CLAYTRONICS

PROGRAMMABLE MATTER

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A REPORT BY

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ABSTRACT

This report introduces a new and yet to be properly explored branch of technology, The Programmable Matter. Programmable Matter is a technology that enable us to control and manipulate 3-dimensional physical artifacts. It is a method which brings the dream of *synthetic reality* closer to reality. This technology has reached a point where we can realistically build a programmable matter system which is guided by design principles which will allow it to ultimately scale to millions of sub-millimeter catoms. The system, which follows the principles of a programmable matter, is *Claytronics*. Claytronics substantiate the ambition promised by phenomena of programmable matter. It is used to create dynamic 3 dimensional objects in physical state. This work is potentially revolutionary in the sense that it holds out the possibility of radically altering the relationship between computation, humans, and the physical world. This paper also introduces the hardware and software components of the Catoms, the crucial part of the claytronics system, along with their challenges and requirement. We also present a novel application of modular robotic technology. We describe an application — a 3D fax machine, which exploits inter-module communication and computation without requiring self-reconfiguration. As a result, this application may be feasible sooner than applications which depend upon modules being able to move themselves.

Claytronics will be a test-bed for solving some of the most challenging problems we face today: how to build complex, massively distributed dynamic systems. It is also a step towards truly integrating computers into our lives—by having them integrated into the very artifacts around us and allowing them to interact with the world.

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1. INTRODUCTION TO PROGRAMMABLE MATTER

In the words of **Goldstein*** *"Programmable matter refers to a technology that will allow one to control and manipulate three-dimensional physical artifacts (similar to how we already control and manipulate two-dimensional images with computer graphics). In other words, programmable matter will allow us to take a (big) step beyond virtual reality, to synthetic reality, an environment in which all the objects in a user's environment (including the ones inserted by the computer) are physically realized. Note that the idea is not to transport objects nor is it to recreate an objects chemical composition, but rather to create a physical artifact that will mimic the shape, movement, visual appearance, sound, and tactile qualities of the original object."*

Programmable matter is a proposed digital material having computation, sensing, actuation, and display as continuous properties active over its whole extent. Programmable matter would have many exciting applications, like paintable displays, shape-changing robots and tools, rapid prototyping, and sculpture-based haptic interfaces. Programmable matter would be composed of millimeter-scale autonomous microsystem particles, without internal moving parts, bound by electromagnetic forces or an adhesive binder.

Goldstein*- *Seth Copen Goldstein is an associate professor in the Computer Science Department at Carnegie Mellon University***.**

2. INTRODUCTION TO CLAYTRONICS

Claytronics is a form a programmable matter that takes the concept of modular robots to a new extreme. 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). The claytronics project combines modular robotics, systems nanotechnology and computer science to create the dynamic, 3-Dimensional display of electronic information.

The enabling hardware technology behind synthetic reality is Claytronics, a form of programmable matter that can 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).

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 determine their relative location and orientation. Using that information they would then form a network in a distributed fashion and organize themselves into a hierarchical structure, both to improve locality and to facilitate the planning and coordination tasks. The goal (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 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 Nano fiber-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 that the system appears to be a single coordinated system.

	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 Electromagnets	Electrostatics	Aerosol
Adhesion mechanism	Nanofiber Adhesives Magnets	Programmable nanofiber adhesives	Molecular surface adhesion and covalent bonds
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

3. GOALS OF CLAYTRONICS

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.

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.

4. ENSEMBLE PRINCIPLE

The ensemble principle states '*A robot module should include only enough functionality to contribute to the ensemble's desired functionality*.'

Realizing the goal requires new ways of thinking about massive numbers of cooperating millimeter-scale units. Most importantly, it demands simplifying and redesigning the software and hardware used in each catom to reduce complexity and manufacturing cost and increase robustness and reliability. For example, each catom must work cooperatively with others in the ensemble to move, communicate, and obtain power.

5.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 we have the following four design principles:

* Each catom should be self-contained, in the sense of possessing everything necessary for performing its own computation, communication, sensing, actuation, locomotion, and adhesion.
* To support efficient routing of power and avoid excessive heat dissipation, no static power should be required for adhesion after attachment.
* 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.
* For economic viability, manufacturability, and reliability, catoms should contain no moving parts
* .

