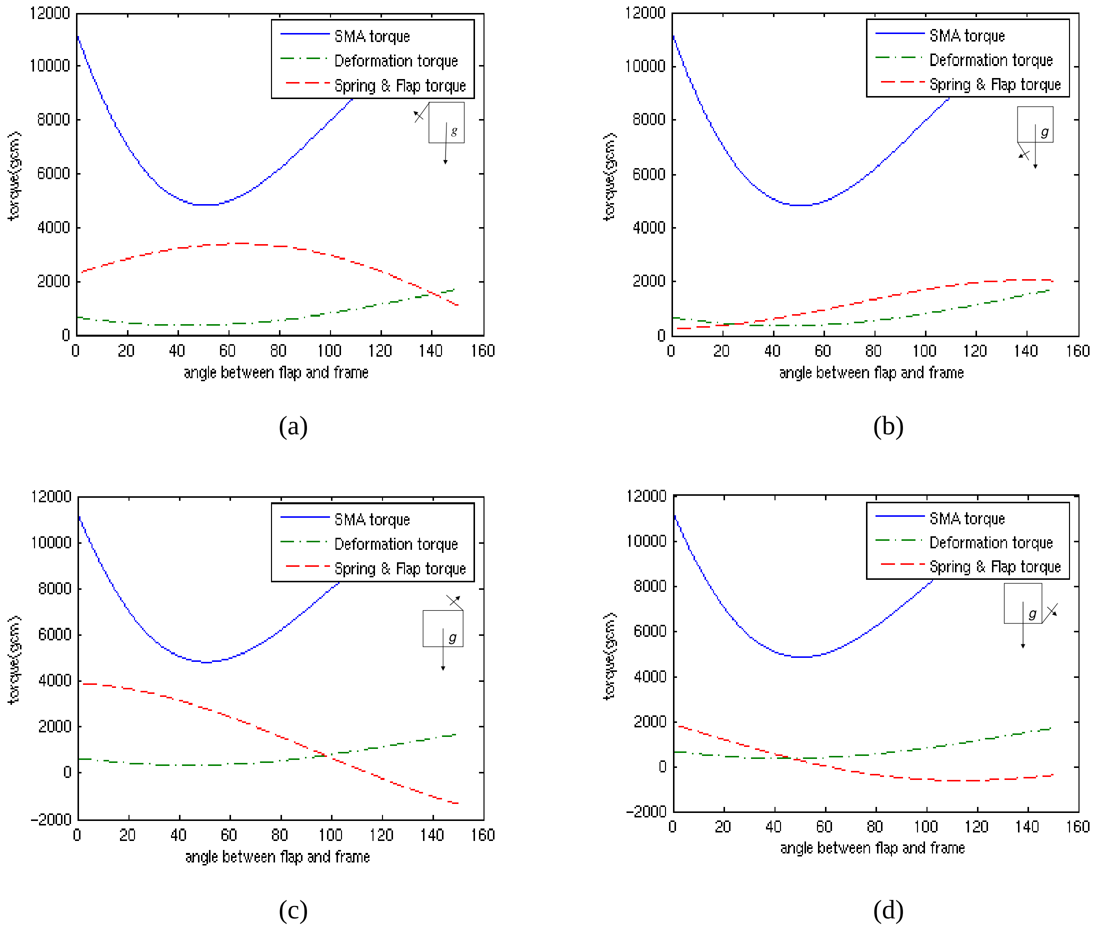


Figure 7: Existing system at various orientations with respect to gravity.

testing of the catom, we encountered cases related to Figures **??**a, **??**d, and **??**d, the net torque generated by the spring and the weight of the flap becomes lower than the deformation torque needed by the SMA roughly at the angle of 45 degrees. Therefore, the fixed catom does not have enough torque to move the other catom.

6.3 Power

The prototype Catoms were powered individually by on board batteries. Although this is not the proposed solution to battery maintenance problems, our analysis shows that efficient power transfer between catoms is possible with methods explained earlier. In that case, we could greatly reduce the weight of the onboard batteries and rely on frequent recharging.

6.4 Communications and Control

Global communication among catoms occurs via ZigBee, a low-power wireless mesh networking protocol. Optical connections between properly aligned and attached catoms will allow them to speak to their neighbors and infer relative positioning information.

Each catom controls its sensors and actuators using I^2C, a distributed local bus. The sensors and actuators on each of the six faces are controlled by small 8-bit microcontrollers with suitable peripherals, which in turn communicate to a single master, which handles intercatom communications as well as power routing and regulation.

