Claytronics: A Scalable Basis For Future Robots

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Extended Abstract

Claytronics is a form a programmable matter that takes the concept of modular robots to a new extreme. The concept of modular robots has been around for some time. (See [14] for a survey.) Previous approaches to modular robotics sought to create an ensemble of tens or even hundreds of small autonomous robots which could, through coordination, achieve a global effect not possible by any single unit. In general the goal of these projects was to adapt to the environment to facilitate, for example, improved locomotion. Our work on claytronics departs from previous work in several important ways. One of the primary goals of claytronics is to form the basis for a new media type, *pario*. Pario, a logical extension of audio and video, is a media type used to reproduce moving 3D objects in the real world. A direct result of our goal is that claytronics must scale to millions of micron-scale units. Having scaling (both in number and size) as a primary design goal impacts the work significantly.

The long term goal of our work is to render physical artifacts with such high fidelity that our senses will easily accept the reproduction for the original. When this goal is achieved we will be able to create an environment, which we call *synthetic reality*, in which a user can interact with computer generated artifacts as if they were the real thing. Synthetic reality has significant advantages over virtual reality or augmented reality. For example, there is no need for the user to use any form of sensory augmentation, e.g., head mounted displays or haptic feedback devices will be able to see, touch, pick-up, or even use the rendered artifacts.

Claytronics is our name for an instance of programmable matter whose primary function is to organize itself into the shape of an object and render its outer surface to match the visual appearance of that object. Claytronics is made up of individual components, called *catoms*—for Claytronic atoms—that can move in three dimensions (in relation to other catoms), adhere to other catoms to maintain a 3D shape, and compute state information (with possible assistance from other catoms in the ensemble). Each catom is a self-contained unit with a CPU, an energy store, a network device, a video output device, one or more sensors, a means of locomotion, and a mechanism for adhering to other catoms.

A Claytronics system forms a shape through the interaction of the individual catoms. For example, suppose we wish to synthesize a physical "copy" of a person. The catoms would first localize themselves with respect to the ensemble. Once localized, they would form an hierarchical network in a distributed fashion. The hierarchical structure is necessary to deal with the scale of the ensemble; it helps to improve locality and to facilitate the planning and coordination tasks. The goal (in this case, mimicking a human form) would then be specified abstractly, perhaps as a series of "snapshots" or as a collection of virtual deforming "forces", and then broadcast to the catoms. Compilation of the specification into local actions would then provide each catom with a local plan for achieving the desired global shape. At this point, the catoms would start to move around each other using forces generated on-board, either magnetically or electrostatically, and adhere to each other using, for example, a nanofiber-adhesive mechanism. Finally, the catoms on the surface would display an image; rendering the color and texture characteristics of the source object. If the source object begins to move, a concise description of the movements would be broadcast allowing the catoms to update their positions by moving around each other. The end result is the global effect of a single coordinated system.

The core concepts in claytronics are hardly new; from science fiction (e.g., [35, 4]) to realized reconfigurable robots (e.g., [39]), to proposed modular robots (e.g., [8]), scientists and writers have contemplated the automatic synthesis of 3D objects or . However, technology has finally reached a point where we can for the first time realistically build a system guided by design principles which will allow it to ultimately scale to millions of sub-millimeter catoms. The resulting ensemble can be viewed as either a form of programmable matter suited for implementing pario or as a swarm of modular robots.

1 Scaling and Design Principles

A fundamental requirement of Claytronics is that the system must scale to very large numbers of interacting catoms. In addition to previously stated principles for the design of modular robots [22] we have the following four design principles:

1. Each catom should be *self-contained*, in the sense of possessing everything necessary for performing its own computation, communication, sensing, actuation, locomotion, and adhesion.

	Macro	Micro	Nano
Dimensions	> 1 cm	> 1 mm	< 10 microns
Weight	10’s of grams	100’s of mg	< 1 mg
power	< 2 Watts	10’s of mW	10’s of nW
Locomotive mechanism	Programmable Magnets	Electrostatics	Aerosol
	Electromagnets		
Adhesion mechanism	Nanofiber Adhesives	Programmable nanofiber adhesives	Molecular surface adhesion and covalent bonds
	Magnets		
Manufacturing methods	Conventional manufacturing and assembly	Micro/Nano-fabrication and micro-assembly	Chemically directed self-assembly and fabrication
Resolution	Low	High	High
Cost	$$$/catom	$/catom	Millicents/catom

Figure 1: *A summary of the characteristics of the different catom design regimes.*

2. To support efficient routing of power and avoid excessive heat dissipation, *no static power* should be required for adhesion after attachment.

