Presentation at 1st Very Small Robots Workshop, McLean, VA

Millimeter-Scale Robotics at The MITRE Corporation

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MITRE Nanosystems Group

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

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

Molecular Devices, Circuits, & Nanocomputer Architectures R&D	Quantum Device Modeling & Analysis	Novel Techniques for Nanofabrication	Bio-Nanotechnology R&D
Millimeter-Scale Robotics	Carbon Nanotube Based Circuits & Materials	Nano-Power R&D	Nanosensors R&D

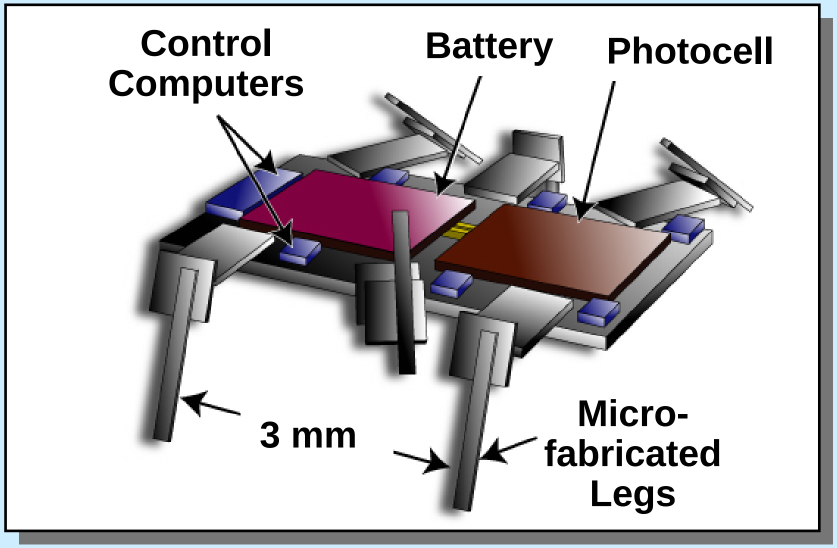
12-Year R&D Effort Started
with Central Question:

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**



Conceptual drawing of MITRE Millirobot

Rationale

Explore the nature of future info. systems

Nanometer-Scale Electronics

Micron-Scale Machines

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

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

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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**

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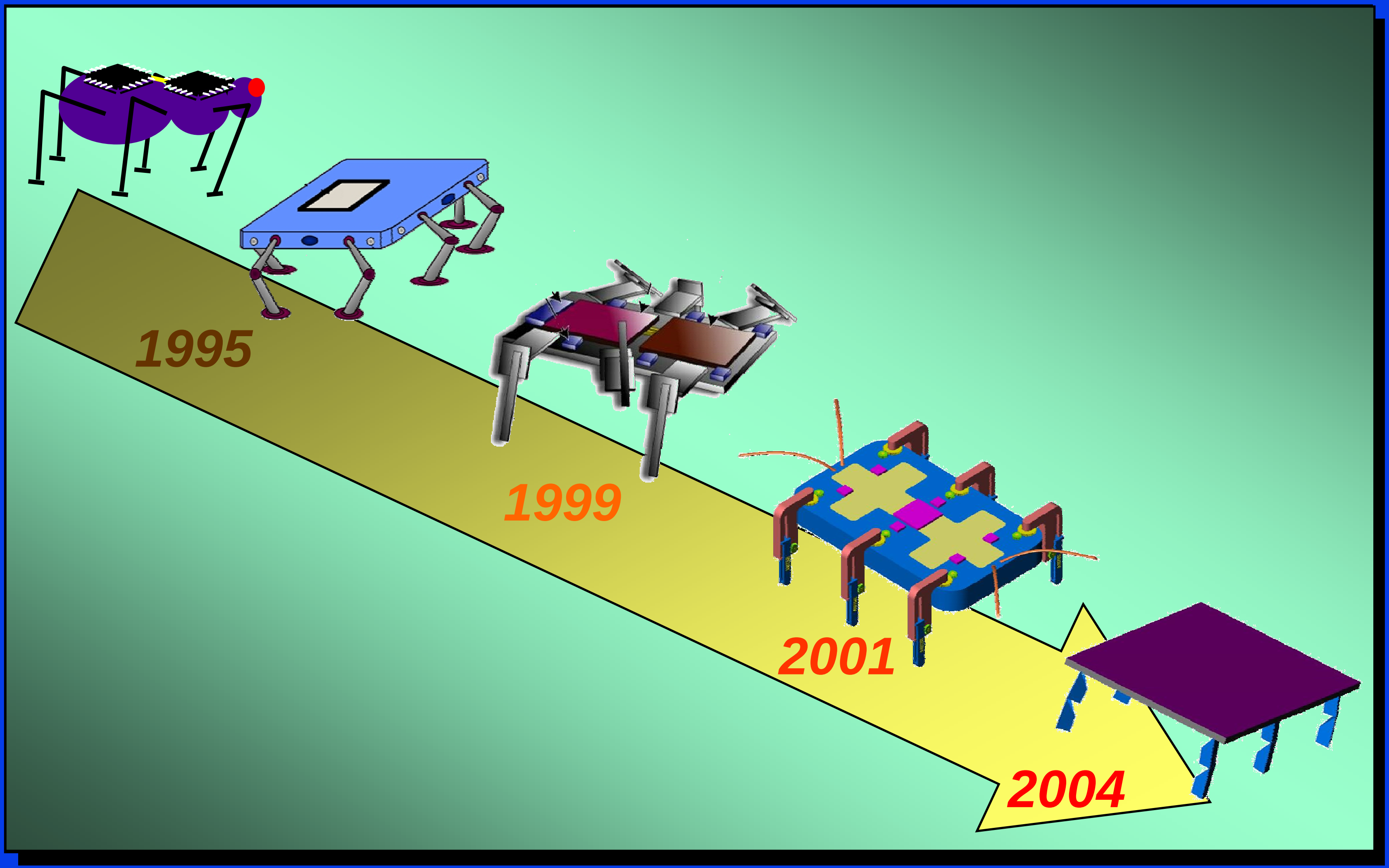
Ten Year Evolution of the MITRE Millirobot



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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 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

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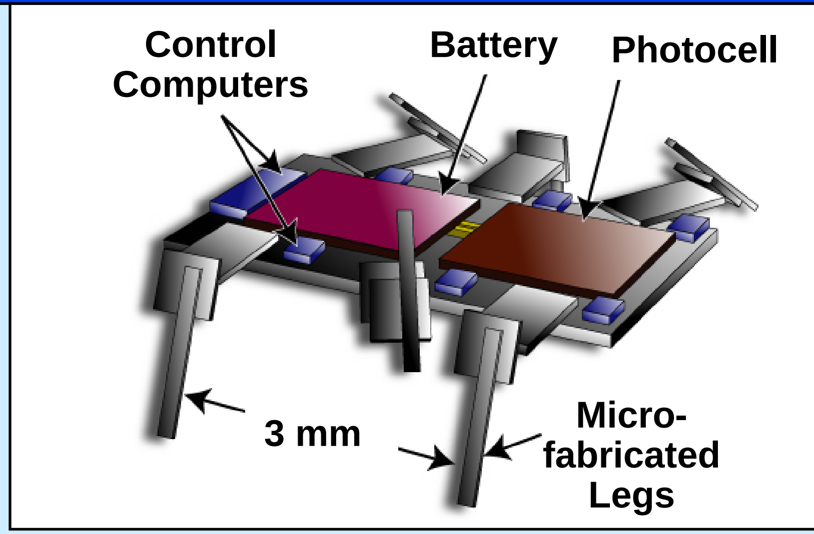
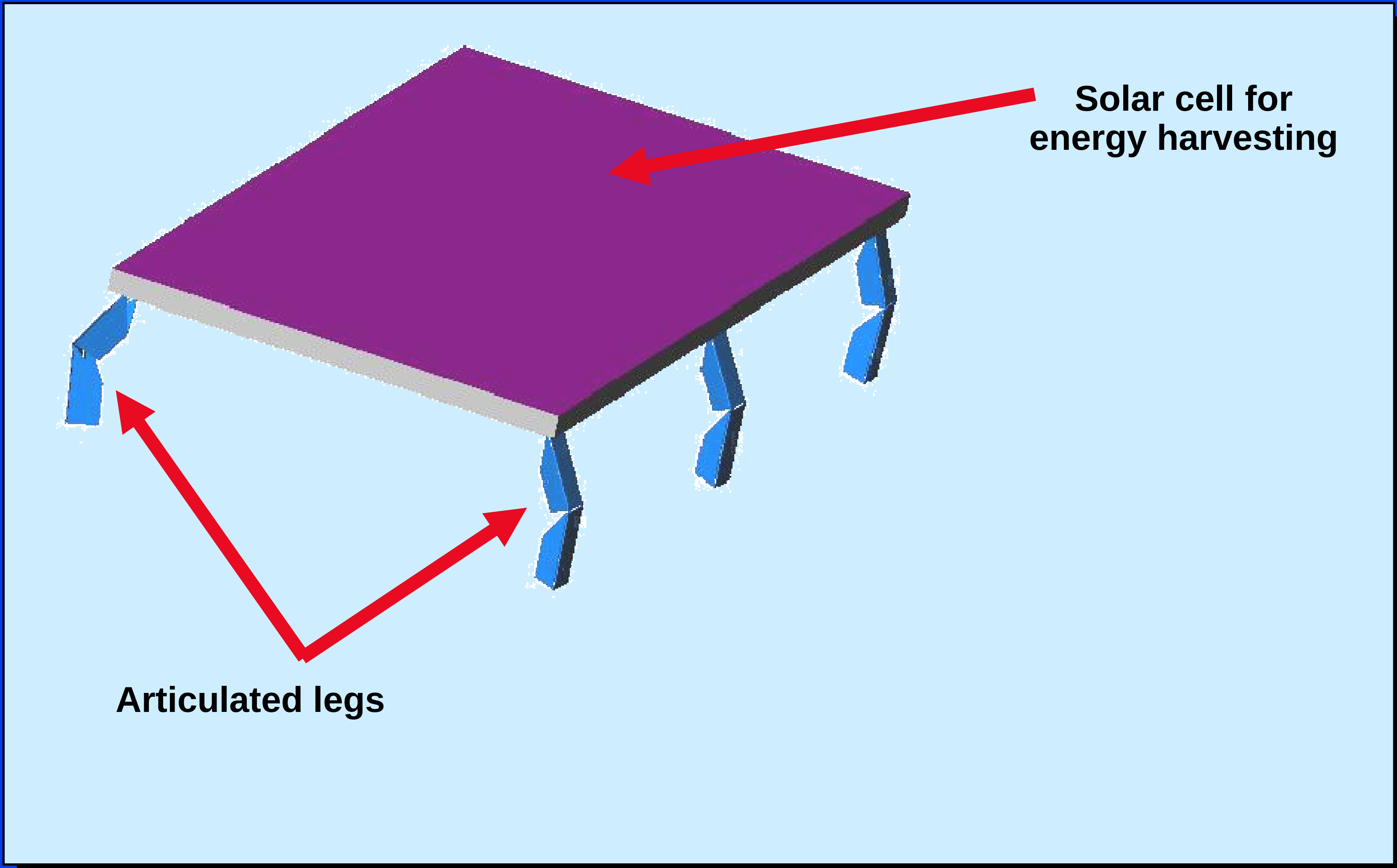
Essential Features of Millirobot System Design