6. CLAYTRONICS HARDWARE

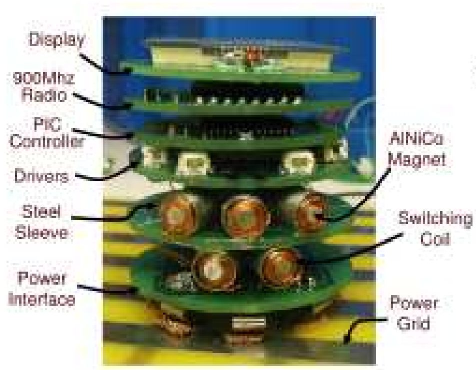
Each catom is a self-contained unit with a CPU, an energy store, a network device, a video output device, one or more sensors, a means of locomotion, and a mechanism for adhering to other catoms.

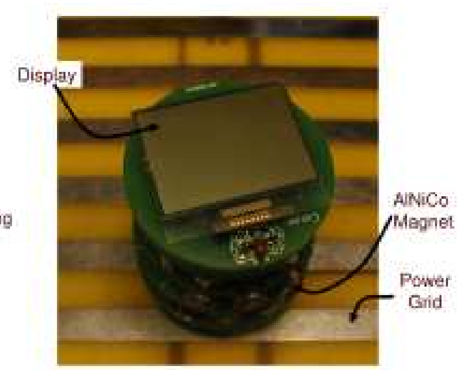
At the current stage of design, claytronics hardware operates from macroscale designs with devices that are much larger than the tiny modular robots that set the goals of this engineering research. Such devices are designed to test concepts for sub-millimeter scale modules and to elucidate crucial effects of the physical and electrical forces that affect Nano scale robots.

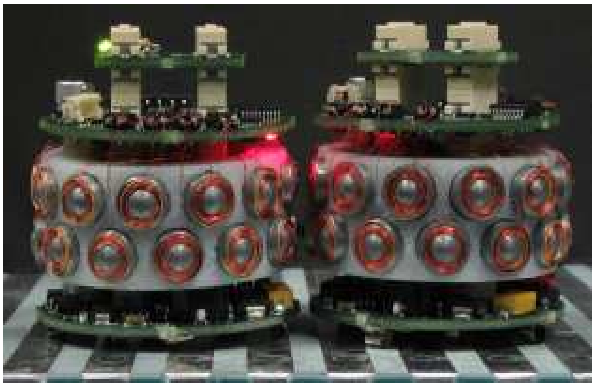
6.1 Planar catoms

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

This planar catom is approximately 45 times larger in diameter than the millimeter scale catom for which its work is a bigger-than-life prototype. It operates on a two-dimensional plane in small groups of two to seven modules in order to allow researchers to understand how micro-electro-mechanical devices can







move and communicate

6.2 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.

6.3 Stochastic Catoms

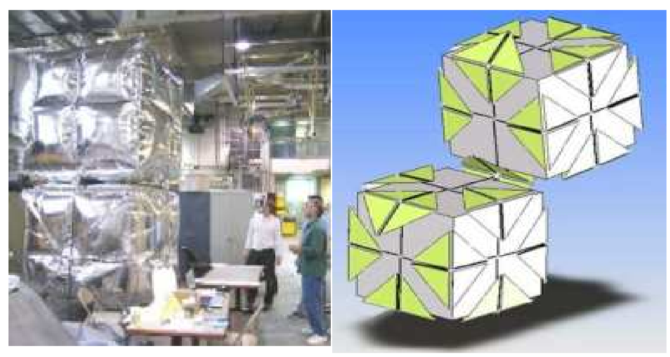
It integrate random motion with global objectives communicated in simple computer language to form predetermined patterns, using a natural force to actuate a simple device, one that cooperates with other small helium catoms to fulfill a set of unique instructions.

Depending upon the scale of the device, actuation of the module's motion can be created with various sources of energy, including currents of air, electrostatics or, in the case of a study of the phenomenon during Andrew's Leap, Carnegie

Mellon's summer enrichment program, the propelling motion of high school students throwing helium-filled balloons. From such forces, a module derives an initially incoherent motion that causes random contacts with other modules. In these contacts, the module evaluates the appropriateness of forming a connection with the other module. The module makes its decision by evaluating the relation of its form in the instance of the contact location to the ensemble's overall goal for a predetermined shape. Based on this evaluation, the module either forms a bond or continues in motion.

