Claytronics – Programmable Matter

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Abstract— The paper represents the concept of new emerging technology called Claytronics. This paper introduces a new branch of technology, the programmable matter. Claytronics combines modular robotics, system nanotechnology and computer science to create 3-D objects that a user can interact with. This idea is basically termed as programmable matter.

Key words: Claytronics, Catoms, MELD, LDP, Ensemble, Pario

I. INTRODUCTION

Claytronics is a programmable matter whose basic function is to organize itself in a specific manner in order to form the shape of an object and render its physical and visual appearance. Claytronics in made up of individual atoms called as Catoms-for Claytronic Atoms. Programmable matter is a proposed digital material having computation, sensing, actuation and display as continuous properties active over its whole extent. Each catom 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. Objects featuring these catoms can be radically altered in form and function. Colors of walls can be changed on just one click, models of cars can be changed on just one simple click, sofa can become table etc.

II. SCALING AND DESIGN PRINCIPLES

Basically there are four basic design principles:

- Catom should contain no moving parts.
- Coordination should be performed via local control.
- No static power should be required for adhesion after attachment.
- Each catom should be self-contained.

III. HARDWARE

Each catom comprises of following components:

- Central Processing Unit
- Energy storage device
- Network Device
- Video Output Device
- One or more sensors as required
- Mechanism for adhering to other catoms

At the current stage of design, claytronics hardware operates from macro-scale 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.

Properties	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	Magnets	Programmable nano fibre adhesives	Covalent bond, Molecular surface adhesion
Manufacturing methods	Conventional	Nano Fabrication	Chemically directed self assembly
Resolution	Low	High	High

Table 1: A Summary of the Characteristics of the Different Custom Regimes

A. *Electrostatic Latches*

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. A simple and robust inter-module latch is possibly the most important component of a modular robotic system.

B. *Stochastic Catoms*

Stochastic Catoms 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 fulfil a set of unique instructions.

C. *Cubes*

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.

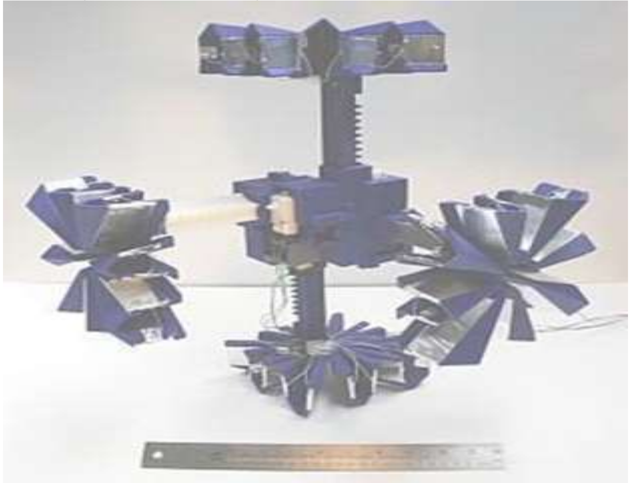

Fig. 1: Cubes

D. Planar Catoms

The self-actuating, cylinder-shaped planar catom tests concepts of motion without moving parts, power distribution, data transfer and communication that will be eventually incorporated into ensembles of nano-scale robots. It provides a test bed 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

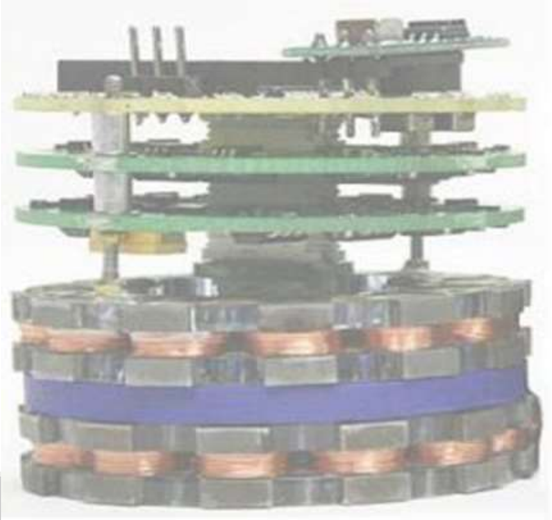

Fig. 2: Planar catoms

E. Giant Helium Catoms

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.