- 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

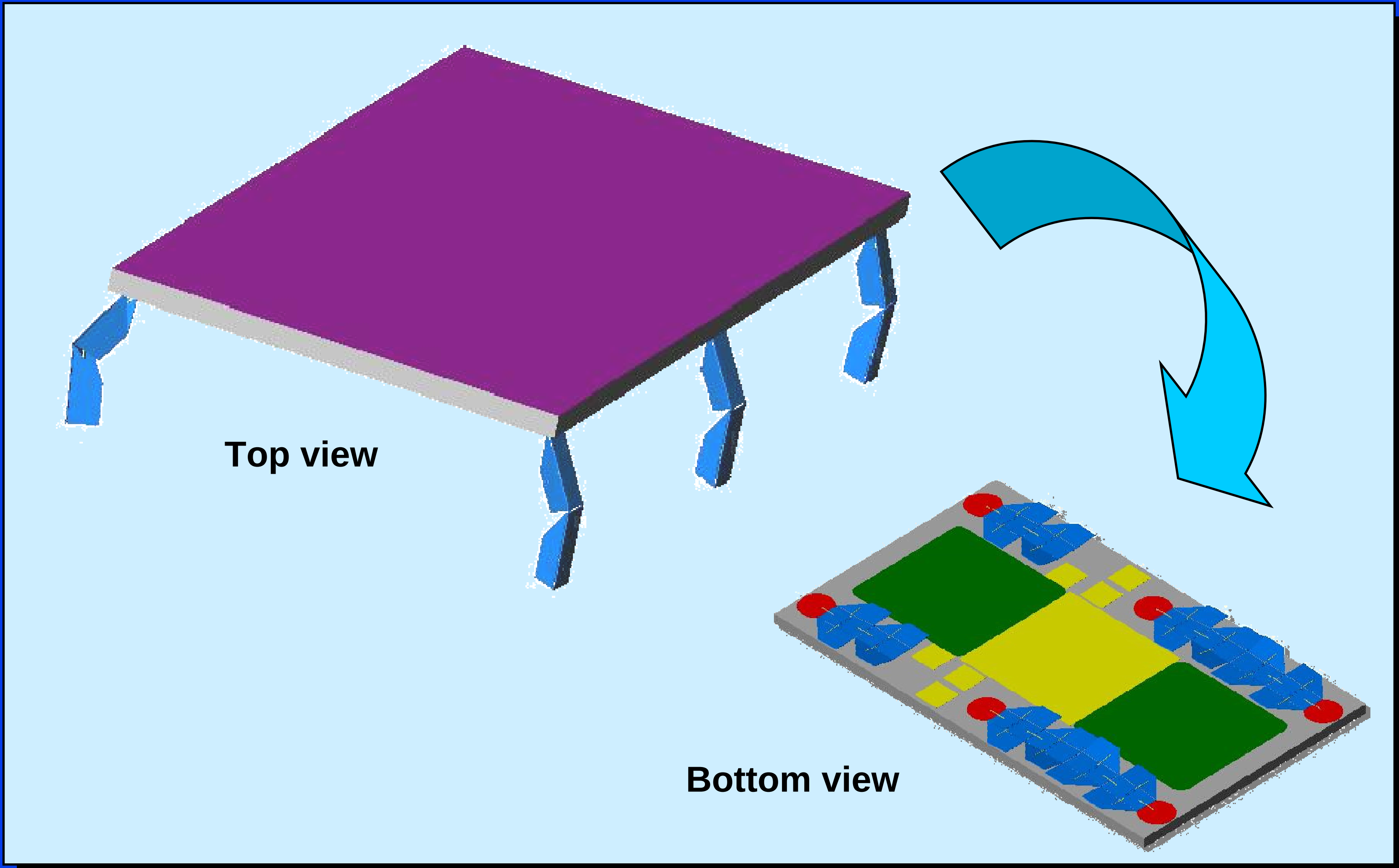


Full-Scale Millirobot Mockup on a Dime

Present Millirobot Design



Present Millirobot Design



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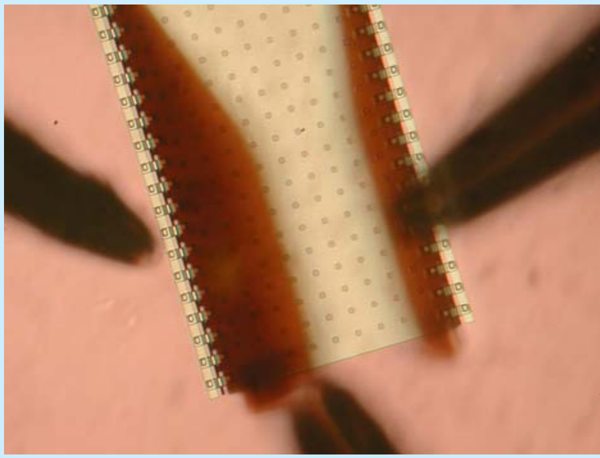
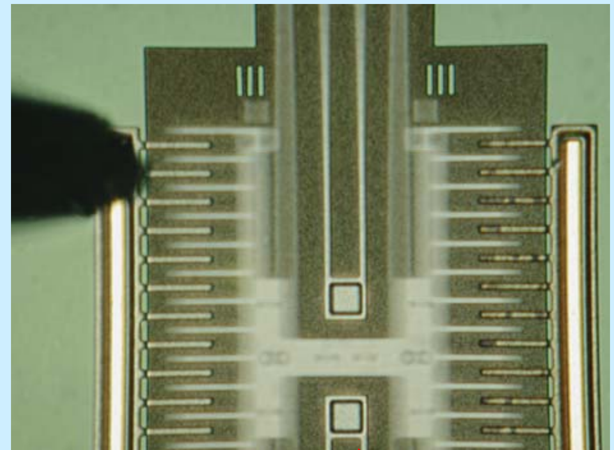
Present Millirobot Design