6.4 Giant Helium Catoms

Provide a larger-than-life, lighter-than-air platform to explore the relation of forces when electrostatics has a greater effect than gravity on a robotic device, an effect simulated

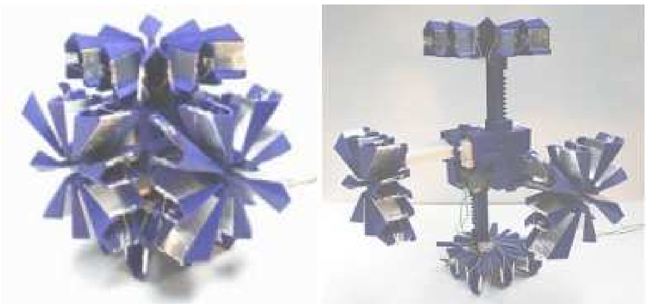


with a modular robot designed for self-construction of macro-scale structures.

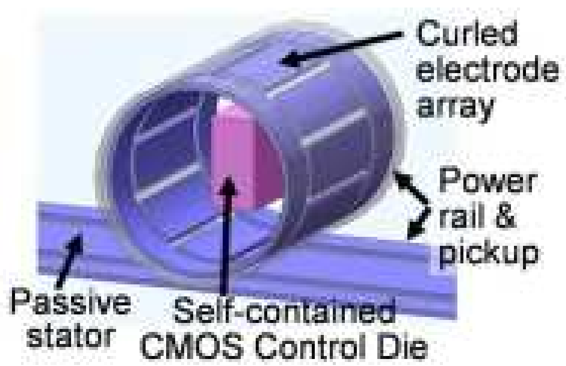
The Giant Helium Catom provides researchers a macroscale instrument to investigate physical forces that affect microscale devices. The GHC was designed to approximate the relationship between a near-zero-mass (or weightless) particle and the force of electromagnetic fields spread across the surface of such particles. Such studies are needed to understand the influence of surface tensions on the engineering of interfaces for nanoscale devices.

6.5 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.



6.6 Millimeter scale catom



The millimeter scale catom consists of a tube and a High voltage CMOS die attached inside the tube. The tubes are fabricated as double-layer planar structures in 2D using standard photolithography. The difference in thermal stress created in the layers during the fabrication processes causes the 2D structures to bend into a 3D tube upon release from the substrate. The tubes have electrodes for power transfer and actuation on the perimeter.

7. CLAYTRONICS

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. Scientists are just beginning to explore the software design principles needed.

The main parts of the software can be categorized into **specification, compilation, and runtime support**.

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. The 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. Once catoms are localized a hierarchical communication network is formed, 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 which can then be further optimized.

7.1 DISTRIBUTED COMPUTING IN CLAYTRONICS

Research scientists and engineers of the Carnegie Mellon-Intel Claytronics Research Program 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 notable characteristic of a claytronic matrix is its huge concentration of computational power within a small space. For example, an ensemble of catoms with a physical volume of one cubic meter could contain 1 billion catoms. Computing in parallel, these tiny robots would provide unprecedented computing capacity within a space not much larger than a standard packing container. This arrangement of computing capacity creates a challenging new programming environment for authors of software. 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.

