A Modular Robotic System Using Magnetic Force Effectors

B. Kirby, B. Aksak, J. Hoburg, T. Mowry, P. Pillai

***Abstract*— One of the primary impediments to building ensembles with many modular robots is the complexity and number of mechanical mechanisms used to construct the individual modules. As part of the Claytronics project—which aims to build very large ensembles of modular robots—we investigate how to simplify each module by eliminating moving parts and reducing the number of mechanical mechanisms on each robot by using force-at-a-distance actuators. Additionally, we are also investigating the feasibility of using these unary actuators to improve docking performance, implement inter-module adhesion, power transfer, communication, and sensing.**

In this paper we describe our most recent results in the magnetic domain, including our first design sufficiently robust to operate reliably in groups greater than two modules. Our work should be seen as an extension of systems such as Fracta [7], and a contrasting line of inquiry to several other researchers' prior efforts that have used magnetic latching to attach modules to one another but relied upon a powered hinge [8] or telescoping mechanism [10] within each module to facilitate self-reconfiguration.

Fig. 1. *Three magnetic-based planar catoms. Videos demonstrating their movement capabilities are available at http://www.cs.cmu.edu/˜claytronics/iros07/planarcatom/.*

I. INTRODUCTION

Advances in manufacturing and electronics open up new possibilites for designing modular robotic systems. As the robots become smaller, it becomes possible to use *force-at-a-distance* actuators—e.g., actuators which cause one module to move relative to another via magnetic or elecric fields external to the modules themselevs. Furthermore, as the cost and power consumption of electronics continue to decrease, it becomes increasingly attractive to use complex electronics rather than complex mechanical systems. In this paper, we explore how a single device that exploits magnetic forces can be harnessed to unify actuation, adhesion, power transfer, communication, and sensing. By combining a single coil with the appropriate electronics we can simplify the robot—reducing both its weight and size—while increasing its capabilities.

The robots described in this paper are the result of our explorations into the underlying ideas of the Claytronics project [2], which is investigating how to design, build, program, and use ensembles comprised of massive numbers of modular robots. Thus, one of the main driving design criteria for any individual mechanism is: *will it support scaling the ensemble to larger numbers of units?*. A direct outgrowth of this design criteria is that each unit in the ensemble must be inexpensive, robust, and easy to manufacture. Hence mechanisms used for locomotion, adhesion, communication, etc., must be as simple as possible. One way to achieve this is to use inexpensive and robust resources—e.g., computation—to reduce mechanical complexity. Furthermore, since we are interested in the ensemble as a whole, we do not require that individual units be self-sufficient. For example, a single unit does not need the ability to move independently within its environment as long as it can contribute to the overall motion when it is connected to the ensemble. We call this design principle the *ensemble axiom:* each unit contains only the minimum abilities necessary to contribute to the aggregate functionality of the ensemble.

Choosing the right mechanism for locomotion is a key design decision. In addition to scalability, the size of the unit must also be taken into account. At the macroscale, complex mechanisms such as motors are effective. However, other approaches become viable as units scale down in size which increases the surface-to-volume ratio and decreases the moment of intertia. Our current robots, which we call *planar catoms*[1], are small enough that we can explore a mechanism designed around *magnetic field* force-at-a-distance actuators. As the units decrease further in size, actuators based upon *electric field* forces become viable and are appealing because they use less current, produce less heat, and weigh less than magnetic actuators. Smaller units could also harness surface forces such as surface tension or even Van der Waals' forces. The size scale also affects power transfer and storage: because electrical resistance increases as contact

This work was supported by DARPA, NSF, and Intel.

Kirby, in SCS at CMU, 5000 Forbes Ave, 15213 `bkirby@cs.cmu.edu`

Aksak in ME at CMU `aksak@me.cmu.edu`

Hoburg in ECE at CMU `hoburg@ece.cmu.edu`

Mowry, Pillai at Intel Pittsburgh Research {`todd.mowry`, `padmanabhan.s.pillai`} `@intel.com`

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[1] "Catom" is short for "claytronics atom."

size decreases, direct electrical connections between robots become increasingly impractical as they continue to shrink. We chose the centimeter scale for our initial prototypes to keep the small-scale prototyping costs of our onboard circuitry reasonable.