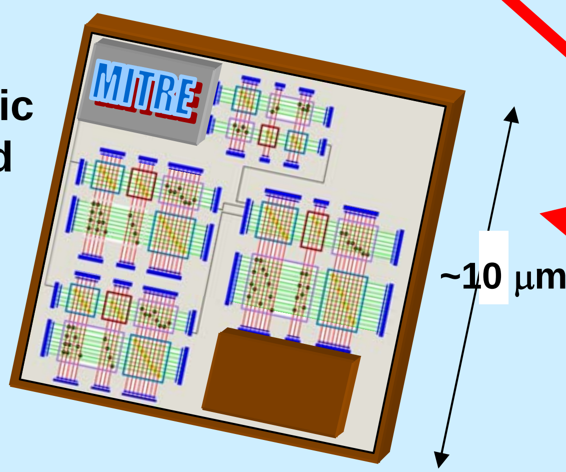
Hollow Folding Legs

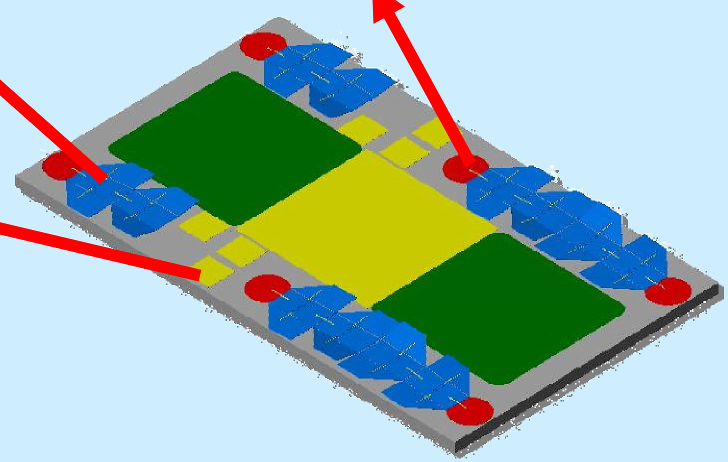


Electrostatic Actuators

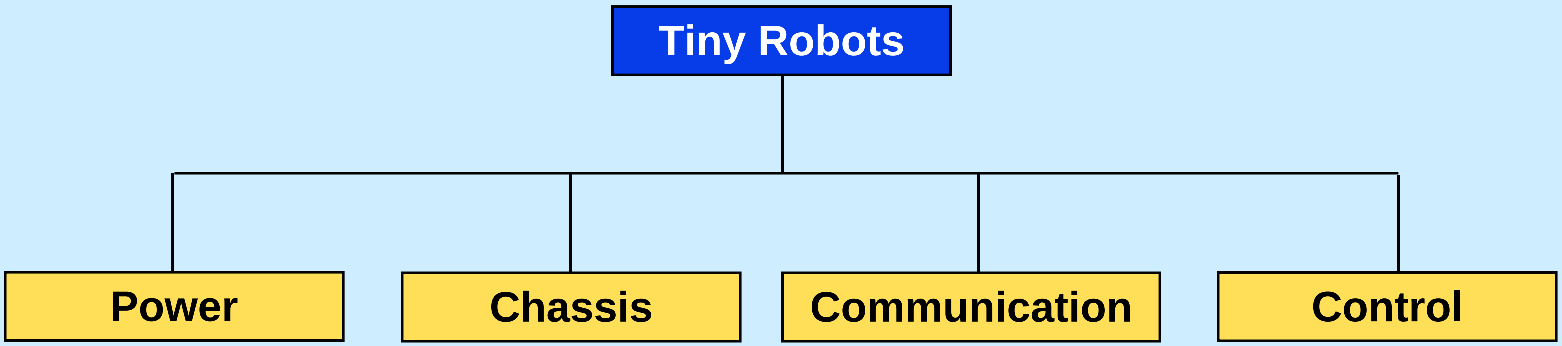


Nanoelectronic Sensors and Controllers





Hierarchical Engineering of Tiny Robots



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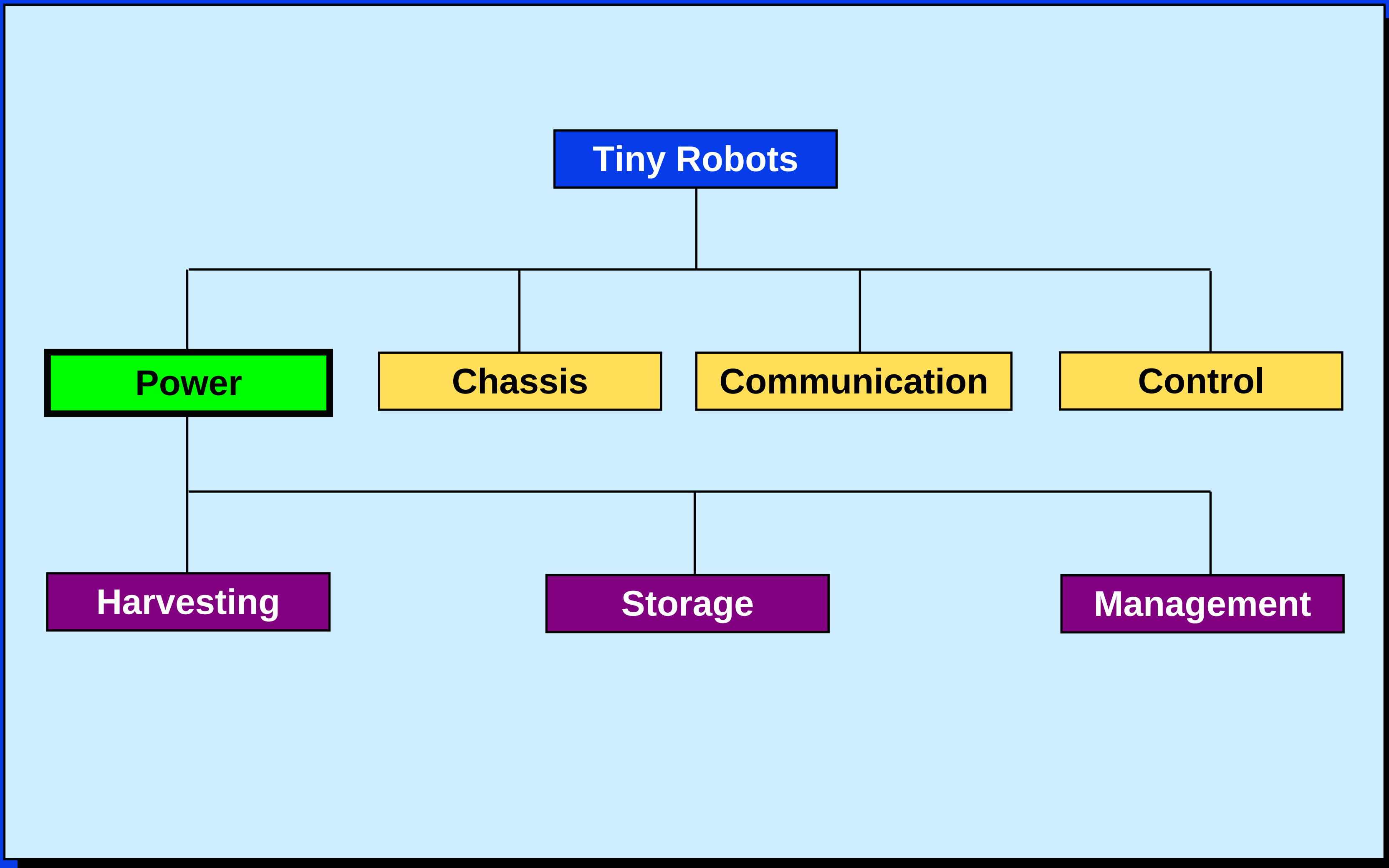

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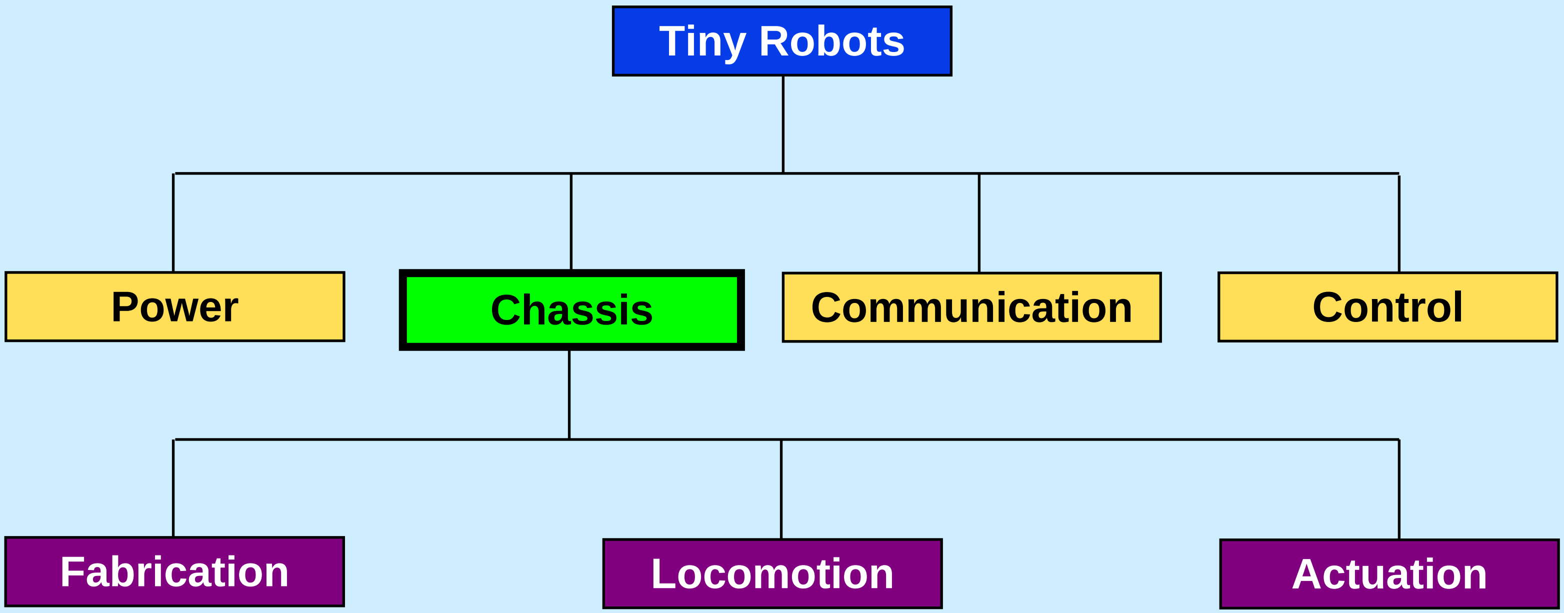

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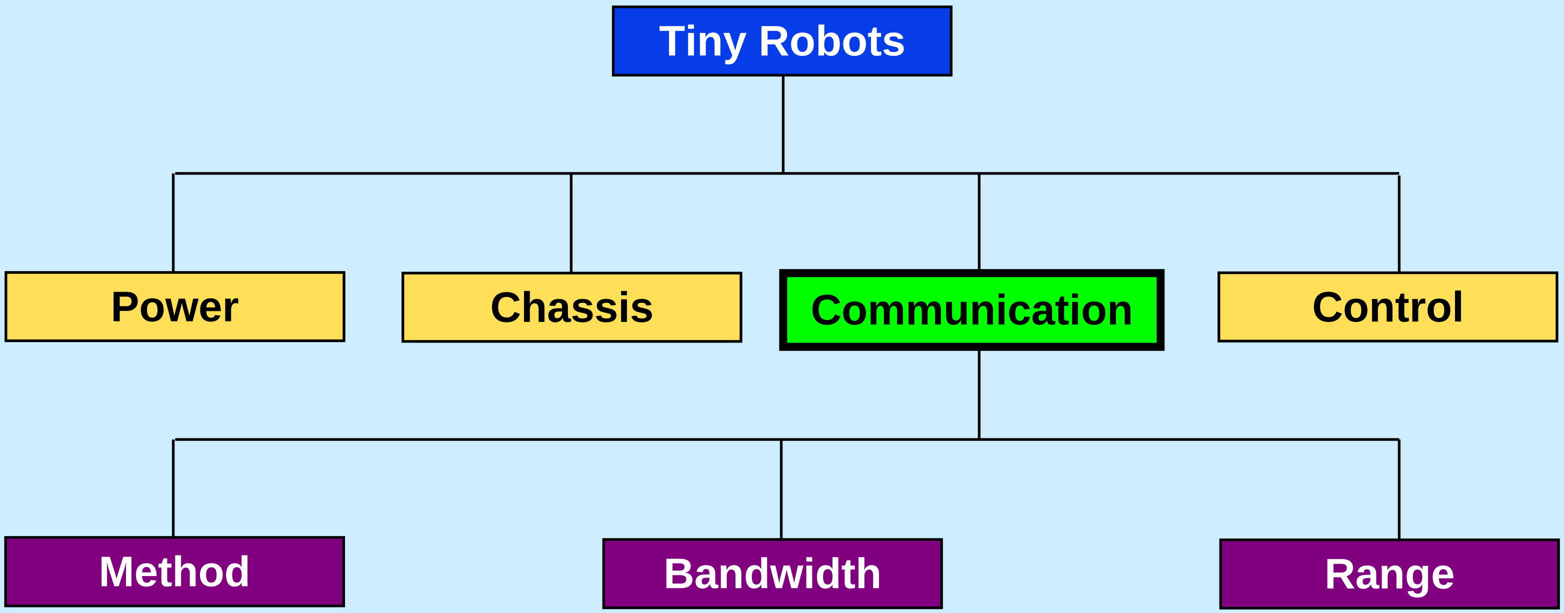

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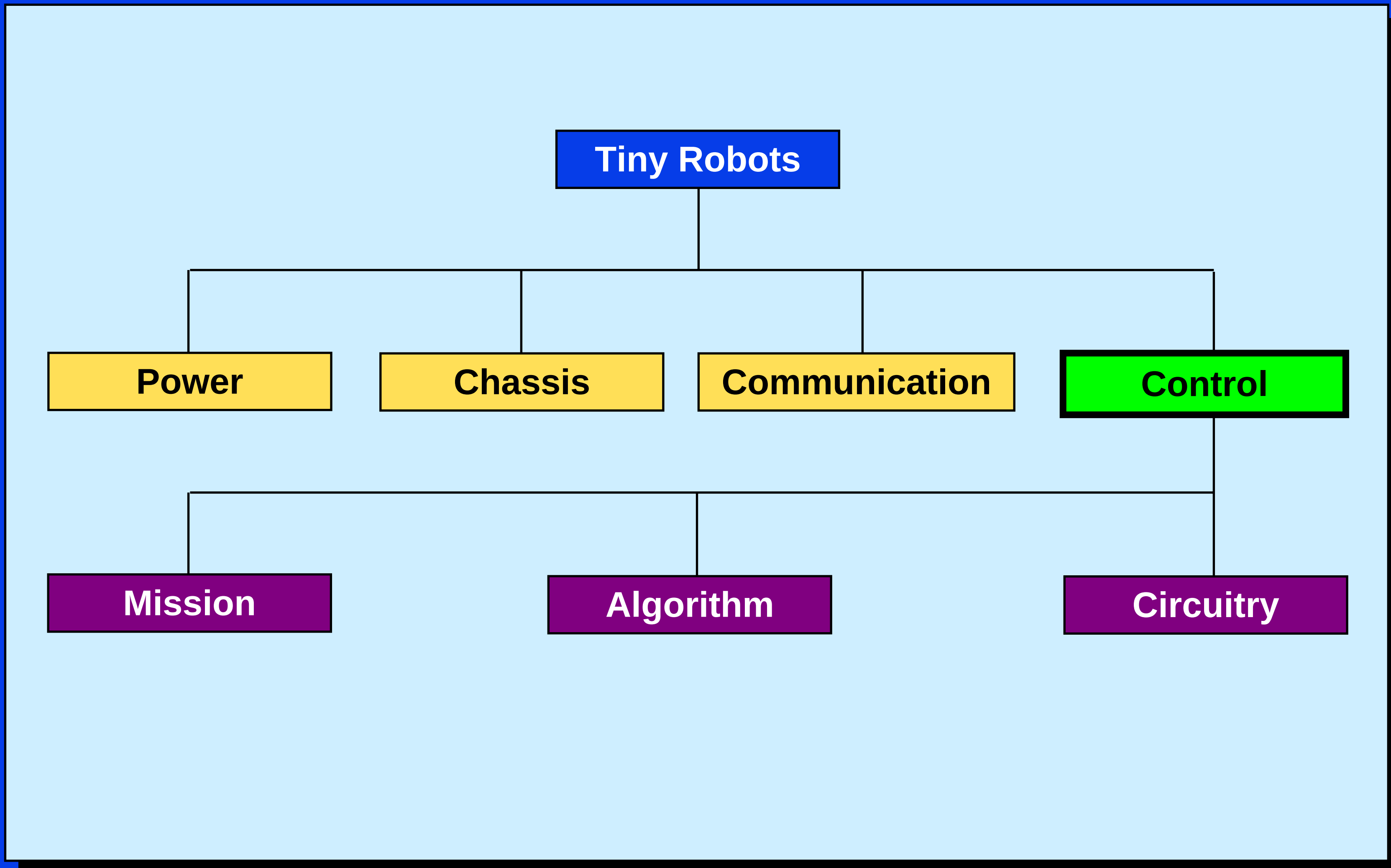