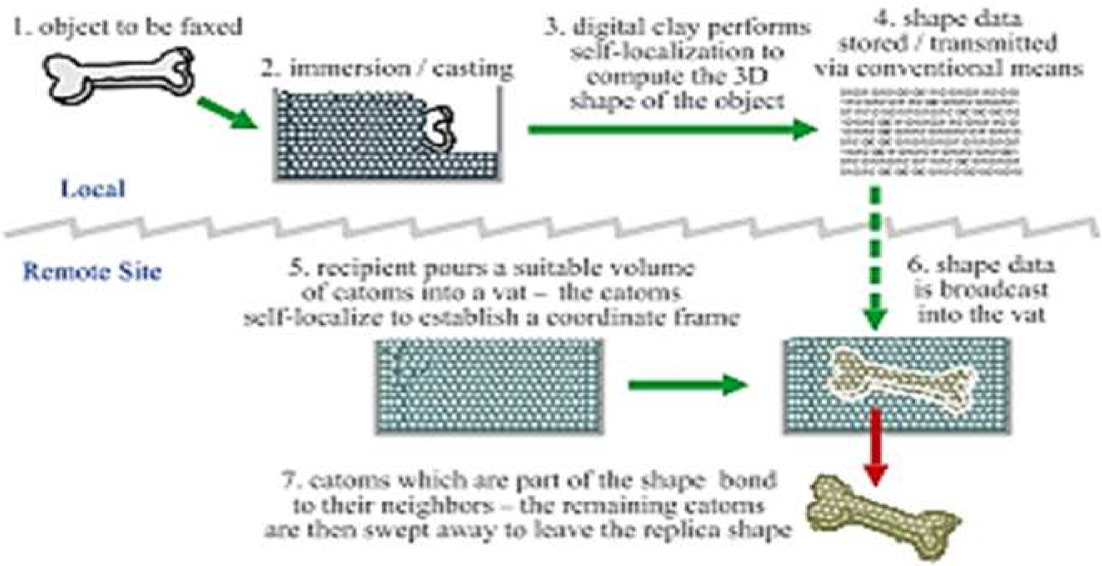
Languages to program a matrix require a more abbreviated syntax and style of command than the lengthy instructions that widely used network languages such as C++ and Java employ when translating data for computers. In contrast to that tightly linked programming environment of multi-functional machines, where C++, Java and similar languages evolved, a claytronic matrix presents a software developer with a highly organized, single-purpose, densely concentrated and physically dynamic network of unwired nodes that create connections by rotating contacts with the closest neighbors. The architecture of this programming realm requires more than instructions that move packets of data through unstable channels. Matrix software must also actuate the constant change in the physical locations of the anonymous nodes while they are transferring the data through the network.

In this environment, the processes of each individual catom must be entirely dedicated to the operational goal of the matrix, which is the formation of dynamic, 3-dimensional shapes. Yet, given the vast number of nodes, the matrix cannot dedicate its global resources to the micro-management of each catom. Thus, every catom must achieve a state of self-actuation in cooperation with its immediate neighbors.

8. APPLICATION OF CLAYTRONICS

3D FAX MACHINE

A 3D fax machine which exploits inter-module communication and computation without requiring self-reconfiguration. As a result, this application may be feasible sooner than applications which depend upon modules being able to move themselves. In this new approach to 3D faxing, a large number of sub-millimeter robot modules form intelligent “clay” which can be re-shaped 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.



Key properties, required by such a material would be:

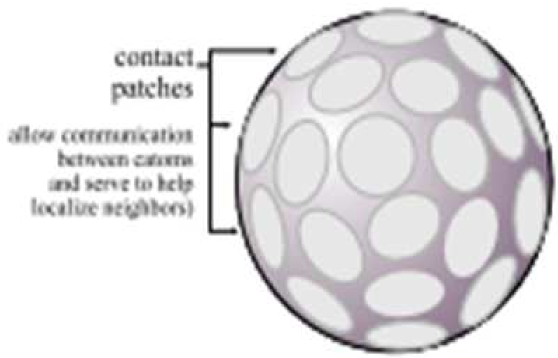
8.1 Physical Characteristics:

Suppose this material is composed of tiny, sub-millimeter particles that stick together, e.g., spheres covered with a self-cleaning Nano fiber adhesive. The combination of discrete parts and adhesion would permit the required malleability for this application. In an alternative implementation, the spheres could be covered with thin insulated plates, permitting the spheres to adhere to each other under software control through the establishment of an appropriate electric field on each plate.

8.2 Electronic properties:

Suppose further that each of these particles is actually a micro-fabricated silicon sphere, its surface covered with electronic circuitry. A 300 micron (radius) sphere has a surface area of 1.13mm Current embedded microprocessors can be fabricated in only 0.26mm using mature process technology. With specialized design and modest process improvements it is feasible that an entire system can be embedded on such a sphere, including microprocessor, memory, communications, power distribution, and sensor circuits.