On each face, the Giant Helium Catoms cube carries a novel electrostatic latching system that enables the device to move across the faces of other catoms and to communicate with them.

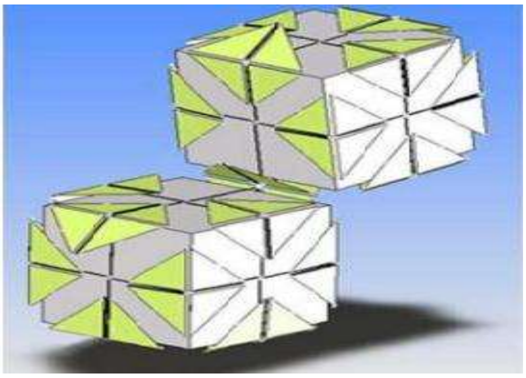

Fig. 3: Communication between two GIANT HELIUM CATOMS

Among the six faces, the triangular flaps provide each catom with the means to form an electrostatic latch with another cube from 24 positions - providing the cubes with a capacity to move at right angles in any direction. In addition to motion, the latches also equip the GHC with the means to communicate across the ensemble of catoms. In Figure 3, one Giant Helium Catom pivots across the surface of another, revealing the positions and attachments of triangular electrostatic flaps.

F. Future excogitation:

In the present design, the catoms are only able to move in two dimensions with respect to each other. But, for successful completion of the project, the catoms will be required to move in all the three dimensions relative to each other. The goal of the researchers is to develop a millimeter scale catom with no moving parts, to allow for mass manufacturability. Millions of these microrobots will be able to emit variable colour and intensity of light, allowing for dynamic physical rendering. The design goal has shifted to creating catoms that are simple enough to only function as part of an *ensemble*, with the ensemble as a whole being capable of higher function.

As the catoms are scaled down, an onboard battery sufficient to power it will exceed the size of the catom itself, so an alternate energy solution is desired. Research is being done into powering all of the catoms in an ensemble, utilizing the catom-to-catom contact as a means of energy transport. One possibility being explored is using a special table withpositive and negative electrodes and routing the power internally through the catoms, via “virtual wires.”

Another major design challenge will be developing a genderless unary connector for the catoms in order to keep reconfiguration time at a minimum. Nanofibers provide a possible solution to this challenge. Nanofibers allow for great adhesion on a small scale and allow for minimum power consumption when the catoms are at rest.

IV. SOFTWARE

A. Functions of Software:

It is required that the software must organize all the communications and actions between millions of sub-millimetre scale claytonic atoms (i.e...catoms).So, the software requires many advanced algorithm and programming languages. The researchers and engineers of Carnegie Mellon-Intel Claytronics Research Lab launched a wide range of projects to develop the necessary software to facilitate communication between catoms.The goal of a claytronics matrix is to dynamically form three dimensional shapes. However, the vast number of catoms in this distributed network increases complexity of micro-management of each individual catom. So, each catom must perceive accurate position information and command of cooperation with its neighbours. In this environment, software language for the matrix operation must convey concise statements of high-level commands in order to be universally distributed. Languages to program a matrix require a more abbreviated syntax and style of command than normal programming languages such as C++ and Java. The Carnegie Mellon-Intel Claytronics esearch Project has created two new programming languages: Meld and Locally Distributed Predicates (LDP)

B. MELD:

Meld is a declarative language, a logic programming language originally designed for programming overlay networks. By using logic programming, the code for an ensemble of robots can be written from a global perspective, enabling the programmer to concentrate on the overall performance of the claytronics matrix rather than writing individual instructions for every one of the thousands to millions of catoms in the ensemble.

