

Claytronics - A Synthetic Reality

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Abstract— "Claytronics" is an emerging field of electronics concerning reconfigurable nanoscale robots ('claytronic atoms', or catoms) designed to form much larger scale machines or mechanisms. Also known as "programmable matter", the catoms will be sub-millimeter computers that will eventually have the ability to move around, communicate with each others, change color, and electrostatically connect to other catoms to form different shapes. Claytronics technology is currently being researched by Professor Seth Goldstein and Professor Todd C. Mowry at Carnegie Mellon University, which is where the term was coined. According to Carnegie Mellon's Synthetic Reality Project personnel, claytronics are described as "An ensemble of material that contains sufficient local computation, actuation, storage, energy, sensing, and communication" which can be programmed to form interesting dynamic shapes and configurations.

Index Terms— programmable matter, nanoscale robots, catoms, atoms, electrostatically, LED, LATCH

1 INTRODUCTION

Imagine the concept of "programmable matter" -- micro- or nano-scale devices which can combine to form the shapes of physical objects, reassembling themselves as we needed. An ensemble of material called catoms that contains sufficient local computation, actuation, storage, energy, sensing & communication which can be programmed to form interesting dynamic shapes and configurations. Claytronics is the way of bringing this concept into reality. With claytronics, millions of tiny individual devices -- "claytronic atoms" or "catoms" -- would assemble into macro-scale objects, connecting and disconnecting as they move. The current large proof-of-concept catoms (measuring 4.4 centimeters) connect and move via magnets, much like the "replicating" robots, operating at scales where electromagnetic or electrostatic connections are used for reassembling. The catoms could have LCD or LED surfaces able to produce a faintly glowing image, so that what appeared to be a person made of millions of tiny microbots would actually look like the person.

This has been an interesting development recently that combines nanotechnology with telepresence. The idea is that you create small robots or 'catoms' of a few millimeters in size (eventually perhaps even a few nanometers in size) and then have them organise themselves into a shape that you determine remotely. For example you might have an individual located at a remote location have a 'claytronic' model of himself move, gesture and generally mirror all of his actions. It would be as if he had projected a solid image of himself. This technology would enable engineers to work remotely in physically hostile environments or surgeons to perform intricate surgery on enlarged claytronic replicas of organs, at the same time the actual organs are being worked upon by a claytronic replica of the surgeon.

This technology may seem a little far fetched and more than a little sci-fi, however work has already begun on such technol

ogy. Backed by the microchip manufacturer Intel, first generation catoms, measuring 4.4 centimeters in diameter and 3.6 centimeters in height have already been created. These catoms,

which are ringed by several electromagnets are able to move around each other to form a variety of shapes. Containing rudimentary processors and drawing electricity from a board that they rest upon. So far only four catoms have been operated together. The plan though is to have thousands of them moving around each other to form whatever shape is desired and to change colour, also as required. This technology is still in its infancy, but promises the potential of affected humanity quite profoundly in future decades.

2 CATOMS

Each of the individual robots comprising these shapes would be a "claytronic atom," or catom. Likely spherical in shape, a catom would have no moving parts. Rather, it would be covered with electromagnets to attach itself to other catoms; it would move by using the electromagnets to roll itself over other catoms.

The catoms' surfaces would have light-emitting diodes to allow them to change color and photo cells to sense light, allowing the collective robot to see. Each would contain a fairly powerful, Pentium-class computer.

For now, the researchers are trying to build a two-dimensional version, with each catom being a cylindrical device a little more than an inch in diameter with its side encircled by 24 electromagnets.

A large, moving shape such as a human replica might contain a billion catoms. A system with a billion computer nodes, is something on the scale of the entire Internet. Unlike the real Internet, our thing is moving."

This will require new schemes for quickly organizing and reorganizing such a large computer network.

A moving shape will necessarily force catoms to constantly and quickly change positions, breaking connections with one set of catoms and establishing new connections with others.

3 HARDWARE COMPONENTS

At the current stage of design, claytronics hardware operates from macroscale d

esigns with devices that are much larger than the tiny modular robots that set the goals of this engineering research. Such devices are designed to test concepts for sub-millimeter scale modules and to elucidate crucial effects of the physical and electrical forces that affect nanoscale robots.

Planar catoms test the concept of motion without moving parts and the design of force effectors that create cooperative motion within ensembles of modular robots.

Electrostatic latches model a new system of binding and releasing the connection between modular robots, a connection that creates motion and transfers power and data while employing a small factor of a powerful force.

Cubes employ electrostatic latches to demonstrate the functionality of a device that could be used in a system of lattice-style self-assembly at both the macro and nano-scale.