In keeping with our design principle, we demonstrate 45mm diameter cylindrical modular robots (see Figure 1) that can move in a plane and use a single, no-moving-parts mechanism—an electomagnetic coil—for *locomotion and adhesion* (Section III), *power transfer* (Section IV), and *communication and topology sensing* (Section V). The ability to implement a number of features using the same mechanism allows us to reduce the weight, volume, and overall complexity of the unit. However, since no robot can move, obtain power, or sense its neighbors without the cooperation of its neighbors, an increased burden falls on the programmer to provide these capabilities. To aid in the task of developing the software for these robots, we have developed a physics-based simulation environment for claytronic ensembles. Two important features of the simulator are that it interfaces with our 2D hardware prototypes, and that it can simulate both 2D and 3D ensembles up to hundreds of thousands of catoms (see Section VI).

II. RELATED WORK

The effort to produce reliable and robust modular robotic systems has led researchers to explore a large design space of mechanisms for locomotion, adhesion, communication, and power. Ostergaard, et al. survey different locomotion and adhesion mechanisms for self-actuating robots in [4].

Of the many research efforts the most relevant to our work is Fracta [7]. Fracta is a two dimensional modular robot which uses a combination of permanent magnets and electromagnets for locomotion and adhesion. It is the only other internally actuated system which has no moving parts. As in our planar catoms, to move a module requires communication between the moving module and its neighbors. The two main differences between Fracta and planar catoms are due to changes in underlying techology and the use of permanent magnets. Fracta modules are constrained to be in a hex-lattice whereas the planar catoms have additional actuators and can be arranged in a cubic or hex lattice, as well as more arbitrary formations. Significant advances in VLSI enable us to create smaller lighter units which do not use permanent magnets. We also harness the magnets for more than locomotion and adhesion, i.e., the magnets also serve as the main mechanism for power transfer, sensing, and communications.

Planar catoms are our first step along the path towards realizing three dimensional claytronics. Part of their raison d'etre is to understand the ensemble axiom and how the tradeoff between individual unit hardware complexity and computation affects design. As such, work in externally actuated modular robots is also relevant. For example, neither programmable parts [1] nor 3D stochastic robots [9] have any moving parts. Both of these systems simplify each robot by using external forces for actuation. The robots rely on the external forces and move stochastically, adhering to each other under control of the program running on the robot. The ensemble principle is carried even further in the latter project; robots are unpowered until they adhere to a powered robot.

Earlier prototypes of the planar catoms described in this paper have been demonstrated at AAAI [5] and have been briefly described in the general media. This paper is the first complete description and introduces the ideas behind using a single device (electromagnets) to implement locomotion, adhesion, power transfer, communication, and sensing.

III. LOCOMOTION

Using the ensemble axiom as a guiding design principle requires that we design very small robotic modules capable of actuating relative to one another. As discussed earlier, to make reliable modules that can be readily scaled down in size, we have taken the extreme position of eliminating all moving parts within our robotic modules. Motion without moving parts is achieved instead by the use of force-at-a-distance actuation between modules. The mechanisms that work well for this purpose are highly dependent on the absolute scale of the module design. We chose the centimeter-range for our prototypes, as it was the smallest size we could implement self-contained modules using commercially available electronic components and circuit board design techniques. At this scale we are well beyond the practical application of surface tension, Van der Waals force, or electrostatic attraction, and therefore employ electromagnetism for our actuation.

A. Relative Motion using Pairs of Electromagnets

In keeping with the ensemble axiom, planar catom motion requires two modules to perform the simplest locomotion. Our actuation can be likened to a rotary linear motor, e.g. a stepper motor in which the stator and rotor are mechanically decoupled into two separate, identical modules set side by side. Rather than permanent magnets, both catoms generate their fields with the appropriate polarities via electromagnets. Catoms in contact may orbit each other in a clockwork fashion by simultaneously activating electromagnets adjacent to the pair currently in contact. The magnetic force will create a torque that pivots the two catoms about the edge and onto the next face. Once in position, the catoms can again activate the next adjacent pair and continue their orbit.

In ideal conditions, this motion takes as little as 50ms to complete one step, or 1.2s for a complete revolution. However, unlike a stepper motor, which is carefully designed with tight mechanical tolerances and excellent axial alignment, our catoms must regularly deal with mechanical misalignment both in and out of the plane of motion. As magnetic force falls off proportional to the cube of the distance, these small misalignments seriously compromise the efficiency of our motion. When using simple open-loop control, it is necessary to power the coil for much longer than needed for the ideal case, to give the catoms time to exert themselves over farther distances. In some generations of