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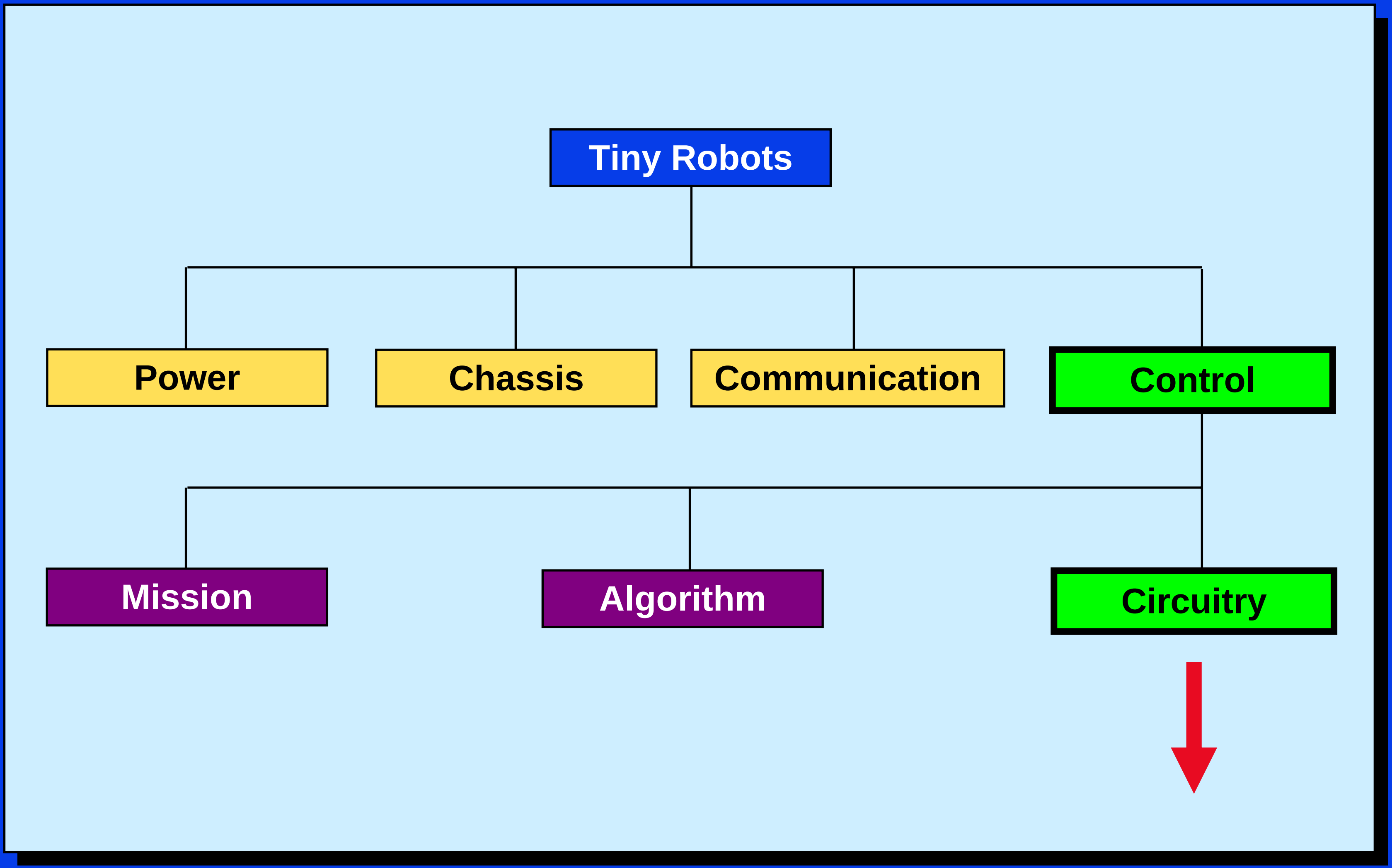

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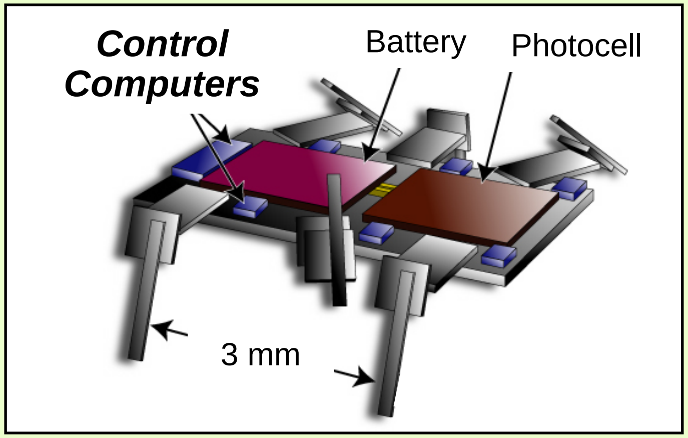
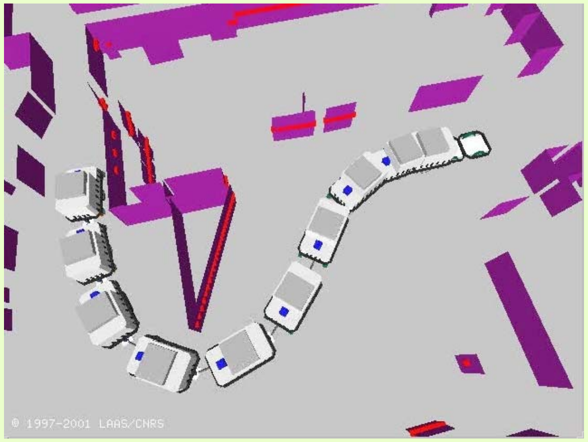
Scope of Millirobot Control Circuitry

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

Millimeter-scale Robot



Robot Obstacle Avoidance



Figures from http://www.laas.fr/RIA/RIA-demo-trailer-navigation-fr.html

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

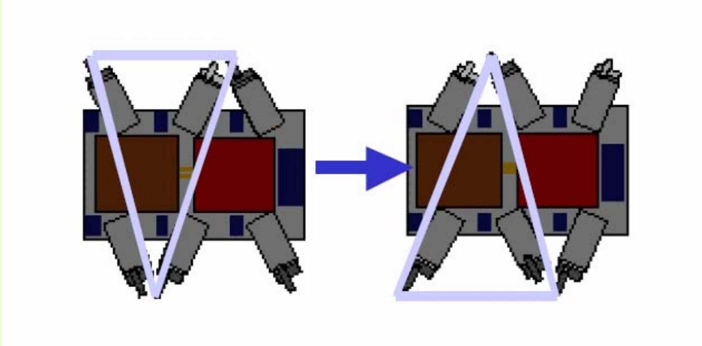
↓

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

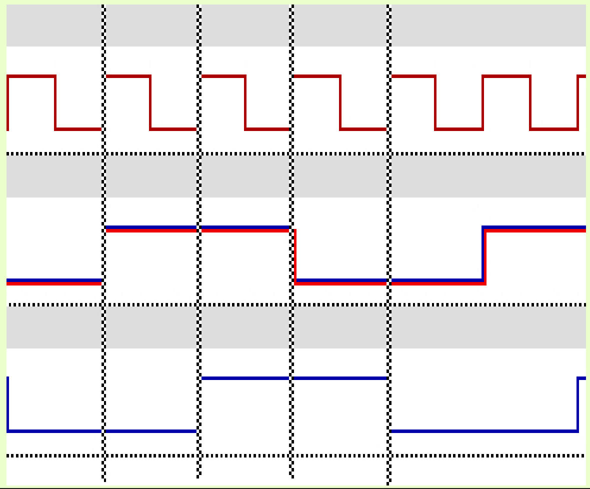
Millirobot Nanoelectronic Control Circuits