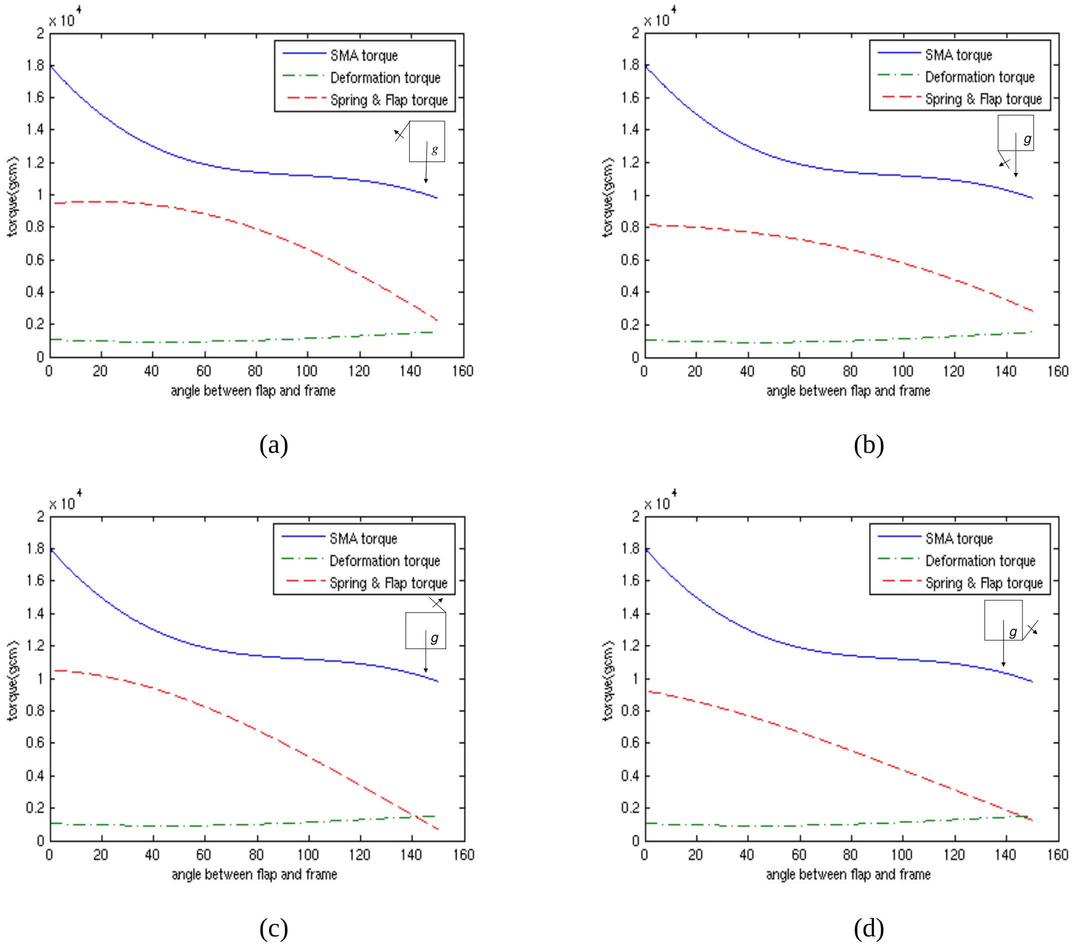


Figure 8: Proposed system at various orientations with respect to gravity.

6.4.1 Catom programming

Each catom exposes an API of low-level commands to control actuators and get sensor readings. It can be instructed to set any of the 24 flaps to an angle between 0 and 90 degrees and turn on or drain the high voltage on any of the flaps. Sensor functions allow each catom to return the current flap angle based on potentiometer readings, the high voltage settings on any face, and the battery voltage. Catom-level control is distributed among six slave boards and one master board. Commands are interpreted by the master board and relayed to relevant slave boards. By default, the catoms are programmed to wait for commands and then act upon them, but intelligent coordination code can be readily incorporated into the main program loop.

The catoms communicate wirelessly using a UDP-based packet system. Packets are sent to issue commands and return data. The master boards accept commands, relay them to slave boards if necessary, and then return acknowledgement packets containing relevant data. These commands can be issued by a global controller or by individual catoms. Middleware was developed to control and coordinate the catoms. This allows us to globally control and coordinate the catoms from a terminal interface. Middleware tools also allow for sending and receiving individual packets and timing actions to create shapes. These tools could be used by higher level programs for user-friendly control.

6.4.2 Catom electronics

The electronics for our prototype have additional constraints not present in our long term design. Rather than make the catoms intelligent and autonomous, we aimed to make them as simple as possible and expose their abilities to a host computer, so that we could quickly test a variety of different actuation strategies. Each prototype had its own power source, a pair of 18.4V lithium polymer batteries. Communications were handled using ZigBee, a low power, low bandwidth networking protocol which is great for coordinating a handful of modules but may not be tractable on a larger scale. Reprogramming the modules was done using a tether.