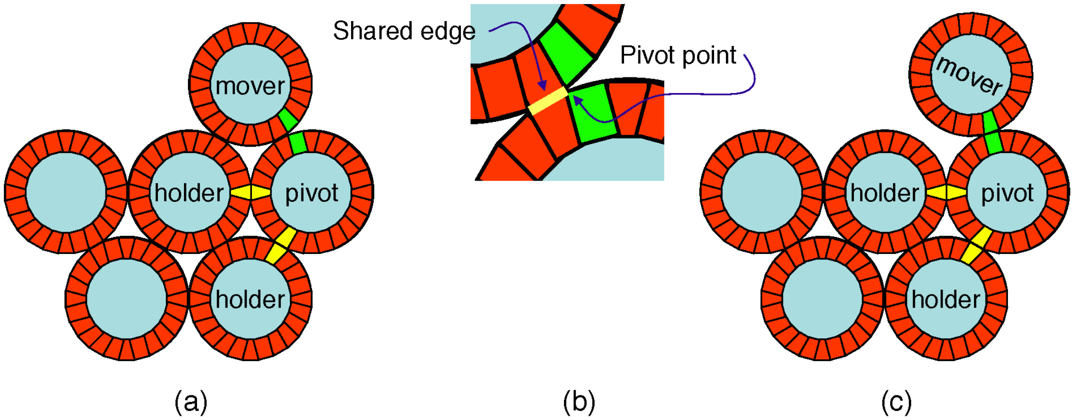

Fig. 2. *A typical movement scenario. (a) is the start configuration. (b) is a blow up of the mover-pivot pair. (c) is the final configuration. The yellow magnets exert a small holding force. The green magnets exert a large force to move the mover around the pivot.*

prototypes, this conservative on-time has been 10-20x longer than the ideal. This variability in performance thus has a large effect on power efficiency, and suggests why closed-loop control is highly desirable in our system yet generally not implemented in standard stepper motors.

B. Ensemble Motion

While the basic motion primitive requires the participation of only two catoms, any motion which performs actual work, i.e., motion which changes the configuration of the ensemble, requires the involvement of more than two catoms. We distinguish three types of catoms in ensemble motion. The *mover* catom moves around a *pivot* catom with respect to the rest of the ensemble. The others surrounding the pivot catom, *holders*, keep the pivot catom in formation as the mover moves around it.

In a basic movement scenario, the pivot catom and all its neighbors except the mover catom actuate their magnets with a low holding force (the yellow magnets in Figure 2a). The mover and pivot then energize the magnets used to move the mover catom (the green magnets in Figure 2a and b). This causes the mover catom to pivot around the edge it shares with the pivot catom, resulting in Figure 2c.

C. Magnet Design and Constraints

Our initial investigations focused on permanent magnet solutions, as these have provide a holding force without a static power dissipation. We experimented with programmable or “soft” magnetics, using AlNiCo magnets that can be made to change polarity when subjected to brief pulses from an encompassing electromagnet. Unfortunately these were too weak to generate useful forces for us, and are known to degrade over time when subjected to large numbers of polarity shifts. We also considered using the surrounding electromagnet as our primary actuator, using the soft magnetic material only as a passive holding actuator, but the AlNiCo had poor permeability and low saturation, preventing us from generating enough force in the electromagnets. By using a more traditional electromagnet core material, we were able to design magnets with effective force. Additionally, as we will see in later sections, the electromagnets can be used for other purposes. Thus, the planar catoms use the same electromagnets for locomotion, adhesion, power delivery, communication, and sensing.

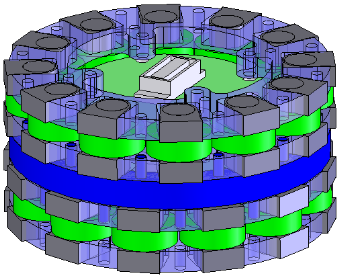

Fig. 3. *The main body of the catom is comprised of two rings of magnets offset by 15 degrees.*

The design constraints involved in determining the size, shape and number of magnets are numerous. First and foremost, the magnets must provide sufficient torque to rotate a catom around a shared edge (e.g., the highlighted edge in Figure 2b). The torque required is influenced by catom mass and diameter, as well as the friction between a catom and the floor. The electromagnets themselves are quite heavy as they have a large copper winding and the core and flux shunt are composed of steel. The minimum amount of core material is dictated by magnetic flux saturation—reducing the cross-sectional area of the core would dramatically reduce magnet strength. The copper coil is limited by the power density—reducing the cross-sectional area of the coil would force proportionaly higher current through less material, increasing heat dissipation and dramatically lowering the effective duty cycle of the actuator. Friction cannot be lowered arbitrarily as low friction constants make the movement between catoms unstable (e.g., the catoms tend to fly away from each other).

