Millimeter-Scale Robotics at The MITRE Corporation

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24 February 2005
Outline

- Introduction: Why are we interested in small robots?
- Evolution of the MITRE millirobot
- Present system design of MITRE millirobot
- Our efforts in engineering and building a tiny robot
  - Nanoelectronic circuits for locomotion (Alex Gates)
  - MEMS chassis fabrication and testing
- Closing remarks
MITRE’s Broadly-Based R&D Program in Nanotechnology

Collaboration of extraordinarily talented young people with senior staff has been integral to our work

Summer 2004 MITRE Nanosystems Group

20 staff performed nanotech R&D at MITRE during Summer ‘04, including 9 outstanding undergrads & high school students
MITRE’s Broadly-Based R&D Program in Nanotechnology

12-Year R&D Effort Started with Central Question:

What should a nanocomputer “look” like?

20 staff performed nanotech R&D at MITRE during Summer ‘04, including 9 outstanding undergrads & high school students
Millimeter-scale Robotics: Integrating Nanoelectronics with Micromachinery

Objective: Reduce the size of electronic devices and systems through the use of integrated nanoelectronics, nanocomputers, and nanosensors

Rationale
Explore the nature of future info. systems

Nanometer-Scale Electronics
Micron-Scale Machines

Next-Generation, Low-Power, Ultra-Lightweight Information Systems

- Ultramiiniature sensors & self-repairing materials
- Smart prosthetics: electronics integrated with living systems
- Information processing as a property of matter

Control Computers
Battery
Photocell
Micro-fabricated Legs

3 mm

Conceptual drawing of MITRE Millirobot
History of MITRE’s Millimeter-scale Robotics Research

- 1995 – Proposed that a miniature walking robot could be used as a demonstration platform for nanoelectronic computers

- 1998 – Attended DARPA Micrites Workshop, which inspired researchers to examine the possibility of using millimeter-scale robotics as a stepping stone to smaller scales

- 2000 – Initial adaptation of system-level designs into something that could be fabricated
Ten Year Evolution of the MITRE Millirobot
Millimeter-scale Robotics Research Goals

- Initial goals of research
  - To identify those technologies which could drive forward the area of tiny robotics
  - To identify those areas that need further innovation and development
  - To show that previously-demonstrated components can be integrated at the system level

- MITRE brings a systems engineering approach to the development of a small-scale robot
  - Integrate “off-the-shelf” components and processes …
  - … but develop and encourage new technology where necessary
Essential Features of Millirobot System Design

- Demonstration platform for integrated nanocomputers & sensors
- Millimeter-scale mobile platform that is
  - Autonomous
  - Self-powered
  - Mass-producible
  - Implemented with readily-available technology
  - Able to communicate wirelessly
- Stepping stone to first microrobots

Full-Scale Millirobot Mockup on a Dime
Present Millirobot Design

- Solar cell for energy harvesting
- Articulated legs
Present Millirobot Design

Top view

Bottom view
Present Millirobot Design

Hollow Folding Legs

Nanoelectronic Sensors and Controllers

~10 \( \mu \text{m} \)

Electrostatic Actuators
Hierarchical Engineering of Tiny Robots

Tiny Robots

- Power
- Chassis
- Communication
- Control
Hierarchical Engineering of Tiny Robots

Power

Chassis

Communication

Control

Harvesting

Storage

Management
Hierarchical Engineering of Tiny Robots

Tiny Robots

Power

Chassis

Communication

Control

Fabrication

Locomotion

Actuation
Hierarchical Engineering of Tiny Robots

- Tiny Robots
  - Power
  - Chassis
  - Communication
    - Method
    - Bandwidth
  - Control
    - Range
Hierarchical Engineering of Tiny Robots

- Tiny Robots
  - Power
  - Chassis
  - Communication
    - Mission
    - Algorithm
    - Control
    - Circuitry
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Scope of Millirobot Control Circuitry

- Motor control circuits
- Motor driver circuits
- Voltage regulator (high voltage for motors, low voltage for circuits)
- Steering, navigation & object avoidance
- Sensor monitoring
- Communications circuits

Millirobot Nanoelectronic Control Circuits

**Approach:**

- Analyze requirements for control circuit
- Design a logic-level control circuit
- Map logic-level design to nanowire architecture
- Simulate final nanowire circuit with SPICE tools

**Rationale**

Millirobot project explores the nature of future info. systems

- Nanometer-Scale Electronics
- Micron-Scale Machines & Sensors
- Next-Generation, Low-Power, Ultra-Lightweight Information Systems
Millirobot Nanoelectronic Control Circuits