This dramatically simplifies the thought process for programming the movement of a claytronics matrix. Meld is a programming language designed for robustly programming massive ensembles. Meld was designed to give the programmer an ensemble-centric viewpoint, where they write a program for an ensemble rather than the modules that make it up. A program is then compiled into individual programs for the nodes that make up the ensemble. In this way the programmer need not worryabout the details of programming a distributed system and can focus on the logic of their program.

Because Meld is a declarative programming language (specifically, a logic programming language), the programs written in Meldare concise.

Both the localization algorithm and the metamodule planning algorithms (papers linked below) are implemented in Meld in only a few pages of code. Because the implementations are so concise, we've found it practical to prove them correct. We have proved correctness of the metamodule planning algorithm as written in Meld. We found this proof to be easier to carry out than a proof on pseudo code.

Furthermore, these implementations are inherently fault-tolerant. They can recover from modules that experience FAIL-STOP errors as the Meld runtime automatically recovers from these errors without any need for the programmer to think about them. Between the ability to perform proofs directly on Meld code and the inherent fault tolerance provided by the runtime, Meld programs are robust.

C. LDP

LDP is a reactive programming language. It has been used to trigger debugging in the earlier research. With the addition of language that enables the programmer to build operations in the development of the shape of the matrix, it can be used to analyse the distributed local conditions. It can operate on fixed-size, connected groups of modules providing various functions of state configuration. A program that addresses a fixed-size module rather than the entire ensemble allows programmers to operate the claytronic matrix more frequently and efficiently.

LDP further provides a means of matching distributed patterns. It enables the programmer to address a larger set of variables with Boolean logic, which enables the program to search for larger patterns of activity and behaviour among groups of modules. LDP approaches the distributed programming problem using pattern-matching techniques. LDP provides programmers the ability to specify distributed state configurations, based on combinations of the state found on connected subgroups of catoms.

The LDP runtime automatically detects occurrences of these distributed Configurations, and triggers user-specified actions in response to the detection event. LDP also allows for the expression of distributed event sequences (through the use of automated history and temporal operators), as well as the expression of particular shapes(through Topological restrictions).These facilities, combined with an array of mathematical and logical operators, allow programmers to express a wide variety of distributed conditions. As withMeld, LDP produces dramatically shorter code than traditional high-level languages (C++, Java,etc.). LDP is descended from work on distributed debugging, and as such its strengths lie in the ability to efficiently detect conditions on variably-sized groups of modules, interface easily with existing low-level code, and easily express a large numbers of common distributed programming idioms. LDP has been used to implement several motions planning algorithms, as well as a variety of low-level utilities such as gradient fields and distributed aggregation.

V. CONCLUSION

Once fully developed and functional, this advanced technology would highly be beneficial, not only to the scientific class of people but also to the common man. It would help users to carry around a lump of claytronics in their pockets that can reshape into any object and even act like 3D TV and create synthetic reality.

VI. ENVISIONING THE FUTURE

The power and flexibility that will arise from being able to "program" the world around us should influence every aspect of the human experience. Claytronics is a technology which can serve as the means of implementing a new communication medium, which we call pario. The idea behind pario is to reproduce moving, physical 3D objects. Similar to audio and video, we are neither transporting the original phenomena nor Recreating an exact replica: instead, the idea is to create a physical artefact that can do a good enough job of reproducing the shape, appearance, motion, etc., of the original object that our senses will accept it as being close enough. The advancements in nanotechnology and computing necessary for claytronics to become a reality are feasible, but the challenges to overcome are daunting and will require great innovation. In an interview, December 2008, Jason Campbell, a lead researcher from Intel Labs Pittsburgh said, "My estimates of how long it is going to take have gone from 50 years down to just a couple more years. That has changed over the four years I've been working on the project.

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