In addition to being strong and compact, the magnets must also be carefully shaped so that they can be placed around the circumference of the catom without interfering with each

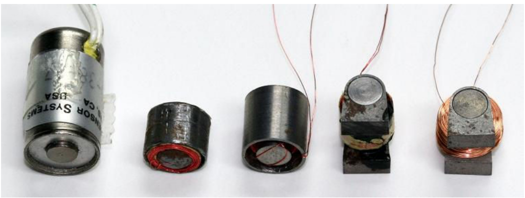

Fig. 4. *A progression of catom magnet designs. The rightmost magnet is our current revision.*

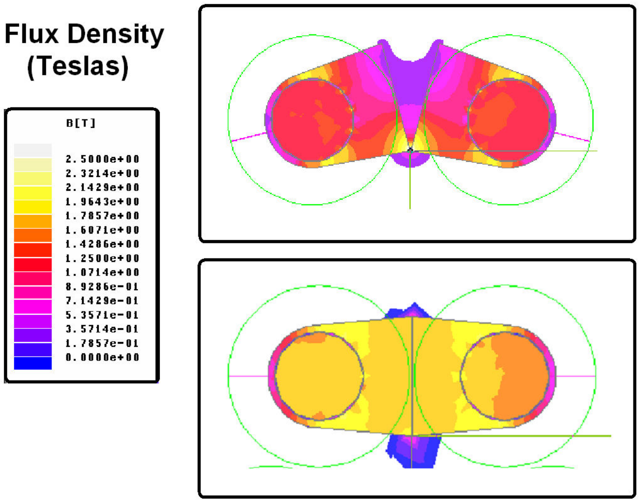

Fig. 5. *At the start of a motion (top), the flux saturates the bottom tip of each magnet, generating the initial torque of 12mN-m. At the end (bottom), the flux is evenly distributed and provides far greater holding torque (200mN-m) for the same power.*

other. Furthermore we want to restrict the lattice packing as little as possible, supporting at least hex and cubic lattices. We used these three factors and the fact that magnetic force falls off with the cube of the distance to determine that 24 magnets would be the best balance of constraints. To prevent the magnet core material from being close enough to cause interference, we stagger the magnets in two rings of twelve spaced 4mm apart as in Figure 3. This has the added benefit of giving us larger effective area for our coil windings. Using more than two rings is prohibitive, because it begins to introduce significant out of plane torques as the magnet layers become farther and farther from the friction plane. With each individual magnet designed to maximuze flux density, reduce saturation, minimize overheating, we finally consider resistance and wire gauge so that our voltage and current requirements can be met with high density surface mount components such as MOSFETs.

Commercially available, off-the-shelf electromagnets proved insufficient for our actuators. They did not fit well in our cylindrical geometry, and had far too conservative power usage and duty cycles to satisfy our torque needs. Thus, we had to design our own magnets. After several iterations (shown in Figure 4), our current design places the coil vertically and uses two thick trapezoidal endplates that combine to form a horseshoe electromagnet. The ends of the horseshow are flat to improve catom-to-catom alignment. The sharp edges of the endplates also provide a natural pivot point. (Initially we tried rounded ends, but this results in an unstable system.) The current design also helps ameliorate the inverse cubic falloff of magnetic force, as at the start of a move operation the actuating magnets already have a narrow but complete flux path, greatly increasing our initial strength. The flux paths may be seen in Figure 5 at both the initial and final stage of a motion step.

The resulting system has 24 magnets arranged in two rings of 12 magnets forming a faceted, self-aligning structure, with a large potential excitation capability and acceptable duty cycles. The coil height is 3mm and has 452 turns of 39 guage wire around a 4.4mm AISI1010 steel core, and presents its flux at the catom's perimeter, 4.2mm from the center of the solenoid, via two 3mm thick flux shunts. When energized at full power for relative motion, these coils are capable of co-generating a torque of 12mN-m. The worst-case torque needed, that of moving one catom about a second fixed catom, is given by the formula $\tau = mgr\mu$, and is around 3mN-m given a .105kg module under low friction circumstances of around .12. When energized for holding torque, they can generate over 200mN-m at full power. By using a small fraction of full power we can generate adequate holding torque without danger of overheating the coils.

D. Control Circuits

When moving a catom the magnets require high excitation currents for short periods of time. Conversely, when holding two catoms together, the magnets are next to each other and thus require very little excitation, but should remain on continuously. The magnet control circuits is designed to support both situations. This greatly simplifies ensemble control, as without a holding force, accurate synchronization between many catoms would be required if they were to hold one catom in place while another rotated about it. We also need control of the polarity, to coordinate an attractive force between two separate catoms. Consequently, our drivers must be capable of independent, bidirectional delivery of over 30 Watts in sub-second bursts, as well as delivering a few watts over multi-minute periods. Fortunately, modern MOSFETs support the required power densities in packages small enough for us to fit the drivers for the entire magnet array onto the catom itself.