3. The coordination of the catoms should be performed via *local control*. In particular, no computation external to the ensemble should be necessary for individual catom execution.

4. For economic viability, manufacturability, and reliability, catoms should contain *no moving parts*.

Catoms share many of the same features as individual robots in modular (self-)reconfigurable robots (MRR) [20, 39, 19, 32, 9, 2, 25, 31, 33, 12, 40, 23, 5, 15]. In both claytronics and MRR the behavior of interest is group behavior. The design goals of the individual robots and catoms are also similar in that the individuals are self-contained. [1] The differences are however many. MRR are designed to reconfigure their shapes in order to achieve a functionality such as physical movement. While scaling to many robots is a stated goal of MRR, it is not primary since typical goals (e.g., such as moving across a terrain) require relatively few cooperating MRRs. In contrast, the original motivating goal of claytronics is to create high-fidelity macro-scale 3D objects from micro-scale components, as reflected in our design principles.

2 Hardware

Even with our design principles, the space of possibilities is enormous. It is helpful to observe, however, that there are several discontinuities in the design space, as summarized in Figure 1. Of interest are three regimes: macro, micro, and nano scale catoms.

At the macro-scale, catoms have a diameter $>$ 1cm and weigh many tens of grams. In light of the design principles stated above, the only viable force that can be used to move and adhere catoms is magnetic; which sets a lower limit on the size and weight of a catom as the magnets have considerable weight and volume. Furthermore, the circuitry needed for the high currents necessary to switch the magnets increases the weight. At this scale, it may not be possible to adhere to the “no static power” design principle. Our current prototype, as shown in Figure 2, is a system composed of catoms that only operate in two dimensions. In this case gravity holds the individual catoms to a surface and we do not have to deal with the adhesion problem.

Much of the weight and size in a macro-scale catom comes from packaging, e.g., chip packages, pins, wires, PCBs, etc.. In fact, in our planer prototype currently under construction we estimate that more than 20% of the weight is packaging and more than 77% goes to the magnets and their support circuits. This is partly because we are hand-assembling the catoms. Our next version will use machine assembly which will allow us to shrink the packaging, resulting in an estimated savings of twofold in weight and fivefold in volume.

Micro-scale catoms have diameters between 1mm and 1cm and weigh less than 1 gram. Almost all packaging is eliminated and the catom is constructed by bonding VLSI dies directly to MEMS-based sensor and actuation dies. The

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[1] Unlike mobile robots, catoms do not need to be completely self-contained with respect to power, as they can be powered by a support structure such as a special power table as in Figure 2. Ultimately, we expect that the system will be self-powered, using specialized power-source catoms.

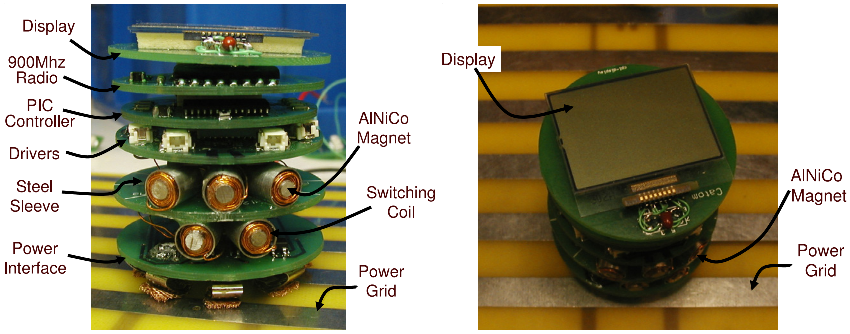

Figure 2: *The side and top views of a partially assembled Planar prototype Catom.*

forces necessary to move a catom are now sufficiently small that electrostatic forces become an option. Macro-scale catoms would require electric field strengths in excess of the dielectric breakdown of air. *Programmable nanofiber-adhesives* (PNA), can be combined with electrostatic actuation to attach catoms without using any static power. PNA is the next step in bio-mimetic adhesives which mainly use van der Waals effects similar to that of the Gecko [29, 1]. The active components for micro-scale catoms are within the realm of current engineering practices using micro- and nano-scale fabrication techniques [30, 28]. The container could be manufactured by casting a spherical transparent polymer film and sputtering indium-tin-oxide (ITO) electrode patches on the film. The patches of ITO would be used both to connect catoms for distributing power as well as used to create capacitive coupling between catoms in order to control their movement.