Although other technologies have been proposed to implement 3D faxing, the modular micro robot approach has certain distinct advantages, notably size and speed. In contrast to 3D fax machine approaches using serial (raster) input and output devices such as a laser scanner and 3D printer, programmable matter would acquire the 3D input shape and generate the 3D output shape in parallel. Thus, rather than taking hours to days the process could take seconds to minutes. Laser scanners and 3D printers also remain many times bulkier than the object being scanned/ reproduced despite years of commercial development. Similar results could be achieved with a much smaller vol-



ume of programmable matter.

9. OVERVIEW OF WORKING OF 3D FAX MACHINE

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.

In the nomenclature of Claytronics system, a connected volume of programmable matter is termed an *ensemble*, a word we use interchangeably here with *mass*. Individual units are termed *catoms*, and in this paper we also use module and particle to mean the same thing as catom.

9.1 SHAPE ACQUISITION

A variety of structured light approaches, most based on scanning lasers, are capable of producing medium to high resolution digital representations of the 3D external structure of an object. Multicamera stereo systems can also capture dense shape information, though with a variety of limitations imposed by non-Lambertian surfaces and the unsolved nature of the correspondence problem.

9.2 Key differences

9.2.1 Contact vs. non-contact sensing

Programmable matter can read the shape of an object by direct contact with its surface. Structured light (laser) and stereo approaches work at some distance and hence impose constraints on object curvature and self-shadowing.

9.2.2 Simplified geometries

Because of the relatively limited geometric possibilities for sphere packing and the absence of large unclosed loops or featureless spaces, the localization problem for a programmable matter ensemble can be significantly easier.

9.2.3 Parallel vs. serial read-in

Programmable matter localization is a highly parallelizable operation. Resolution is a function of the catom size rather than scan rate or the spatial frequency of scanning.

A claytronic ensemble performs self-localization by a multiphase peer-to-peer communication process between the individual catoms in the ensemble. Each catom's surface is covered with contact patches permitting communication between neighbors. The particular surface site used to communicate with a given neighbor identifies the relative geometry of that neighbor to within a known tolerance for successful communication. The high degree of interconnectedness offered in a packed or near-close-packed lattice allows quick convergence for robust location estimation techniques.

Unlike digital sampling in PCM systems where the Nyquist frequency offers a sharp bound on sampling precision, catoms can pack spaces down to the width of a single catom.

9.3 REMOTE TRANSMISSION

After the 3D structure has been determined by digital shape acquisition, many well-known techniques can be used to store, manipulate, and transmit it. A radio or optical bridge would likely be used to extract the shape information from the ensemble and transfer it to a computing device.

9.4 SHAPE RECONSTRUCTION

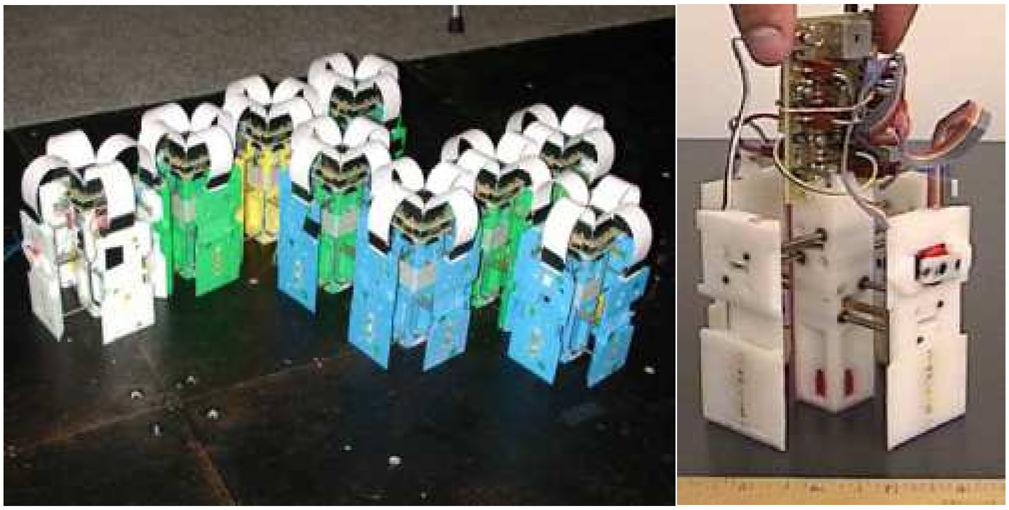
In the final stage of a 3D fax system, the transmitted data is used to reconstruct the structure of the object at the remote site. One method of converting the digital description to a physical replica is to use a 3D printer based on rapid prototyping techniques such as fused deposition modeling or stereo lithography. Such a device can create a physical object from a digital representation by building up the structure layer by layer or line by line.