Our initial controller design implemented 24 full bridges for completely independent control of each magnet. Fitting everything necessary into a 44mm^2 area was a laborious process and greatly increased manufacturing costs. As we continued to investigate the motion and lattice constraints, we realized that no movement circumstances would ever require us to activate more than one of any four consecutive electromagnets around the 24-gon. By separating the full bridges into half-bridges, and using one shared half bridge between these four, we were able to reduce the number of half bridges from 48 to 30, as well as multiplex the magnet control signals. This dramatically reduced the circuit density, as shown in Figure 6, and made pulse width modulation (PWM) signal generation practical for our control signals.

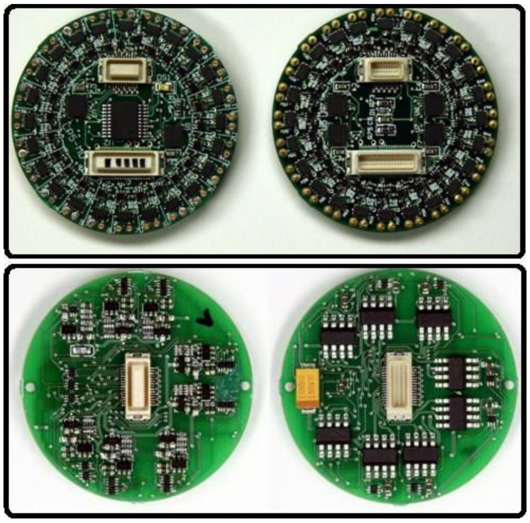

Fig. 6. *Density comparison of implementing independent full bridges (top) vs. multiplexed half-bridges (bottom).*

PWM allows for simple open-loop current control. Thus, in addition to a full-duty, high excitation pulse, we can also generate our low power holding currents that can remain on continuously without harming the electromagnets.

Our current electronics are capable of continuously delivering up to 1.5A at up to 50V. Higher voltages exceed the rating of our high density interconnect and approach the breakdown voltage of our existing semiconductors. Given that this power level is sufficient to cause thermal breakdown in our coils in a matter of seconds, our duty cycles are limited solely by the electromagnets and not our drive electronics.

E. Discussion

We found that the two most important factors in achieving a robust system are the effective magnet torque and the manufacturing precision. Despite several iterations focused solely on maximizing the torque generated, we have only been able to generate four times the torque needed under ideal conditions. This is barely adequate to provide for robust locomotion, as even small misalignments of the magnets can disrupt the system dramatically due to the non-linear falloff of magnetic force. Angular misalignments of the magnets orthogonal to the plane of motion are especially severe as it imparts torques that actually impede motion. Thus, repeatable and precise manufacturing was critical to creating robust designs and required several iterations.

IV. POWER

Keeping each modular robot in the ensemble fully powered is one of the main challenges in building large scale ensembles. This is particularly true as the modules shrink in size because energy output of batteries does not scale well. In keeping with the ensemble axiom, we take as one of our design constraints that the individual units should not require long term power storage, nor should they require an initial charge when they begin operation. Clearly, providing each robot with a tether to a power source is untenable. The ensemble axiom instructs us to minimize self-supporting robots and instead provide mechanisms for the units in the ensemble to share and distribute power. We envision a system in which a few of the units are attached to power sources and then through cooperation distribute power amongst the mass.

Fig. 7. *Using mechanical contacts for power conduction.*

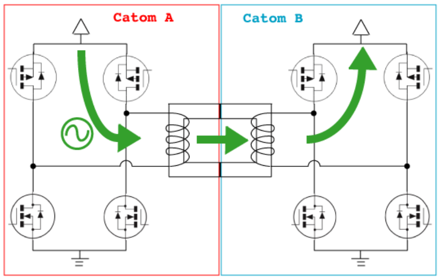

Fig. 8. *An AC wave generated in Catom A induces a current in the coupled magnet of Catom B. This current is passively rectified via the h-bridge protection diodes, providing B with power.*

Our initial attempts at sharing power relied on a power floor and conductive feet as in the Fracta [7] system and the NanoWalker [6]. While effective, it led to unpredictable angular misalignment, preventing robust motion. We next tried DC connections between the units (Figure 7). Such a system requires balancing the need for low resistance electrical contacts between units and the need to keep the spring force and friction between the contacts as low as possible so the power rings don't impede stable movement. While this system works, it is very sensitive to variations in assembly and neighbor orientation, making it impractical for large scale implementation. Additionally, it does not scale well to smaller, more numerous systems as the resistivity will quickly limit the reach. It also requires additional modules to be placed on each robot, reducing its scalability into 3D systems.

