Claytronics, Synthetic Reality, And Robotics

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Robotics IC

www.cs.cmu.edu/~claytronics

Joint work with Sitti, Hoburg, Lee, Aldrich, Seshan, Pfenning, Veloso, Sukthankar, Baker, Kirby, Rister, Reshko, Bowers

audio

Encoding

...01110010...

mp3

video

Encoding

...01110010...

mpeg

pario

Latin: to bear, bring forth, produce; create, make, get

Telepario

San Francisco

Seattle

Pittsburgh

Encoding

...01110010...

Encoding

...01110010...

Encoding

...01110010...
Programmable matter

- An ensemble of material that contains sufficient
  - local computation
  - actuation
  - storage
  - energy
  - sensing & communication
- Which can be programmed to form interesting dynamic shapes and configurations.
Claytronics

- Bring matter under computer control i.e., programmable matter
- Path to the future
  - 1 micron cubed catom
  - Creation of useful artifacts
- Create a enticing system that explores ALL the computer science issues of programmable matter
- Basis for Synthetic Reality/Future Robots

Synthetic Reality - Capture

1. Capture 3D Object
2. Encode 3D model
3. Transmit data

Synthetic Reality - Reproduce

3-5 years
5+ years

A Claytronic Atom: Catom
A Claytronic Atom: Catom

The outside is studded with contacts

A Claytronic Atom: Catom

The outside is coated with organic LEDs
- Low power
- Conforms to shape

Inside the Catom

Inside the Catom
Inside the Catom

Communication

Antenna

Computer

Programmable Magnets

SuperCap

We can buy these today!
Moving the Catom
Moving the Catom

Moving the Catom

Moving the Catom

Moving the Catom
Claytronics Today

- 2D system
- Modular design

Complete Catoms

Magnets For Locomotion

Next Generation 2D catom

ETA: November 15, 2004
First Step, Find and localize

Distributed Localization

Handling Grain Boundaries

Next Step, Create Network

- Use simple local rules to form hierarchy
- 10 line program does this!
- Local only decisions $\rightarrow$ Global effect
Simulation of Future Catoms

Multiple Networks

Unlike current systems, we can only create a single electrical contact between devices, so cooperation is needed to form circuits. An external source provides $V_{dd}$ and ground lines, and separate pathways are formed through the object to power each catom.

We have developed an algorithm that keeps basic static shapes powered. Future work includes leveraging the hierarchy and powering dynamic structures.

And Localization

Getting There From Here

• Goal: Robust ensemble of millions of catoms
• Claytronics Design Principles
  - No Moving Parts
  - Local Control
  - No Static Power
Moore’s Law

Where are we in 50 years?

<table>
<thead>
<tr>
<th></th>
<th>1949 Eniac</th>
<th>2003 greeting card</th>
<th>2050 Programmable matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>5M-23M (2002 $)</td>
<td>1$</td>
<td>1 millicent</td>
</tr>
<tr>
<td>Weight</td>
<td>30 tons</td>
<td>1 oz</td>
<td>20 µg</td>
</tr>
<tr>
<td>Volume</td>
<td>450 M³</td>
<td>1 cm³</td>
<td>1 nm³?? (1 µm³)</td>
</tr>
<tr>
<td>Power</td>
<td>200KW</td>
<td>20mW</td>
<td>2 attowatts</td>
</tr>
<tr>
<td>Cycle time</td>
<td>&gt;200µs</td>
<td>25ns</td>
<td>2 picosec</td>
</tr>
<tr>
<td>Storage</td>
<td>&lt;800B</td>
<td>4KB</td>
<td>16KB</td>
</tr>
</tbody>
</table>

Cogent arguments for both sooner and later exist

Scaling of Claytronics

<table>
<thead>
<tr>
<th></th>
<th>Macro</th>
<th>Micro</th>
<th>Nano</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>&gt;1 cm</td>
<td>&gt;1 mm</td>
<td>&lt;10 microns</td>
</tr>
<tr>
<td>Weight</td>
<td>10's gr</td>
<td>100's mg</td>
<td>&lt;1 mg</td>
</tr>
<tr>
<td>Power</td>
<td>&lt;2 Watts</td>
<td>10’s mW</td>
<td>10’s nW</td>
</tr>
<tr>
<td>Locomotive</td>
<td>Programmable magnets</td>
<td>Electrostatics</td>
<td>Aerosol</td>
</tr>
<tr>
<td>Adhesion mechanism</td>
<td>Nanofiber adhesives</td>
<td>Programmable nanofiber adhesives</td>
<td>Molecular surface adhesion and covalent bonds</td>
</tr>
<tr>
<td>Manufacturing methods</td>
<td>Conventional manufacturing and assembly</td>
<td>Micro/Nano-fabrication and micro-assembly</td>
<td>Chemically directed self-assembly and fabrication</td>
</tr>
<tr>
<td>Resolution</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cost</td>
<td>$$$/catom</td>
<td>$/catom</td>
<td>Millicents/catom</td>
</tr>
</tbody>
</table>

3D Catom Proposal

- Three die
  - Compute die
  - Sense/actuate die
  - Power die
- Connect back-to-back use through die vias
Power

- Caps
- Antenna

Processing

- CPU
- Memory

Sensors and Actuators

- Radio
- Light Sensor
- LED
- Up/Down Sensor
- Camera?
- Mic?
- Pressure?

The Case/Motion

Capacitor formed across two catoms
What about the software?

- Distributed Planning
- Programming Models
- Networking
- ...

Networking: Naming & Routing

Naming
How will programs address catoms?

- Granularity: Individual, multicast, anycast
- Identity: Geographic, based on shape (e.g. arm catoms)

Our approach
- Driven by application needs
- Support multiple naming schemes (at higher cost) until application needs are clear

Routing
How to identify path to destination catoms?

- Traditional ad hoc routing (DSR, AODV, etc.)
  - Relies on flooding → not scalable to Claytronics network sizes
- Geographic (GPSR)
  - Requires planar network interconnect → cannot support arbitrary 3d structures

Our approach
- Use programs to control 3d structure such that GPSR-like routing is possible
- Develop localization techniques

Programming Language/Software Engineering Research

Claytronics & Pario

- Open up an entire new application space
  - Entertainment (interactive clay)
  - Training (live-fire exercises)
  - Design (100x protein model)
  - Interaction (telepario)
  - Rescue (paramedic on demand)
  - Metal Man (fault tolerant robotics)

- Vehicle for studying CS problem of the future:
  How do you design, program, maintain, and use a billion component system?
Claytronics & Pario

• Open up an entire new application space
• Vehicle for studying CS problem of the future:
  How do you design, program, maintain, and use a billion component system?
• Vehicle for creating robot of the future:
  How to design and program a collection of micro/nanorobots to create a useful macroscale robot?

Our Approach:
- Make scaling work for us
- Exploit scale invariance
- Design for scalability in both number & size

Software Systems

• Distributed Computing
  - how to write a program for 1M+ machines? what is the programming model?
• Robot planning, distributed robotics
  - how to plan the coordinated movement, communication and sensing?
• Networking and sensor nets
  - how to geolocate, communicate?
• Emergent Behavior
  - how to self-organize and operate in uncertain environments with unreliable components?
• Many others...
Hardware Systems

• Microrobots, modular robots
  - what is the design of the elements?
• MEMS/nanotech materials
  - how to achieve small scale economically?
• Magnetics and other actuation
  - how to do locomotion, actuation?
• High voltage silicon processing
  - how to achieve manufacturing economies of scale?
• Power systems
  - how to distribute power?
• …