The next discontinuity occurs when catoms are manufactured using nanotechnology, e.g., as in chemically assembled electronic nanotechnology [38, 37, 36, 18, 6, 13, 27, 42, 17, 16, 10, 3]. In this regime, the catoms are small enough, e.g., < 10 microns in diameter, that they are aerosol. While this is currently beyond the state-of-the-art in manufacturing, further scaling of lithographic features in VLSI [26], and advances in MEMS capabilities [11] combined with advances in nanotechnology [7] will enable the integrated construction of such catoms.

In addition to capabilities, the different regimes (macro, micro, and nano) have significantly different economics. Macro-scale catoms require the assembly of multiple parts into a single unit. We expect that this will make the realization of life-size synthetic reality prohibitive due to the cost per catom. The micro-scale catoms may also require assembly, but with many fewer parts, e.g., no boards and the elimination of magnets in favor of electrostatics. At this scale the entire catom will be constructed using a parallel process, e.g., photolithography. Just as VLSI-based computers are commonplace (as opposed to vacuum tube based computers), in this regime, catoms are inexpensive enough that synthetic reality, though expensive, becomes viable. For example, assume a 2mm catom controlled by 3mm^2 of silicon. If half the cost is in the silicon, then, to construct a human sized form with an average depth of 10 catoms would require approximately $1.25x10^7$ catoms or less than one million dollars. In the nano regime they will become sufficiently inexpensive that synthetic reality could be used not only for applications such as telepario, but could be as ubiquitous as embedded processors are today.

3 Software

The essence of claytronics—a massively distributed system composed of numerous resource-limited catoms—raises significant software issues: specifying functionality, managing concurrency, handling failure robustly, dealing with uncertain information, and controlling resource usage. The software used to control claytronics must also scale to millions of catoms. Thus, current software engineering practices, even as applied to distributed systems, may not be suitable. We are just beginning to explore the software design principles needed.

We have broken down the software issues into three main categories: specification, compilation, and runtime support. Our goal is to specify the global behavior of the system in a direct and descriptive manner. The simplest model we are investigating with respect to specification is what we call the Wood Sculpting model. In this model, a static goal shape is specified. We are investigating two alternative compilation methodologies, both of which fit into the general category of single-program-multiple data (SPMD) programming models. In the first, we are compiling the specification into a planning problem. In this approach we are inspired by work done in communicating soccer robots [34] and in the context of reconfigurable robots, by the constraint-based control framework [41] in which a high-level description such as a particular gait which is translated to a distributed, constraint-based controller. Our second approach is based on emergent behavior. Prior work by [21] seems particularly appropriate in this latter approach with respect to claytronics. At the highest level of abstraction a shape is specified in terms of Origami folding directives. Through a process of planning, these folding directives are translated into low-level programs for autonomous agents; achieving the shape by local communication and deformation only.

Underlying the user-level software is a distributed runtime system. This system needs to shield the user from the details of using and managing the massive number of catoms. Our initial steps in this direction use emergent behavior to determine a catoms location and orientation with respect to all catoms as well as to build a hierarchical network for communication between catoms. Efficient localization is achieved by having the catoms determine their relative location and orientation in a distributed fashion. Then as regions of localized catoms join up they unify their coordinate systems. Our algorithm takes O(1) time if the network is capable of broadcast. With a network limited to point-to-point connections the algorithm takes $O(\sqrt[3]{n})$ time in 3D [24]. Once catoms are localized we form a hierarchical communication network, again using simple local programs on each catom. A tree is formed in parallel by having nodes join with their neighbors until all the nodes are in a single tree. This simple algorithm produces a surprisingly efficient tree from which can then be further optimized.

4 Conclusions

Claytronics is one instance of programmable matter, a system which can be used to realize 3D dynamic objects in the physical world. While our original motivation was to create the technology necessary to realize pario and synthetic reality, it should also serve as the basis for a large scale modular robotic system. At this point we have constructed a planer version of claytronics that obeys our design principles. We are using the planer prototype in combination with our simulator to begin the design of 3D claytronics which will allow us to experiment with hardware and software solutions that realize full-scale programmable matter, e.g., a system of millions of catoms which appear to act as a single entity, in spite of being composed of millions of individually acting units.

Acknowlegments

This abstract describes the work and ideas of many individuals including: Brian Kirby, Kevin Bowers, Greg Reshko, and, Ben Rister, with significant contributions from Jonathan Aldrich, Jim Hoburg, Peter Lee, Frank Pfenning, Manuela Veloso, Srinivasan Seshan, and, Metin Sitti as well as Simon Baker, Randal Bryant, Bill Messner, and, Rahul Sukthankar. We would also like to thank Mark Yim for his useful comments. The project is funded in part by NSF, DARPA, and Intel. Finally, we wish to thank the entire Carnegie Mellon community for their support in getting this project off the ground.

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