With programmable matter, shape reconstruction can be implemented in at least two different ways:

First, with a fully-functional claytronic ensemble, i.e., one capable of self-reconfiguration, we could imagine the ensemble reshaping itself on command to conform to the desired shape. Because many catoms can move simultaneously this process would be substantially faster than a raster or planar deposition process.

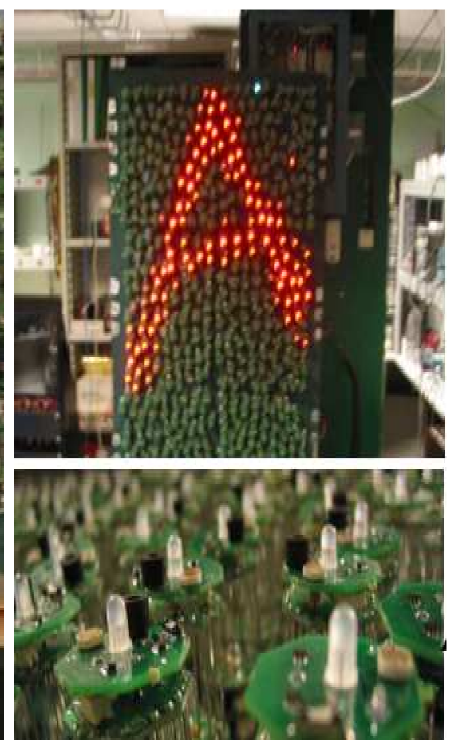
Second, with catoms incapable of self-reconfiguration but equipped with simple inter-catom latches which can selectively bond one module to another, a shape can be formed by what we term digital sand casting. First, an appropriate volume of catoms is used to fill a closed structure such as a bucket. Power is supplied to the ensemble and the desired shape is transmitted to it. The catoms in the ensemble carry out self-localization to identify the coordinate structure within which they sit.

Then, each catom evaluates whether it is or is not part of the target shape. Those catoms which are part of the target shape bond themselves together, while the other catoms simply switch themselves off. The user then pours or sweeps off the unbonded catoms to reveal the reconstructed shape.

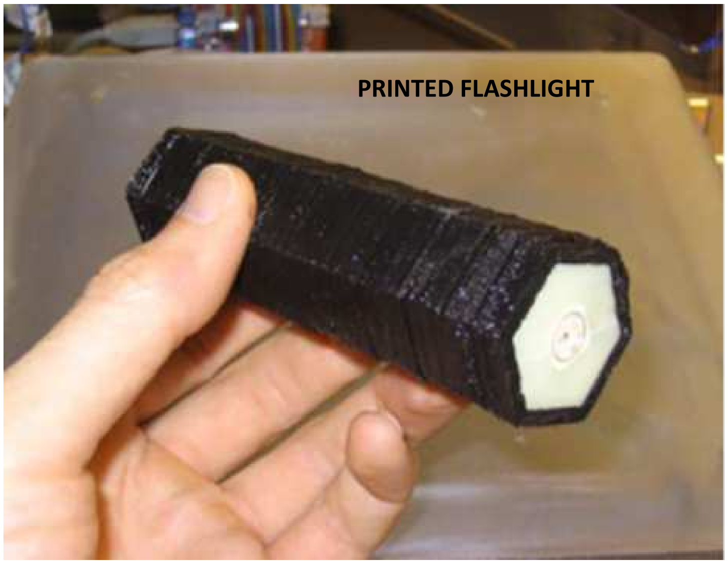


Vona and Rus's Crystalline robot (left) has unit-compressible modules (right) that can change size by a factor of two and latch for reconfiguration and amoeba-like mobility.