- 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



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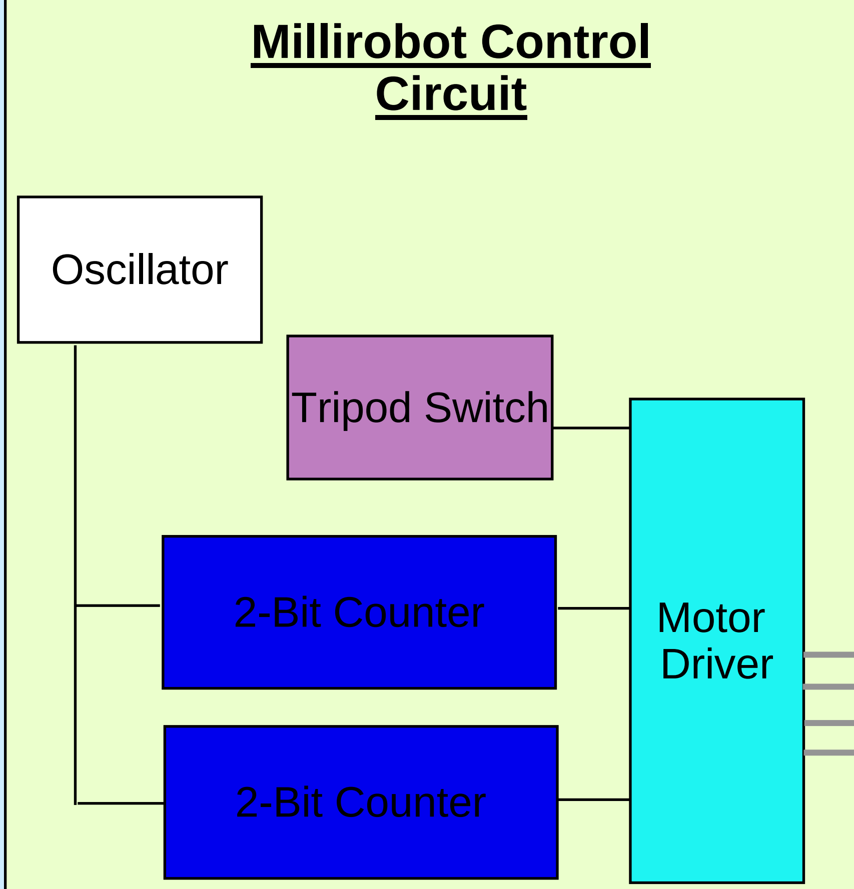
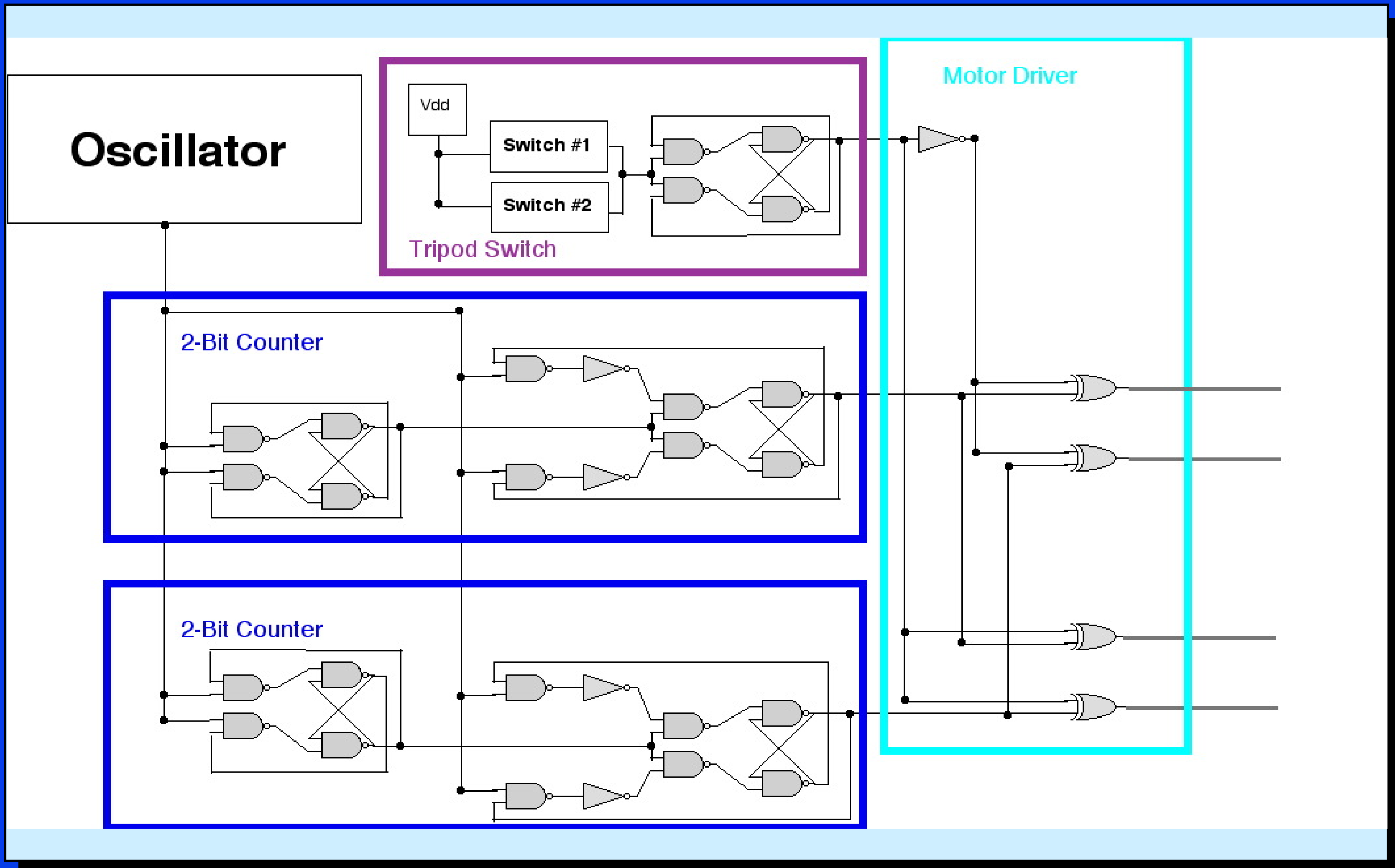
Major Components of Motor Control Circuit

- Tripod Switch
- Oscillator
- 2-Bit Counter starting at 0
- 2-Bit Counter starting at 1
- Motor Driver



Schematic View of Millirobot Motor Control Circuit



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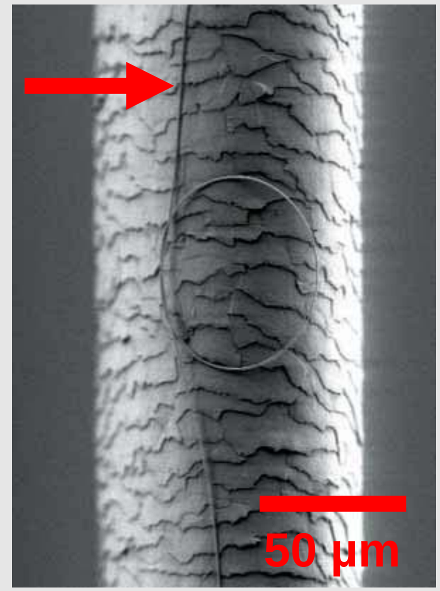
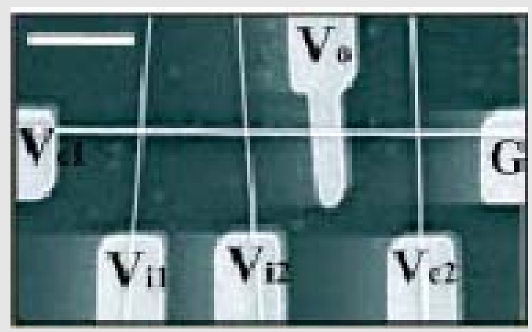
Nanoelectronics Overview

- 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)

Nanowire on a Human Hair



Nanowire Transistors

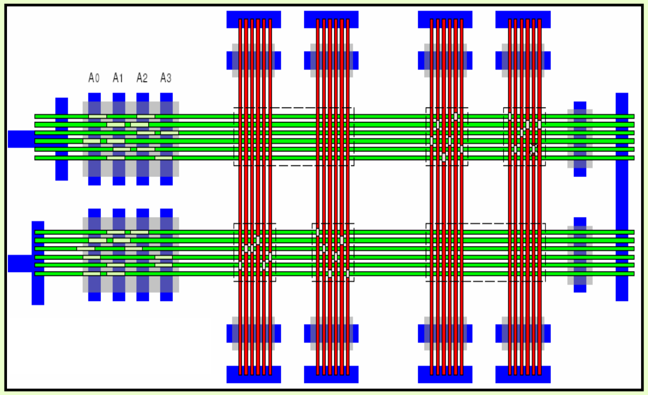


Nanoelectronic Implementation of Robot Control Circuits

DeHon's crossbar architecture:

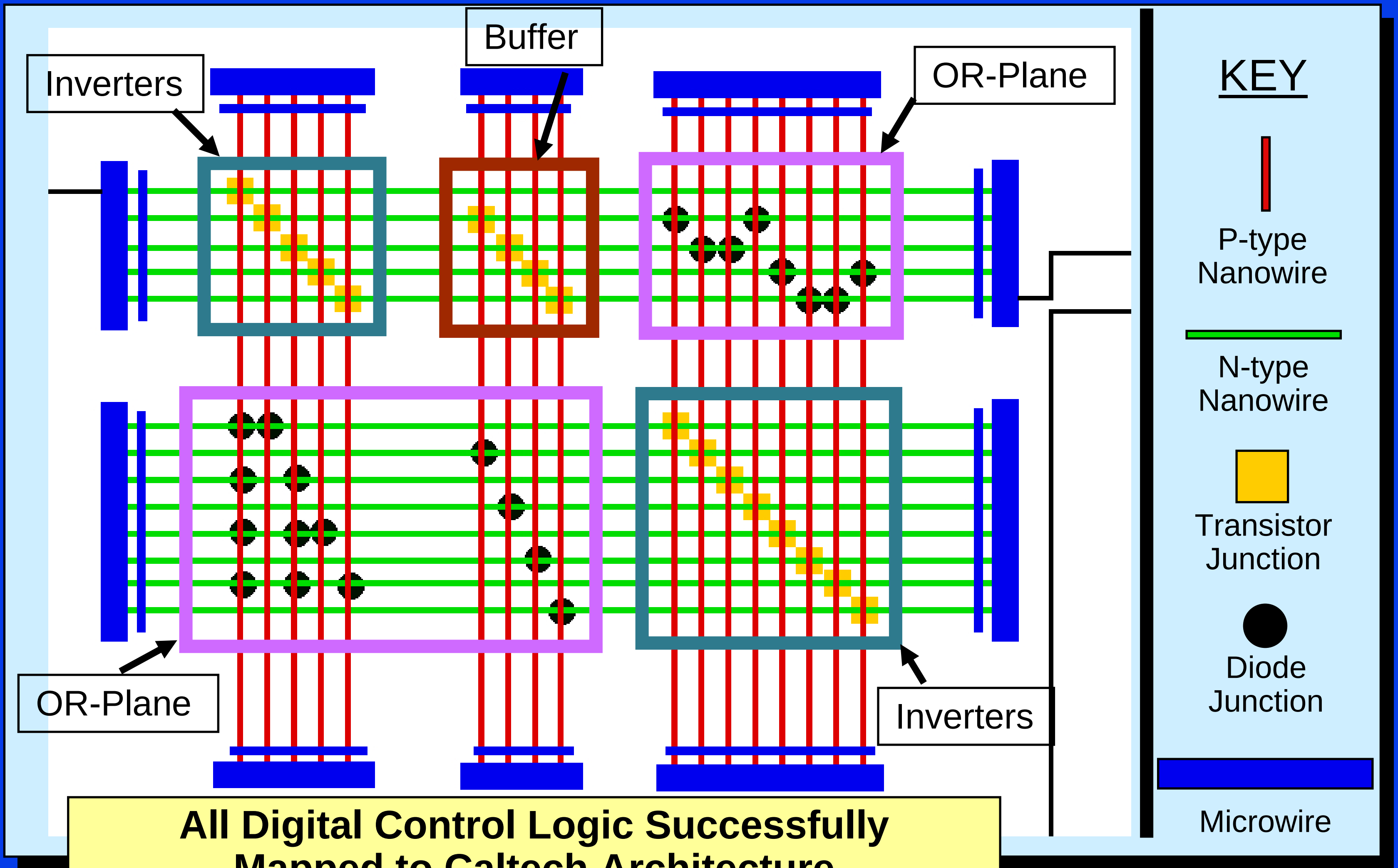
- Utilizes the concept of Programmable Logic Arrays (PLA)
- Composed of a combination of transistors and diodes
- Defect tolerant
- Uses a large number of clocks
- Requires the use of randomized addresses