One way to eliminate additional modules is to capitalize on the connectivity of the large, high power electromagnets between catoms and transfer power inductively. When two catoms are adjacent the flux shunts of their magnets touch and they form a crude but effective transformer. The electromagnet control circuitry is flexible enough to generate AC waveforms, allowing one catom to induce currents in the other as shown in Figure 8. Interestingly, the protection diodes in the h-bridges (in this case provided by the body diode behavior of MOSFETs) act as a full bridge rectifier, meaning that power generation on the receiving catom is completely passive and allows disabled catoms to be powered on. In a sense this method of power delivery is based on a packet switched routing network. Instead of packets of data being delivered, it is packets of power.

Through simple experimentation we can achieve 300mW-s (.3J) of continuous power transfer using a simple square wave at 3kHz at 15 percent efficiency. As movement requires anywhere from 3-10J, significant power storage is required. In testing we used an aerogel capacitor array, tied to the system power bus, to provide .4F at 30V. This fit on the catoms and provided the necessary working voltage. The extremely large energy storage, 180J, was needed to prevent significant voltage decay during a motion discharge. A slightly more complicated system where the charge storage is isolated from the main system power would allow us to adjust the voltage dynamically through standard switch-mode regulation and reduce the needed energy storage. Regulation also eliminates the voltage losses inherent in rectification and transformer coupling, which otherwise would limit power transfer to a few hops.

There are many issues that must be addressed before inductive power can efficiently transfer enough power to become practical. Clearly, higher rates of power transfer must be achieved if the catoms are to charge, move, and recharge in a reasonable time. A main issue is electromagnet construction: the coils are wound on the core and then two shunts are loose-fit onto the ends, creating a square horseshoe. These loose-fit connections introduce slight air gaps, but they could be ameliorated with a press-fit connection. An alternative would be to wind the coil onto a half-torus, which while more expensive to produce would have a minimum flux path, further increasing efficiency.

The fairly high coil resistance of 28Ω also creates constraints. This was originally done to minimize the total current needs of the electromagnet. Each catom module has many layers of connectors between the power source, h-bridges, and electromagnets, and by reducing the current we reduce the power lost in this resistance. Also, since our design goal was to develop as high a torque as possible, we use many turns to saturate the core and achieve near-maximum flux density. Together these decisions suggest we use frequencies in the kHz for power transfer.

Unfortunately, explorations into kHz frequency waveforms reveal additional problems with the current electromagnet construction. We chose a ferrite core, as low carbon steel is inexpensive to machine and has a high maximum flux density, which is critical to generating high torques. It also has a fairly low starting permeability, which means a significant amount of energy is lost establishing the initial magnetic field. This is not a problem when using DC for torque generation, but at high frequencies most of the energy is lost constantly establishing, destroying, and re-establishing the field. Figure 9 shows the results of analysis that confirms the poor high frequency behavior of the current core. This can be best avoided by using a different core material, one with characteristics better matching the new requirements. Pure iron or an exotic like permandur are suitable as a magnetic material, but their other material properties, as well as cost, make them impractical. Silicon steel is a reasonable compromise: it handles higher frequencies dramatically better than carbon steel, while its slightly lower flux density only minimally reduces the developed torque.

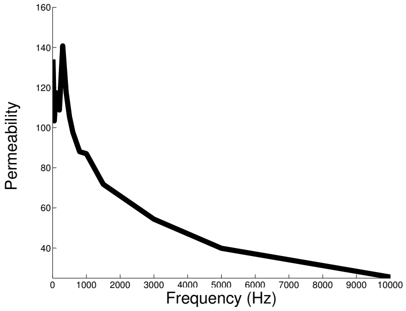

Fig. 9. *The effective permeability of the ferrite core decreases as frequency increases.*

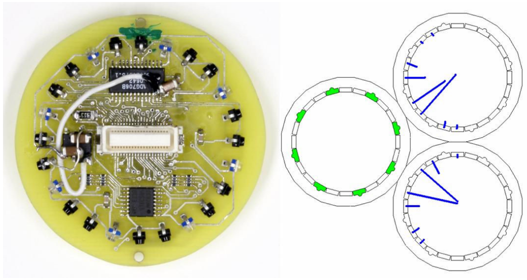

Fig. 10. *(a) IR communication and localization modules. (b) Simple vector summation localizes two catoms.*

V. COMMUNICATION AND SENSING

Communication is perhaps the most important part of a catom module. Ensemble actions such as movement require coordination between catoms, and global communication between catoms and the outside world greatly simplifies maintenance tasks such as reprogramming, debugging, and program interfacing. While a simple wireless network is used for many of the maintenance tasks, local neighbor-neighbor communications is required for two reasons. First, they have been shown to scale in claytronic systems [**?**]. Second, they are often capable of providing the minimal sense feedback we need to allow for accurate motion coordination.