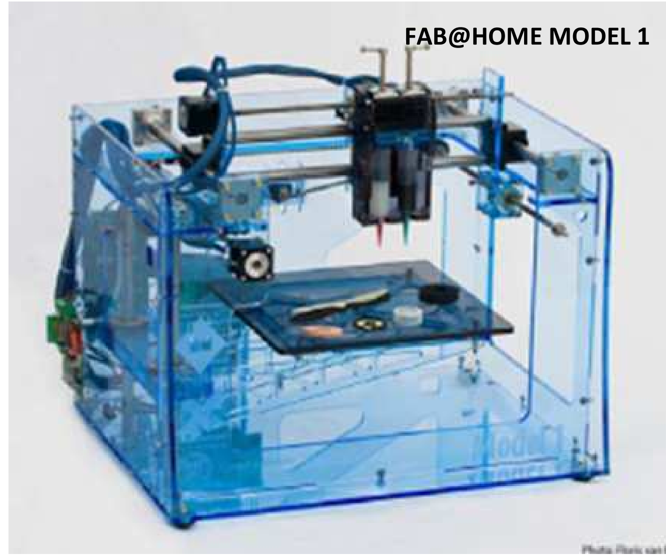
The centimeter-scale paintable display prototype.



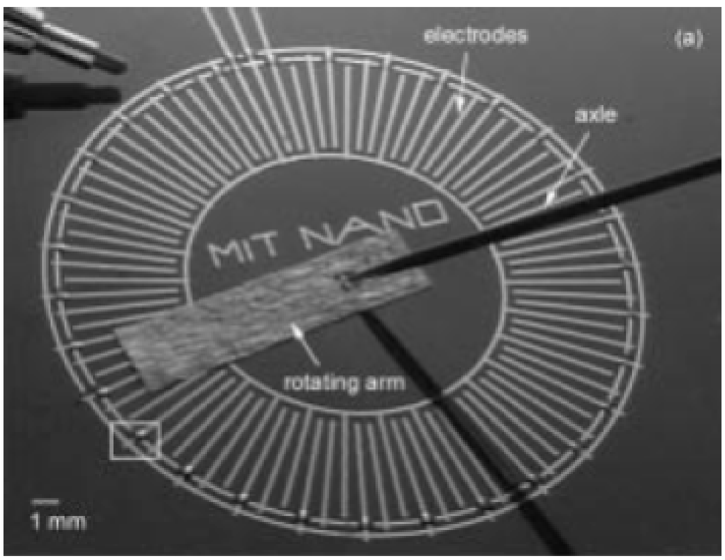
Distributed PostScript rendering on the centimeter-scale paintable display