Examples of Nanowire Circuits Made by DeHon



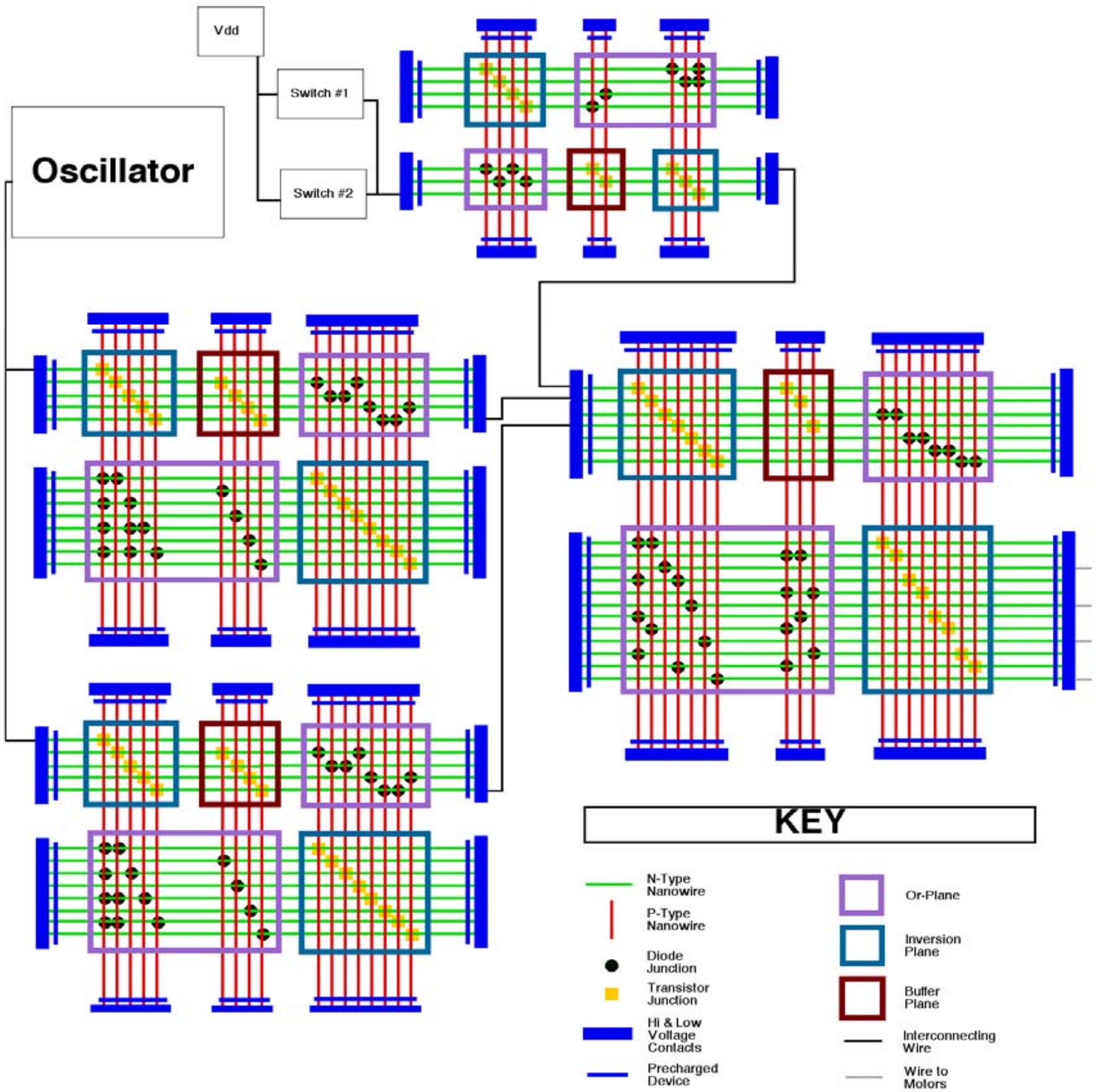
Figures from DeHon, A. et al., "Proc. Intl. Symp. FPGA," pp. 123–132 (2004) and DeHon, A., "Array-Based Architecture for FET-Based, Nanoscale Electronics," IEEE Transactions on Nanotechnology, Vol. 2, pp. 23-32 (2002)

Results:
Crossbar Schematic of 2-bit Counter



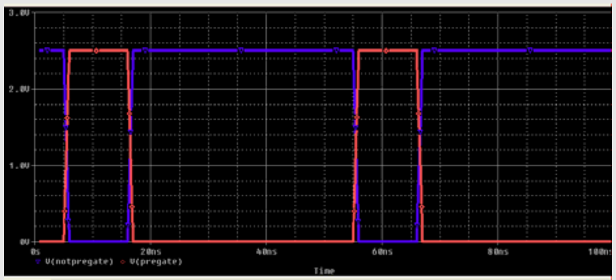
All Digital Control Logic Successfully Mapped to Caltech Architecture

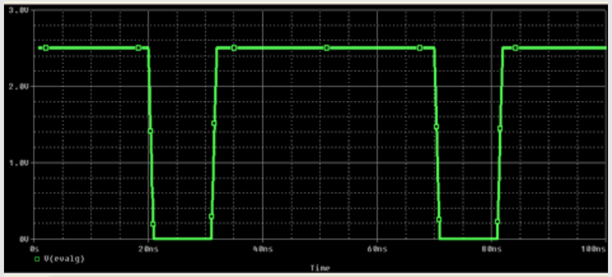
Results:
Final Nanoelectronic Millirobot Control Circuit

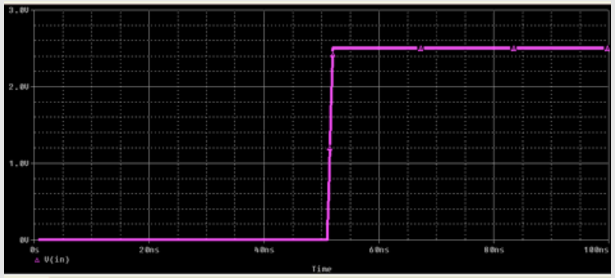


Results:
Inverter Simulation

Simulation Input Functions







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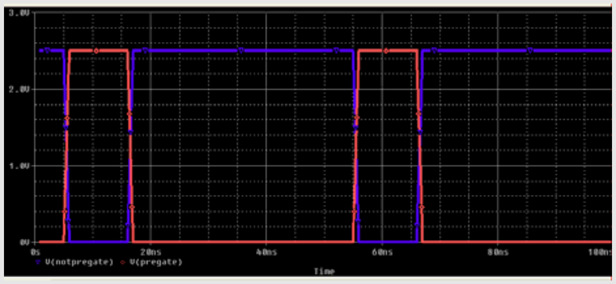
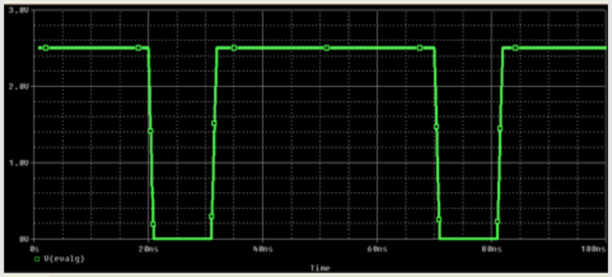
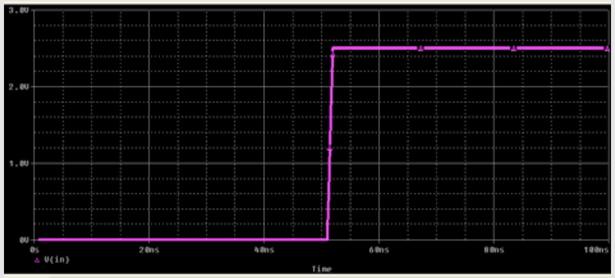
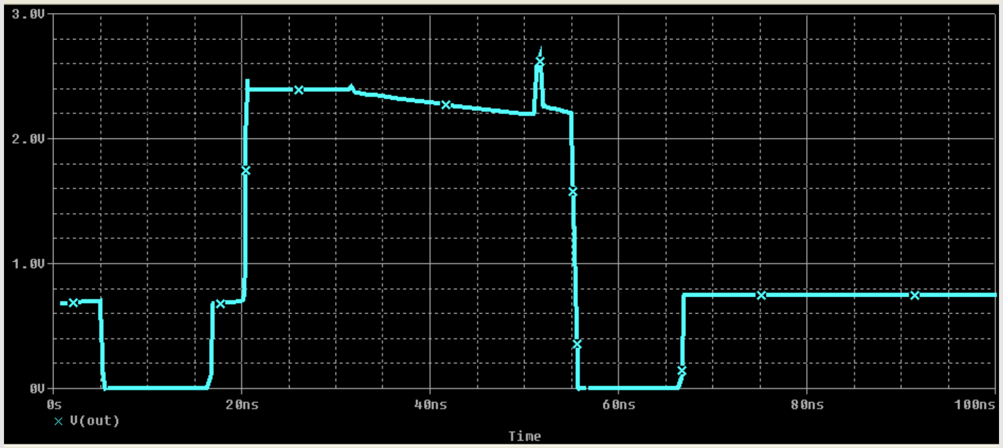






Inverter Output



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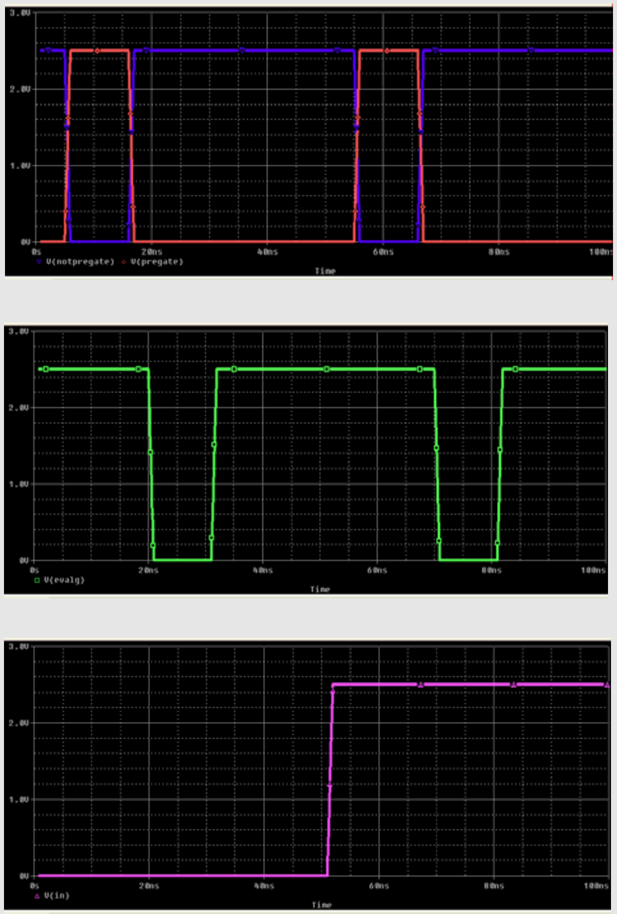