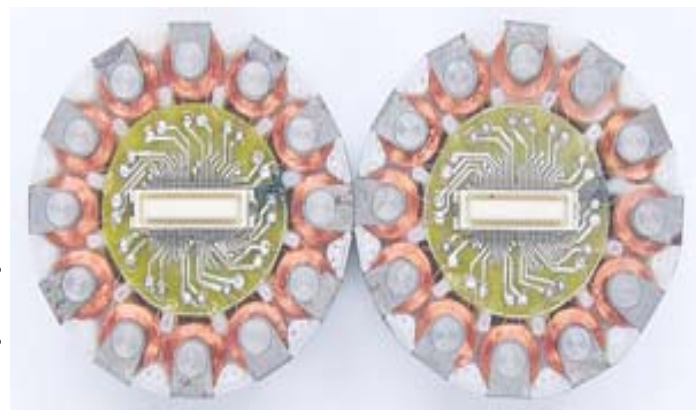
As these creative systems have evolved in the Carnegie Mellon-Intel Claytronics Hardware Lab, they have prepared the path for development of a millimeter scale module that will represent the creation of a self-actuating catom - a device that can compute, move, and communicate - at the nano-scale.

With the millimeter scale modular robot, the Claytronics Hardware Lab will demonstrate the feasibility of manufacturing catoms in the quantities needed to produce dynamic 3-dimensional representations of original objects.

3.1 Planar Catoms

The self-actuating, cylinder-shaped planar catom tests concepts of motion, power distribution, data transfer and communication that will be eventually incorporated into ensembles of nano-scale robots. It provides a testbed for the architecture of micro-electro-mechanical systems for self-actuation in modular robotic devices. Employing magnetic force to generate motion, its operations as a research instrument build a bridge to a scale of engineering that will make it possible to manufacture self-actuating nano-system devices.

The planar catom is approximately 45 times larger in diameter than the millimeter scale catom for which its work is a bigger-than-life prototype.



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Figure:1: planar atoms

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With the millimeter scale modular

Pictured below is a two magnet rings from Planar Catom display the arrangement of their 12 magnets around individual driver boards and the coil design for horseshoe magnets.

A catom sustains a clockwise or counterclockwise motion by a continuous transfer of electro-magnetic force to achieve the opposite motion in the other catom. The planar catom faces unique issues from alignment and friction, which this image suggests.



Figure 2: Planar Catom with LEDs

The picture above displays a planar catom controller ring with light emitting diodes (LEDs) arranged around its perimeter. This board directs the two magnet driver boards embedded in the magnet rings, as shown in the image above.

The custom design of the electronics achieves a very high level of capacity to guide the module's performance. Built with the smallest components commercially available, each controller board contains 5 layers of embedded microcircuits on 45 mm diameter acrylic boards. At this density of circuit design, each of the two controller rings provides approximately 40 times the embedded instrumentation of a standard robotics controller package in 2/5th the space. The resulting capacity of its boards enables the module to carry on board all devices needed to manage its firmware, drivers and 24 magnets.

3.2 Electrostatic Latches:

A simple and robust inter-module latch is possibly the most important component of a modular robotic system. It incorporates many innovative features into a simple, robust device for attaching adjacent modules to each other in a lattice-style robotic system. These features include a parallel plate capacitor constructed from flexible genderless electrodes of aluminum foil and dielectric film to create an adhesion force from electrostatic pressure. Its physical alignment of electrodes also enables the latch to engage a mechanical shear force that strengthens its holding force.

Currently, the electrostatic latch is being tested on a modular

Cube that is 28 cm on a side.

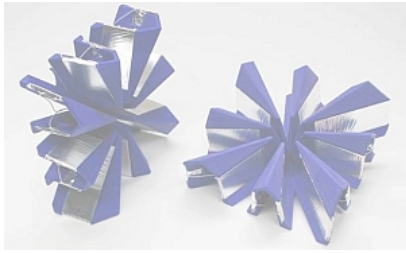


Figure 3: Electrostatic latches

3.3 Cubes

A lattice-style modular robot, the 22-cubic-centimeter Cube provides a base of actuation for the electrostatic latch that has also been engineered as part of this program.

The Cube (pictured below, right) also models the primary building block in a hypothetical system for robotic self-assembly that could be used for modular construction and employ Cubes that are larger or smaller in scale than the pictured device.

The design of a cube, which resembles a box with starbursts flowering from six sides, emphasizes several performance criteria: accurate and fast engagement, facile release and firm, strong adhesion while Cube latches clasps one module to another. Its geometry enables reliable coupling of modules, a strong binding electrostatic force and close spacing of modules within an ensemble to create structural stability.