We chose to work with a distributed system. Though a single microcontroller is often easier to work with than a distributed system of multiple processors, we used multiple processors in order to reduce overall system weight and take advantage of the peripherals of commercially available microcontrollers. Each robot is a cube almost two meters on a side, making light, low resistance wiring a challenge. Each flap requires several connections including two high current wires for heating the SMA. Spreading the logic across several control boards allowed us to distribute the high current power in a star pattern, reducing the necessary amount of wire. Additionally, since our system required a UART, 24 PWM outputs, 26 analog / digital conversion ports, and 48 digital outputs, there were no convenient commercial microcontrollers available that could handle our needs. Splitting the system up allowed us to take advantage of microcontroller peripherals, greatly simplifying the design.

We utilized ZigBee for intercatom communications. MaxStream's XBee module allowed us to treat our wireless network as a multi-drop serial port, where all nodes receive the broadcasts of each other. Since each catom was configured to only respond when a host computer sent it data, we did not have any problems with spurious traffic. To scale in the future, each XBee module can be configured to only forward data packets to its host if the address matches.

For intracatom communication, we implemented I^2C between the mother and daughter boards. To handle the less than ideal conditions of two meter cables, we used higher power buffered line drivers between boards. As flap commands arrive at the motherboard via ZigBee, the mother forwards the requisite commands down to the relevant daughter via I^2C. Once the daughter has responded, the mother sends back a confirmation packet to the host computer with an acknowledgement or the requested information. The mother can also broadcast emergency shutdown or halt conditions to all of her daughters at once.

To control flap angle, we implemented a proportional controller. It reads in a resistance corresponding to the angle of a potentiometer attached to our hinge and varies the power going to the SMA by changing the duty cycle of a pulse-width modulated signal driving a power MOSFET. Higher power heats the SMA more, producing more torque, whereas lower or no power allows the SMA to cool off. While simple, this system was sufficient to test a variety of catom movements.

A serious problem with our prototype design was that our offset pulley design makes it difficult to control the angle. The SMA pulls about a diameter that is offset from the center of rotation, which means that the torque will vary with angle. Additionally, the SMA tends to decline in strength as it contracts, and behavior as evidenced in Figure **??** occurs. For angles below 45 degrees, the torque steadily decreases as the angle increases, which minimizes the overshoot and oscillations common in a proportional controller. However, as soon as the angle crosses 45 degress, the torque increases and the system overshoots to its mechanical stop. The only way to counter this effect would be to carefully cool the SMA at a proper rate, something very dependent on environment temperature and convection. The better solution was instead to modify the mechanical system to remove this behavior, as seen in Figure **??**.

6.5 Adhesion

Our adhesion relies upon strong electrostatic forces generated between flaps. We noticed a major difference between the theorized and the observed experimental results, mainly between the measured electrostatic forces and the theoretically calculated forces. The difference is a few orders of magnitude, where the measured forces are much lower.

There are several factors that are to be considered. One is that the prototypes had electrodes composed of floppy conductors coated with a dielectric material. Although a good seal was established when electrodes were excited, the fact that the conducting surfaces were flexible caused the amount of force necessary to separate them to decrease. This can be explained with peeling effect, where the two electrodes are easily pealed off at the boundary of the contact. The ring of surface that surrounds the boundary can move independently of the contact, so very small forces can actually propagate peeling into the boundary, eventually causing the entire surface to snap off. This could be avoided using rigid electrodes, where peeling would not happen.

Another factor is that there is no easy way to estimate the amount of separation between electrodes. A sub-millimeter separation is virtually impossible to see by eye, so the assumptions on the separation might not hold. Our experiments show that there is always a certain amount of separation caused by non-uniformities or wrinkles in material, though we have yet to devise an experiment that will allow us to accurately measure these gaps.

7 Conclusion

We have described a lightweight construction system to allow the rapid and autonomous deployment of orbital and planetary facilities on the moon and Mars. The construction system is composed of an ensemble of modular robots, called catoms. We designed, constructed, and tested a prototype system composed of two catoms which validated the basic principles underlying out design.

Acknowledgements

This work could not have been done without the amazing and excellent advise, help, and labor of the many people in the Claytronics group. In particular we would like to thank Burak Aksak, Jason Campbell, Babu Pillai, Nels Beckman, Byung Woo Yoon, and Todd Mowry. This work was supported in part by DARPA, NSF, CMU, and Intel Corporation.