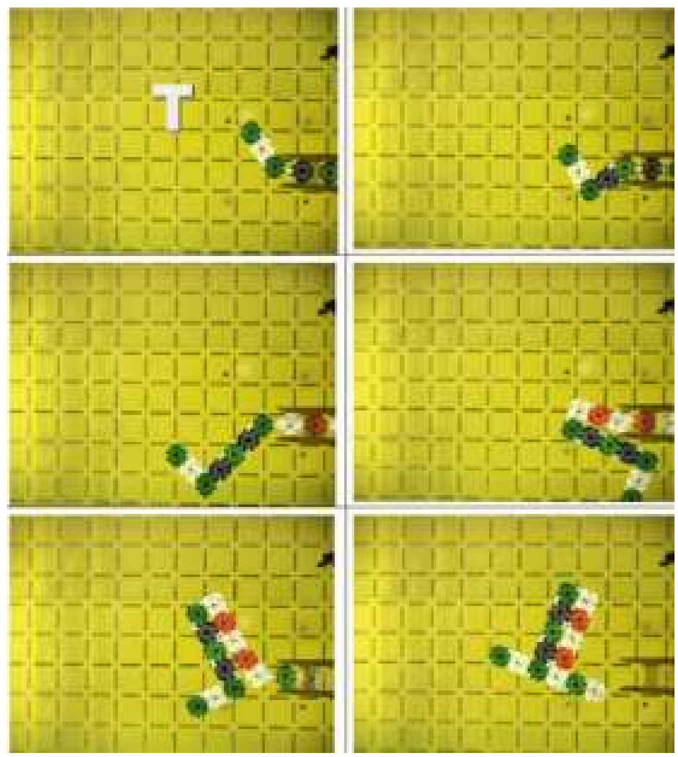
PRINTED FLASHLIGHT



FAB@HOME MODEL 1

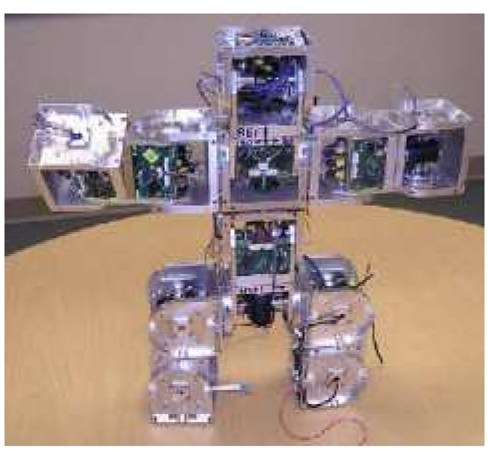


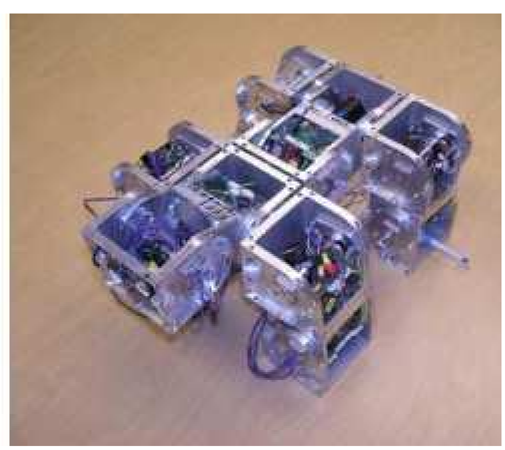
Ink-Jet printed electrostatic induction motor



Digital fabrication of the letter "T," by folding a sequence of magnetic tiles that code for the structure

Shen's SuperBot configured as a biped walker (left) and as a quadraped walker (right)





10. SUMMARY

Programmable matter is a technology that allows us to control and manipulate 3-dimensional physical artifacts, in a similar way how we already control and manipulate two-dimensional images with computer graphics. In other words, programmable matter will allow us to take a big step beyond virtual reality, to *synthetic reality*, an environment in which all the objects in a user's environment (including the ones inserted by the computer) are *physically* realized.

Claytronics is an instance of programmable matter, a system which can be used to realize 3D dynamic objects in the physical world. This technology not only realizes *pario* and *synthetic reality*, it also serves as the basis for a large scale modular robotic system.

The Claytronics system is essentially an embedded system, consisting of hardware and software parts, brought together for achieving a special purpose.

The hardware machine is known as *Catoms*. 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.

The software part, on the other hand, is taken care by Meld is a declarative language, which based on P2, a logic-programming language originally designed for programming overlay networks. It greatly simplifies the thought process needed for programming large ensembles. Initial experience shows that this also leads to a considerable reduction in code size and complexity.

One of the novel applications of the Claytronics project is 3D printing and Fax machine- which exploits inter-module communication and computation without requiring self-reconfiguration. As a result, this application may be feasible sooner than applications which depend upon modules being able to move themselves.

11. CONCLUSION

The report told you about the advances made in the field of programmable matter and the claytronics system. The scientists at Carneige Mellon University, in association with Intel is doing research on this field of technology and striving to make Catoms of Micro and Nano scale, which follows the principles laid by the phenomena of programmable matter. The Massachusetts Institute Of Technology have also made contribution in the field of designing of programmable matter.

With the advancement in technology, development of simpler and intuitive programming language along with consolidation and miniaturization of memory and other functional parts of Catoms, we can see a day in the future, when the images we see in the television will take physical forms and occupy the space, we live in. Not only can that, these completely realistic representations will interact with us in ways the real counterpart does.

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"**Catoms: Moving Robots Without Moving Parts**" by Seth Copen Goldstein and Todd Mowry.

"**Project to build a 3d fax machine**" http://graphics.stanford.edu/projects/faxing/

"**Claytronics project website**," http://www.cs.cmu.edu/~claytronics/

"**Design of Programmable Matter**" by Ara N. Knaian

Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems October 9 - 15, 2006, Beijing, China "**A 3D Fax Machine based on Claytronics**"

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