- Control Circuit Requirements
  - Allow the millimeter-scale robot to walk forward using the statically stable tripod gait
  - Operate with minimized processing and sensor input

- Circuit operation
  - Generate square waves 90° out of phase for each leg set
  - Use as power signals for the comb drive actuators

Tripod Gait

Signals 90° Out of Phase
Major Components of Motor Control Circuit

- Tripod Switch
- Oscillator
- 2-Bit Counter starting at 0
- 2-Bit Counter starting at 1
- Motor Driver
Schematic View of Millirobot Motor Control Circuit

Oscillator

Switch #1
Switch #2

Tripod Switch

Motor Driver

2-Bit Counter

2-Bit Counter
Nanoelectronics Overview

- Nanowires are single crystal strands commonly of Silicon (Greytak, 2004)
- Easily fabricated using Vapor-Liquid-Solid deposition catalytic assisted growth (Gudiksen, 2002)
- At crossbar junctions, transistors and diodes are formed (Cui, 2001)
- Programmable with the addition of electrostatic molecules (Dehon, 2004)
Nanoelectronic Implementation of Robot Control Circuits

DeHon’s crossbar architecture:

- Utilizes the concept of Programmable Logic Arrays (PLA)
- Composed of a combination of transistors and diodes
- Defect tolerant
- Uses a large number of clocks
- Requires the use of randomized addresses

Results:
Crossbar Schematic of 2-bit Counter

All Digital Control Logic Successfully Mapped to Caltech Architecture
Results:
Final Nanoelectronic Millirobot Control Circuit
Results:
Inverter Simulation

Simulation Input Functions

[Graphs showing simulation input functions]
Results: Inverter Simulation

Simulation Input Functions

Inverter Output
Results: Inverter Simulation

Simulation Input Functions

Inverter Output

Advanced Simulation Inverter Output

Figure From:
Results:
Inverter Simulation

Simulation Input Functions

Inverter Output

Advanced Simulation Inverter Output

Figure From:
Results:
Full Circuit Simulation
Results:
Full Circuit Simulation

Logic Simulation
Nanoelectronic Circuits: Conclusions and Future Work

- Nanoelectronic circuits could potentially further miniaturize circuit-machine systems

- **Future Work:**
  - Nano-oscillator needed to create the control pulse
  - Voltage regulators needed to control the circuit and actuator voltages
  - Interconnect system needed for nanoelectronic-MEMS interface
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Initial Fabrication of the MITRE Millirobot

Rationale
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Nanometer-Scale Electronics
Micron-Scale Machines & Sensors

Next-Generation, Low-Power, Ultra-Lightweight Information Systems
Initial Fabrication of the MITRE Millirobot

- Initial MEMS work was conducted in 2002
- Fabrication performed through MEMSCAP MUMPs (Multi-User MEMS Processes)

Rationale
- Millirobot project explores the nature of future info. systems

Nanometer-Scale Electronics

Micron-Scale Machines & Sensors

Next-Generation, Low-Power, Ultra-Lightweight Information Systems
Initial Fabrication of the MITRE Millirobot
Fabrication and Testing

- Later design iterations built upon our first efforts
  - Refined and improved components
  - Designed new devices
  - Began combining and integrating previously fabricated devices
Selected Devices from Testing
Fabrication and Testing

- New lab under construction here in McLean will have facilities dedicated to tiny robot development

- Capabilities to include:
  - Mechanical manipulation
  - Electrical characterization
  - Electrostatic actuator waveform generation
  - Chemical post-processing
Next Steps in Fabrication

- New fabrication process
  - 5-layer process allows more complex devices and better integration
  - First 5-layer prototypes mid-2005
- “MEMS-plus”
  - Experiment with enhancing MEMS devices with other technologies
  - Shape Memory Alloy (SMA), Silicon-On-Insulator (SOI)
Acknowledgements

- Previous Millirobot team members
  - Johann Schleier-Smith - Kevin Wegener
  - David Routenberg - Alan Christiansen
  - Thomas Sullivan - Noam Tene
  - Andrea Jensenius - James Ellenbogen
Summary of Ideas

- Multi-functionality of materials
  - Structures as actuators
  - Electronics as structures
- Biological inspiration…
  - But not bio-mimicry
- Efficiency
  - Don’t waste anything
  - Look at the system, not the components
- Power
  - Design around it from the start