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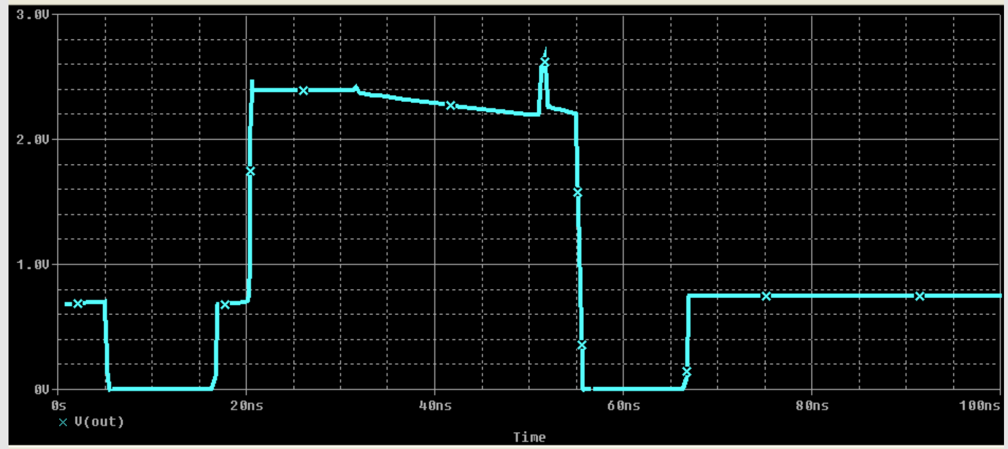


Advanced Simulation Inverter Output

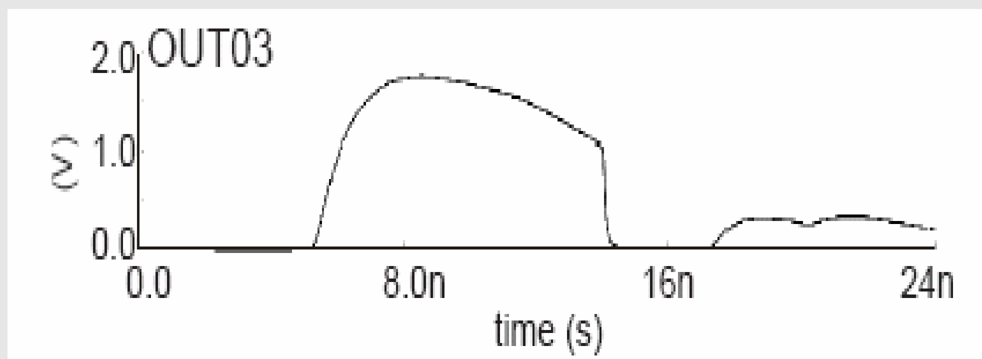
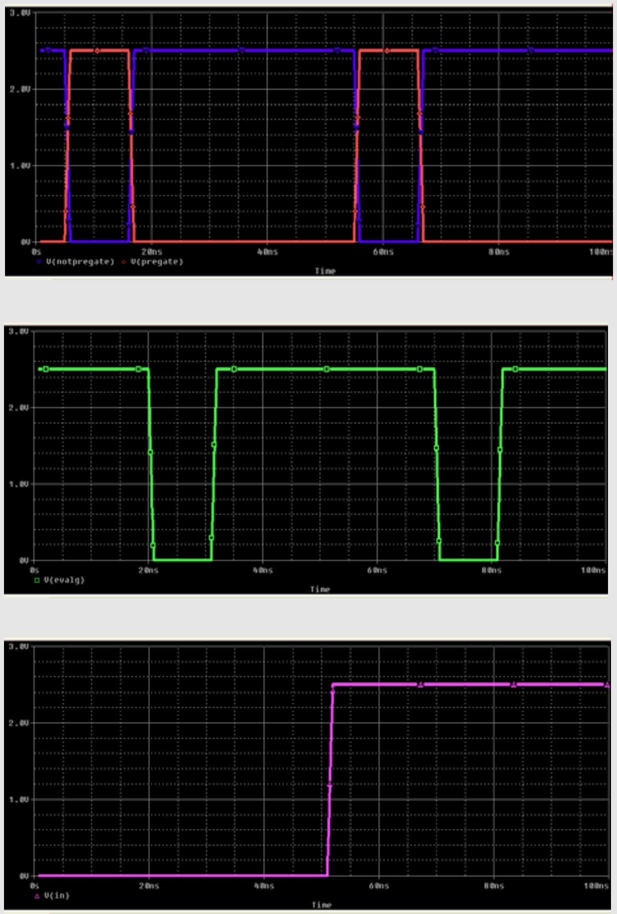


Figure From:
S. Das et al. "Architectures and Simulations for Nanoprocessor Systems Integrated on the Molecular Scale." *Submitted for Publication.*

Results:
Inverter Simulation

Simulation Input Functions



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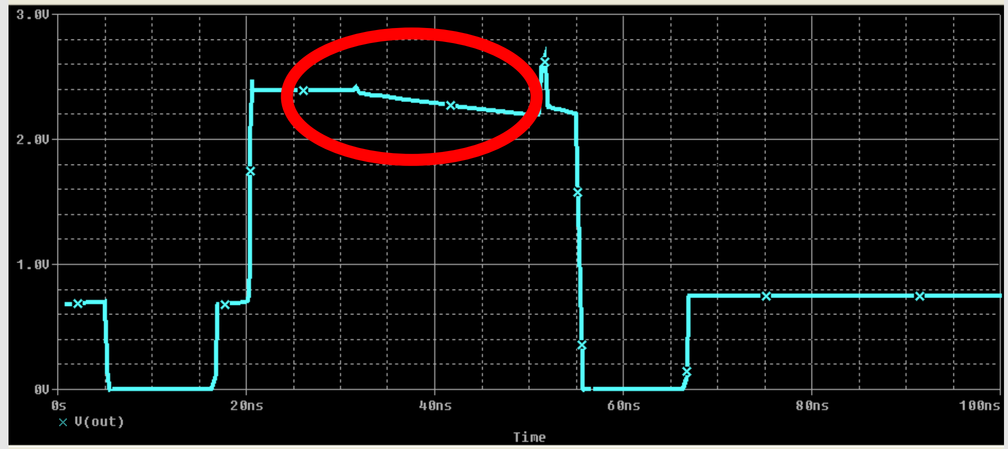

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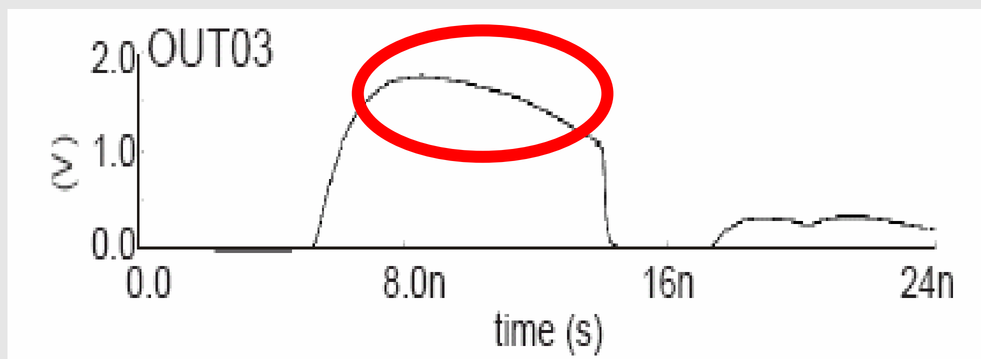

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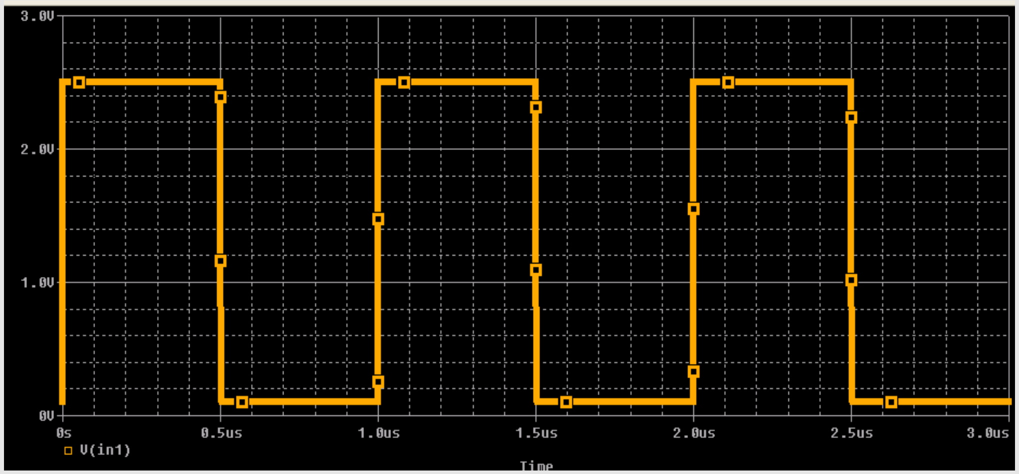
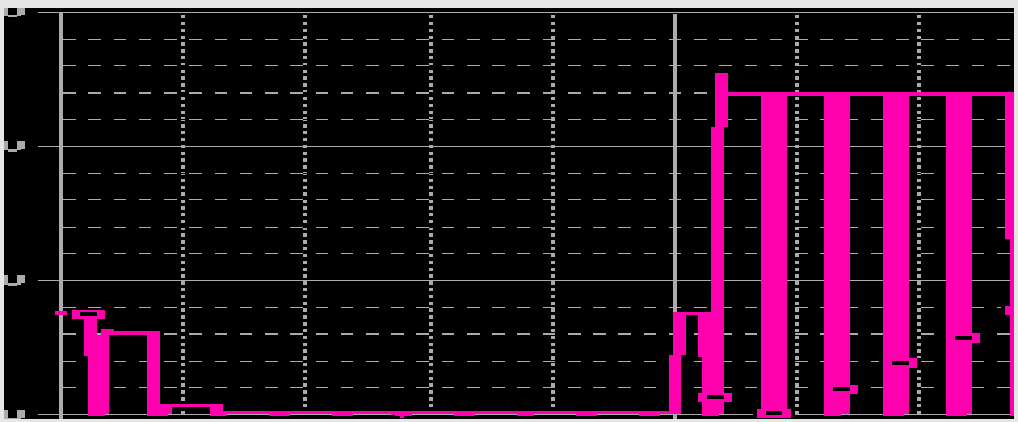
Results:
Full Circuit Simulation