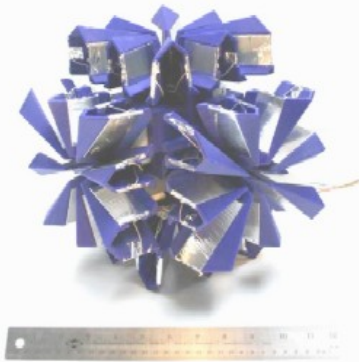


Figure 4: Cube catoms

4 SOFTWARE

In a domain of research defined by many of the greatest challenges facing computer scientists and roboticists today is perhaps the creation of algorithms and programming language to organize the actions of millions of sub-millimeter scale catoms in a claytronics

As a consequence, the research scientists and engineers have formulated a very broad-based and in-depth research program to develop a complete structure of software resources for the creation and operation of the densely distributed network of robotic nodes in a claytronic matrix. A large, moving shape

such as a human replica might contain a billion catoms. A system with a billion computer nodes, is something on the scale of the entire Internet. . . . Unlike the real Internet, our thing is moving.

Because of its vast number of individual computing nodes, the matrix invites comparison with the worldwide reservoir of computing resources connected through the Internet, a medium that not only distributes data around the globe but also enables nodes on the network to share work from remote locations. The physical concentration of millions of computing nodes in the small space of a claytronic ensemble thus suggests for it the metaphor of an Internet that sits on a desk. In the Carnegie Mellon-Intel Claytronics Software Lab, researchers address several areas of software development.

4.1 Programming languages

Researchers in the Claytronics project have also created Meld and LDP (Locally Distributed Predicates). These new languages for declarative programming provide compact linguistic structures for cooperative management of the motion of millions of modules in a matrix.

4.2 Integrated Debugging

In directing the work of the thousands to millions of individual computing devices in an ensemble, claytronics research also anticipates the inevitability of performance errors and system disfunctions. Such an intense computational environment requires a comparably dynamic and self-directed process for identifying and debugging errors in the execution of programs

4.3 Shape Sculpting

The team's extensive work on catom motion, collective actuation and hierarchical motion planning addresses the need for algorithms that convert groups of catoms into primary structures for building dynamic, 3-dimensional representations. Such structures work in a way that can be compared to the muscles, bones and tissues of organic systems

4.4 Localization

The team's software researchers are also creating algorithms that enable catoms to localize their positions among thousands to millions of other catoms in an ensemble. This relational knowledge of individual catoms to the whole matrix is fundamental to the organization and management of catom groups and the formation of cohesive and fluid shapes throughout the matrix.

5 APPLICATIONS

- i. This technology would enable engineers to work remotely in physically hostile environments.
- ii. Surgeons to perform intricate surgery on enlarged claytronic replicas of organs, whilst the actual organs are being worked upon by a claytronic replica of the surgeon.
- iii. A 3-D Fax machine is a new approach to 3D faxing, a large number of submillimeter robot modules form an intelligent clay which can be reshaped via the external application of mechanical forces. This clay can act as a novel input device, using

intermodule localization techniques to acquire the shape of a 3D object by casting.

The process of remotely reproducing a facsimile of an object requires three phases: acquisition, transmission, and reproduction. In the first phase, the system senses the object and creates a digital representation of the visible, external structure. The shape information is then transmitted to the remote site. Finally, using the transmitted data, a facsimile of the object is reconstructed at the remote site.

Building a moving, sensing, color-changing replica of each person out of nanotech robots makes every meeting a face-to-face meeting. This is the 3D Video conferencing. We feel that the person, continents away, as sitting beside you.

iv. 3D TVs and films may also be possible using this claytronics.

v. It might be useful for producing 3-D shapes in the computer-aided design process.

vi. Claytronics antennas could change shape to improve reception of different radio frequencies.

vii. Claytronics cell phone might grow a full-size keyboard, or expand its video display as needed.

6 DISADVANTAGES

i. With so many catoms, the system will have to compensate for the inevitable failure of individual catoms. Computers don't deal well with failure.

ii. Algorithm and programming the combined motion of catoms to form a 3D shape is a very ridiculous task.

iii. Even the nodes of the Internet have some addresses and accessing them is hard. Accessing each catom without any address is a very difficult task.

iv. At present, only four individual catoms are made to communicate with each other. But, the thought of making billions of catoms to communicate may take a few decades.

v. Even though the mentioned applications are possible, the cost involving the manufacturing of these catoms may not be affordable.

7 CONCLUSION

Unpredictable is the future though, changes in the technology trends prepares everybody for tomorrow. Biotechnology, Genetics, Space science, Nanotechnology, Material science, robotics and many more fields of technology managed to make their way out from science fiction in last 4 to 5 decades. Claytronics is an exception, It was never existed in science fiction as a science or technology until recent years, and yet here we are discussing the possibilities of programming the matter.

According to Moore's Law, the transistors count in an Integrated Circuit almost doubles every year. This shows the rapid development in the electronics in the recent decades. If this continues the concept of Claytronics will not be hard to achieve.

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