For global communications we use a packet-based API over a 802.15.4 network using Maxstream Xbee modules. This enables serial-speed communications between individually addresable catoms or a host computer, as well as a general broadcast mode.

Our primary investigations into local communications focus on IR emitter and detection systems. By having many transmitters and receivers, a catom communicates independently with all of its neighbors. Our current system uses 8 transmitters and 16 emitters staggered equally around the perimeter of the catom as in Figure 10a. Increasing the number of receivers gives more angle information, enabling catoms to localize to their neighbors and determine which faces are connected.

Localization is a straightforward process. One catom broadcasts a high value pulse on all of its transmitters while its neighbors simultaneously check their sensors. By doing a vector sum of the resulting sensor values as in Figure 10b, each neighbor can determine which face is most likely in contact with transmitting catom. This simple sensing is all that is needed to allow coordinated relative motion, as well as provide for closed loop control.

A system currently under investigation uses magnetic induction to detect connected faces as well as provide very specific local communications. This is promising as it will reduce each catom module to a set of unary actuators capable of providing power, communications, and locomotion. One implementation places a small sense resistor on the unshared end of each of the 24 coils. A mirrored current monitor would provide a voltage corresponding to the instantaneous current through the coil, which could be sampled by the microcontroller. Externally induced currents can easily be inferred by the lack of an existing control signal presently driving that coil. Useful communication speeds would require extremely high sampling rates, but localization would require only the grossest sensing capabilities.

VI. CONTROLLING THE CATOMS

In the full vision of Claytronics, the catoms will collectively execute a suite of applications to perform sensing, effect shape changes to the ensemble, and interact with the users in the physical environment. To facilitate the development of these and other high-level, distributed applications, we have developed an accurate simulation environment as well as a layered software stack to provide lower-level hardware control [3]. The simulator is designed to accurately model catoms by providing a multithreaded execution environment to simulate running code simultaneously in a multi-catom ensemble. It also models the dynamic interactions between catoms and the physics of the world they operate in.

In addition to simulation, our goal is to develop a framework allowing programs to be run unaltered on both the simulator and real hardware. To do so we have developed a multi-level API which is used to interact with the hardware catoms from within the simulator, communicating wirelessly to the catom hardware using our global communications hardware. This interaction ranges from debug-level variable manipulation and teleoperation up to communication with fully autonomous hardware modules. This development system allows us to match the behavior of the actual hardware with the simulated results, and to rapidly develop software that can work entirely in simulation, entirely on the real hardware, or a mixture of the two.

The level 0 API (summarized in Figure 11) provides access to the individual components of the catom. When using this API, the control software breaks up high-level actions (e.g., rotate catom clockwise one position) into the series of commands neccesary to achieve the desired motion. Each actuation or sensing operation includes a timestamp argument, **s**, that indicates when the catom firmware should carry out the operation. By including this simple scheduling facility at the lowest layer, we can write code that performs operations synchronously on multiple catoms, even when teleoperated from within the simulator over a shared, relatively high-latency wireless network. In this teleoperation mode, the simulator periodically resynchronizes all of the catoms by broadcasting a SYNCH packet; future operations will be executed at timestamps specified relative to the receipt of this packet. This API has proven very useful in debugging the logic used to control the catoms. During execution of the program the user can check whether or not the real hardware is in the same configuration as the simulated hardware. The main limitation of this API is that

Messages From High-level Software or Simulator

Message	args	Response
PING		ACK
	check which catoms are alive	
MAGNET	m,p,l,s,d	ACK, NACK
	turn on magnet **m** with polarity **p** at power level **l** at time **s** for **d** msec.	
MRESET	m, s	ACK, NACK
	turn off magnet **m** at time **s**.	
SYNCH	e	SLEW
	reset timer to 0 and set epoch to **e**.	
SENSE_T	s	ACK, NACK
	start sensing cycle as transmitter at time **s**.	
SENSE_R	s	ACK, NACK, IRLEVELS
	start sensing cycle as reciever at time **s**.	
MSENSE_T	s	ACK, NACK
	start magnet-based sensing cycle as transmitter at time **s**.	
MSENSE_R	s	ACK, NACK, MLEVELS
	start magnet-based sensing cycle as reciever at time **s**.	
POWER_T	m,s	ACK, NACK
	start sending power on magnet **m** at time **s**.	
SET_IR	t, s, d	ACK, NAK
	turn on IR number **t** at time **s** for **d** msec.	
GET	c	ACK, NAK
	get value of catom variable **c**.	

