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Claytronics: The Building Block of New Virtual World

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Abstract: *This paper introduces a new branch of technology, the programmable matter. Claytronics is an abstract future concept that combines nanoscale robotics and computer science to create individual nanometre-scale computers called claytronic atoms, or catoms, which can interact with each other to form tangible 3-D objects that a user can interact with. This idea is more broadly referred to as programmable matter. Claytronics has the potential to greatly affect many areas of daily life, such as telecommunication, human-computer interfaces, andentertainment.*

Keywords*-Claytronics,Catoms,Macro,Nano,MELD,LDP*

I. Introduction

Claytronics is a 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. Programmable matter is a proposed digital material having computation, sensing, actuation and display as continuous properties active over its whole extent. 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. Objects featuring these catoms can be radically altered in form and function. Furniture can morph into new types, for instance. bed could suddenly become a sofa, or a large table. Chairs can be instantly moulded to precisely suit the individual. Walls, carpets, ceilings, doorsand other surfaces can modify their colour or texture on demand. Many vehicles now make use of claytronics. Car surfaces can change colour at the touch of a button or they can self-heal: fixing bumps, scratches and other damage. Tyres can be instantly adapted for different terrain types or weather conditions. Transparent windows can be instantly blacked-out for privacy.

II. Scaling And Designprinciples

Four basic design principles

1. Each atom should be selfcontained.
2. No static power should be required for adhesion afterattachment.
3. Coordination should be performed via localcontrol.
4. Catom should contain no movingparts.

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

PROPERTIES	MACRO	MiCRO	NANO
DIMENSIONS	>1 cm	>1 mm	<10 microns
WEIGHT	10’s of grams	100’s of mg	<1 mg
POWER	2 watt	10’s of mW	10’s of nW
LOCOMOTIVE MECHANISM	Programmable magnets	Electrostatics	Aerosol
ADHESION MECHANISM	Magnets	Programmable nano fibre adhesives	Molecouler surface adhesion,covalent bonds
MANUFACTURING METHODS	Conventional	Nano- Fabrication	Chemically directed self assembly
RESOLUTION	Low	High	High

III. Hardware

The basic hardware of a claytronic atom comprises of

1. Central ProcessingUnit
2. EnergySource
3. NetworkDevice
4. Video OutputDevice
5. One or moreSensors
6. Mechanism for adhering to othercatoms

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 nanoscale robots.

Planarcatomstesttheconceptofmotionwithoutmovingpartsandthedesignofforceeffectorsthatcreatecooperativemotionwithinensemblesofmodularrobots.

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.

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 fulfill a set of unique instructions.

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.

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.

A. Future Design

In the current design, the catoms are only able to move in two dimensions relative to each other. Future catoms will be required to move in 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 asamean of energy transport. Onepossibility being explored isusingaspecialtablewith positive and negative electrodes and routing the power internally through the catoms, via “virtualwires.”

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. Tasks ofSoftware

Organizing all of the communication and actions between millions of sub-millimeter scale catoms requires development of advanced algorithms 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 most important projects are developing new programming languages which work more efficiently for claytronics. 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 informationand 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 syntaxandstyleofcommandthannormalprogramminglanguagessuchasC++andJava.

The Carnegie Mellon-Intel Claytronics Research 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 programmingoverlaynetworks.Byusinglogicprogramming,thecodeforanensembleof 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 claytronicsmatrix.

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 worry about 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 Meld are 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 ofthe metamodule planning algorithm as written in Meld. We found this proof to be easier to carry out than a proof on pseudocode.

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. They have been demonstrated on ensembles containing millions of modules, as shown in the video on the right.

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 analyze 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 withBooleanlogic, which enables the program to search for larger patterns ofactivityand behaviour among groups ofmodules.

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 with Meld, 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.

D. DistributedWatchpoints

Performance errors for thousands to millions of individual catoms are hard to detect and debug, therefore, claytronics matrix operations require a dynamic and self-directed process for identifying and debugging errors. Claytronics researchers have developed Distributed Watchpoints, an algorithm-level approach to detecting and fixing errors missed by more conventional debugging techniques. It establishes nodes that receive surveillance to determine the validity of distributed conditions. This approach provides a simple and highly descriptive set of rules to evaluate distributed conditions and proves effective in the detection of errors.

E. Algorithms

Two important classes of claytronics algorithms are shape sculpting and localization algorithms. The ultimate goal of claytronics research is creating dynamic motion in three dimensionalposes. Alltheresearchoncatommotion,collectiveactuationandhierarchical motion planning require shape sculpting algorithms to convert catoms into the necessary structure, which will give structural strength and fluid movement to the dynamic ensemble. Meanwhile, localization algorithms enable catoms to localize their positions in an ensemble. A localization algorithm should provide accurate relational knowledge of catomstothewholematrixbasedonnoisyobservationinafullydistributedmanner.

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.

From scientific perspective, this technology would enable engineers to work remotely in physically hostile environments or surgeons to perform intricate surgery on enlarged claytronic replicas of organs, while the actual organs are being worked upon by a claytronic replica of the surgeon. It may help scientists learn how to efficiently manage networks of millions of computers. It will also advance our understanding of nanotechnology.

VI. Future scope

Thepowerandflexibilitythatwillarisefrombeingableto"program"theworldaround 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 closeenough.

As the capabilities of computing continue to develop and robotic modules shrink, claytronics will become useful in many applications. The featured application of claytronics is a new mode of communication. Claytronics will offer a more realistic sense to communication over long distancecalled pario.Similartohowaudioand videoprovide aural and visual stimulation; pario provides an aural, visual and physical sensation. Auser willbeabletohear,seeandtouchtheonecommunicatingwiththeminarealisticmanner. Pario could be used effectively in many professional disciplines from engineering design, education and health care to entertainmentandleisureactivitiessuchasvideogames.

The advancements in nanotechnology and computing necessary for claytronics to becomearealityarefeasible,butthechallengestoovercomearedauntingandwillrequire greatinnovation.Inaninterview,December2008,JasonCampbell,aleadresearcherfrom Intel Labs Pittsburgh said, "My estimates of how long it is going to take have gone from 50 years downto justacouplemoreyears.ThathaschangedoverthefouryearsI've been working on theproject."

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