Responses From Catom Firmware

Command	args
ACK	n, d
	ack previous request, optionally return array **d** of length **n** bytes.
NACK	
	nack previous request.
IRLEVELS	d
	return array **d** of IR reciever powerlevels.
MLEVELS	d
	return array **d** of magnets which sense a neighbor.
SLEW	e, o
	indicate clock reset and previous epoch was **e** and duration of epoch lasted **o** ticks.

Fig. 11. *Level 0 API for catom programming. This API is structured as messages to and from the catom firmware, allowing unmodified control code to run directly on the catom, or run remotely in a simulation environment and teleoperate the catom hardware.*

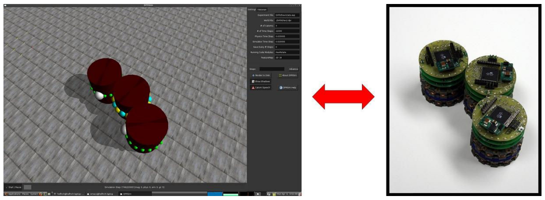

Fig. 12. *Simulator environment is replicated in real hardware using teleoperation.*

many messages are needed in order to achieve any motion step. Consequently, teleoperation of multiple catoms from the simulator is slow, with high-latency feedback, precluding any dynamic controls.

The higher levels of the catom software stack put more control logic in the catom firmware. For example, the level 1 API has MOVER and PIVOT commands which are sent to the mover and the pivot catom respectively. The catom firmware automates the lower-level operations, determining which magnets to turn on and off, what polarity to use, and the duration of the pulses. The next level up is the level 2 API which exploits catom-to-catom communications to further automate motion primitives. For example, the level 2 API has a MOVE command which is only sent to the mover catom. The firmware handles coordination with the pivot catom, and both catoms synchronize and pulse their magnets to achieve the motion.

High-level control software running on top of the firmware have the flexibility to use any combination of the API levels as appropriate. A lattice-style reconfiguration / shape change application, for instance, can ignore low level behavior and just use quasi-static motion control provided at the level 2 API. A chain-style motion application, however, may need finer control to handle the dynamics of catom interactions, and could experiment directly with the magnets via the level 0 API. A catom localization service involving analog-value sensing but high speed digital communication can use both level 0 and level 2 APIs, in addition to exporting its own feature API to other applications running concurrently.

At this point we have implemented a simple program on the simulator to move one catom around two others. Using the level 0 API we can confirm that the logic behind our operations is correct and see that the hardware performs as expected.

VII. CONCLUSIONS

The planar catoms are a successful application of the claytronics design principles. While 45mm scale catoms are physically implemented very differently than the sub-millimeter, our results in locomotion, power transfer, communication, and programming environments seem promising in their applicability. Of particular value is the idea that a simple pattern of unary contact features enables a single module to participate in and contribute to the ensemble.

By using electromagnets as actuators we demonstrate moving robots without moving parts or mechanisms. Careful calculation and assembly accuracy is needed in the construction of the magnet array, but these issues are commonly addressed in miniature manufacturing and do not rule out scaling down in size. While originally intended only for locomotion and adhesion, the inductive coupling offered by the magnet coils has also proven useful for power transfer, communication, and sensing. This ability to use a single mechanism in multiple roles can further reduce the mechanical complexity of a catom.

As expected, simplifying the mechanism increases the algorithmic complexity of completing a motion. Each movement of a single catom requires the participation of the entire ensemble. This makes local communication and sensing critical to the operation of a claytronic ensemble. Also essential are scalable distributed algorithms capable of synthesizing ensemble functionality from the abilities of each individual catom. Our simulator environment allows us to explore these fully while also providing a direct interface to our current hardware.

Multi-purpose magnetic force effectors are a first step towards scalable claytronic hardware. Distilling the complexity of a robotic module into an array of identical features greatly reduces the domain of design constraints that must be addressed during miniaturization. Furthermore, creating hardware that seamlessly integrates into our physics-based simulation environment allows real world scenarios to inform the development of distributed coordination algorithms.

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