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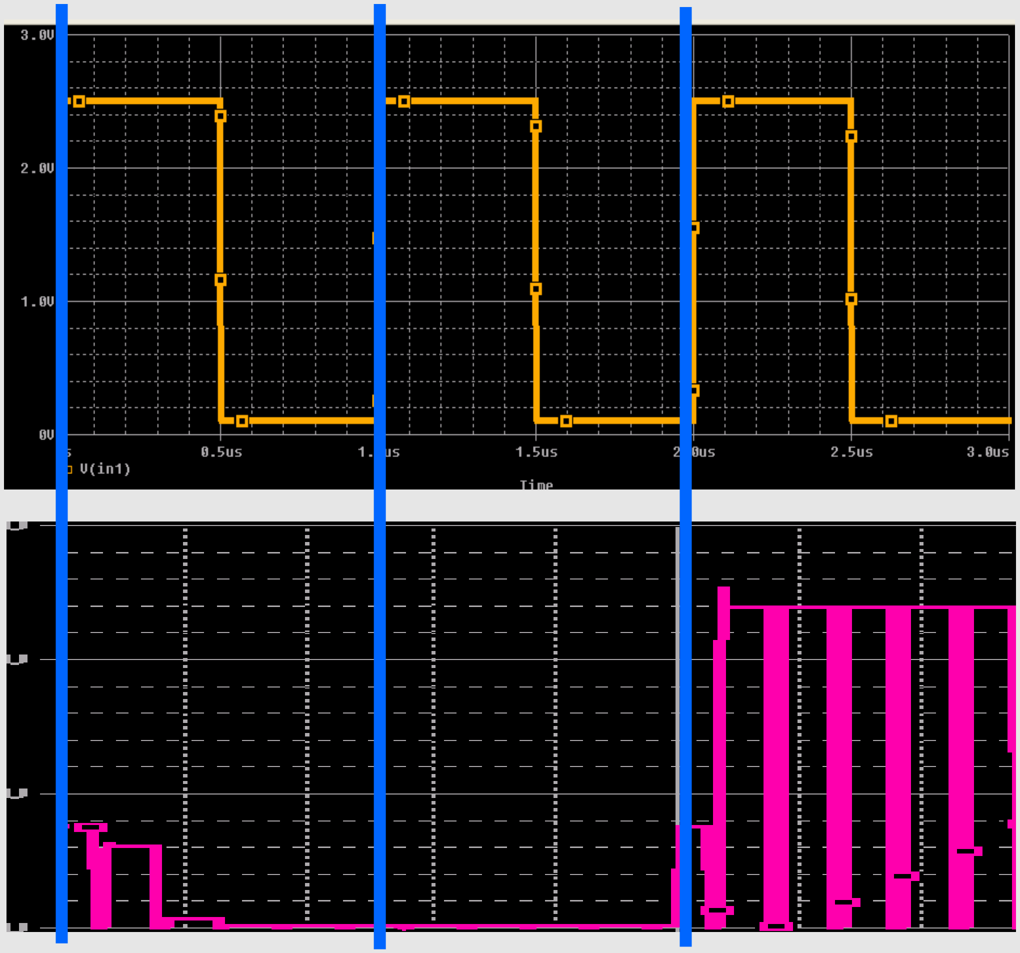
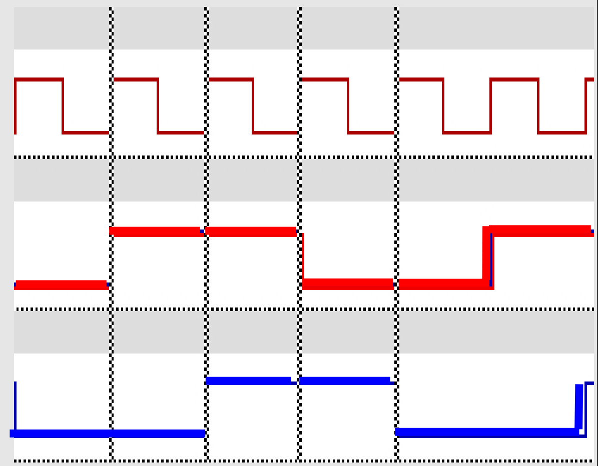


Logic Simulation



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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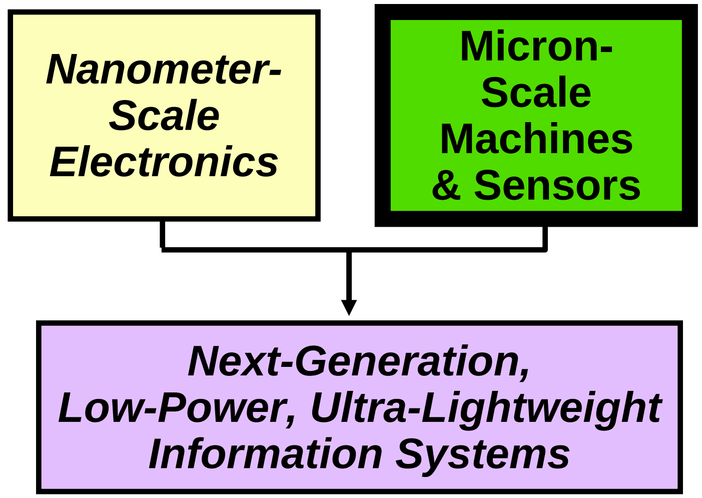
Initial Fabrication of the MITRE Millirobot

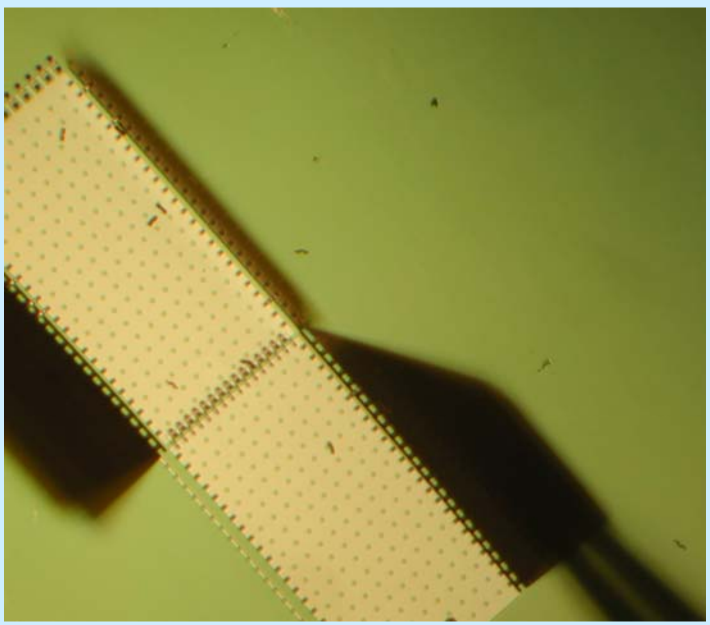
Rationale

Millirobot project explores the nature of future info. systems



Initial Fabrication of the MITRE Millirobot

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



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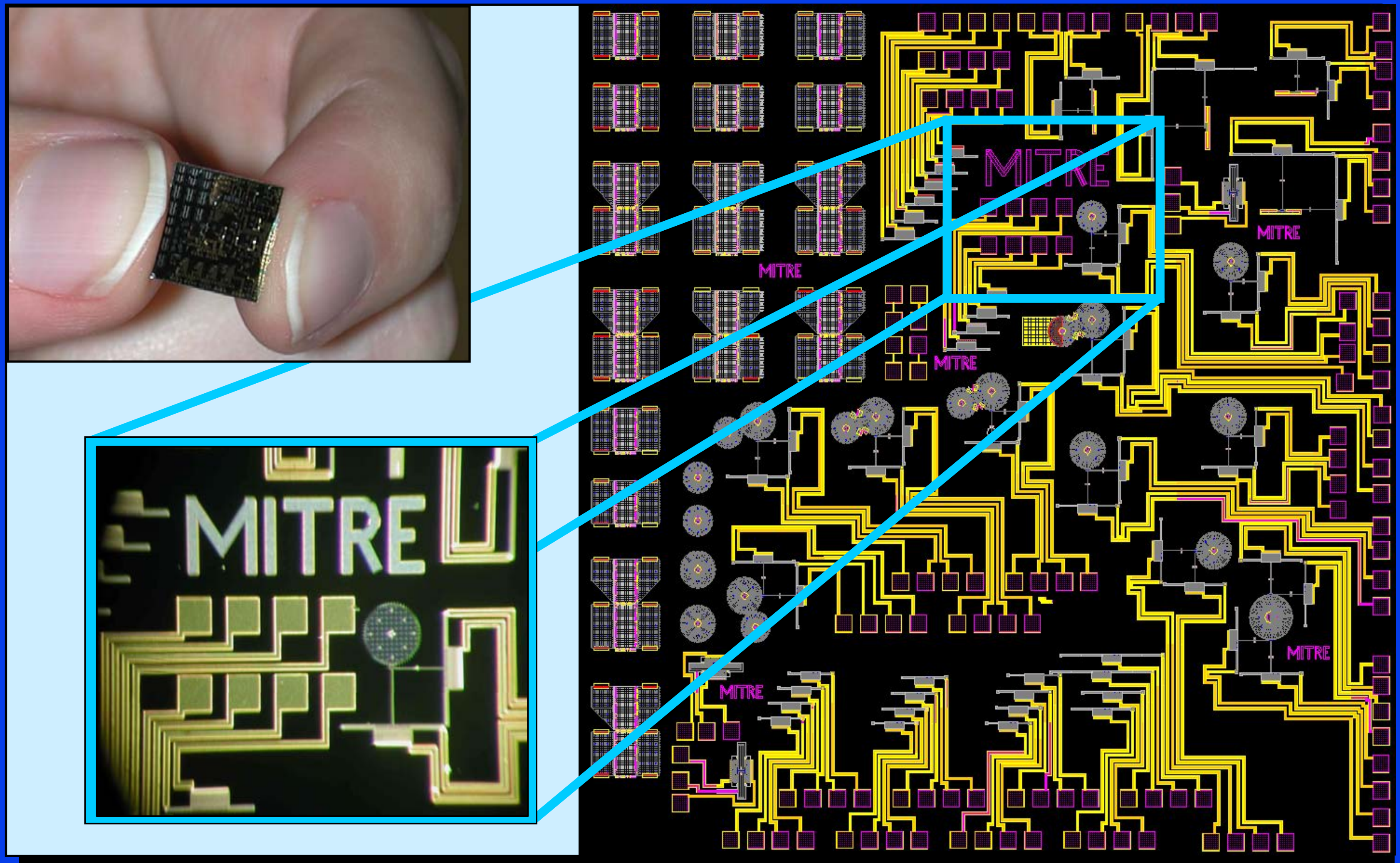

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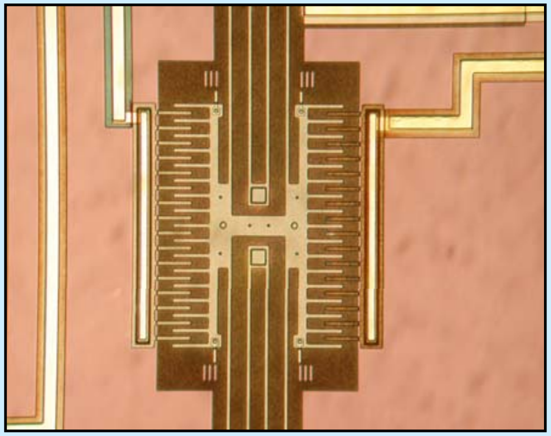
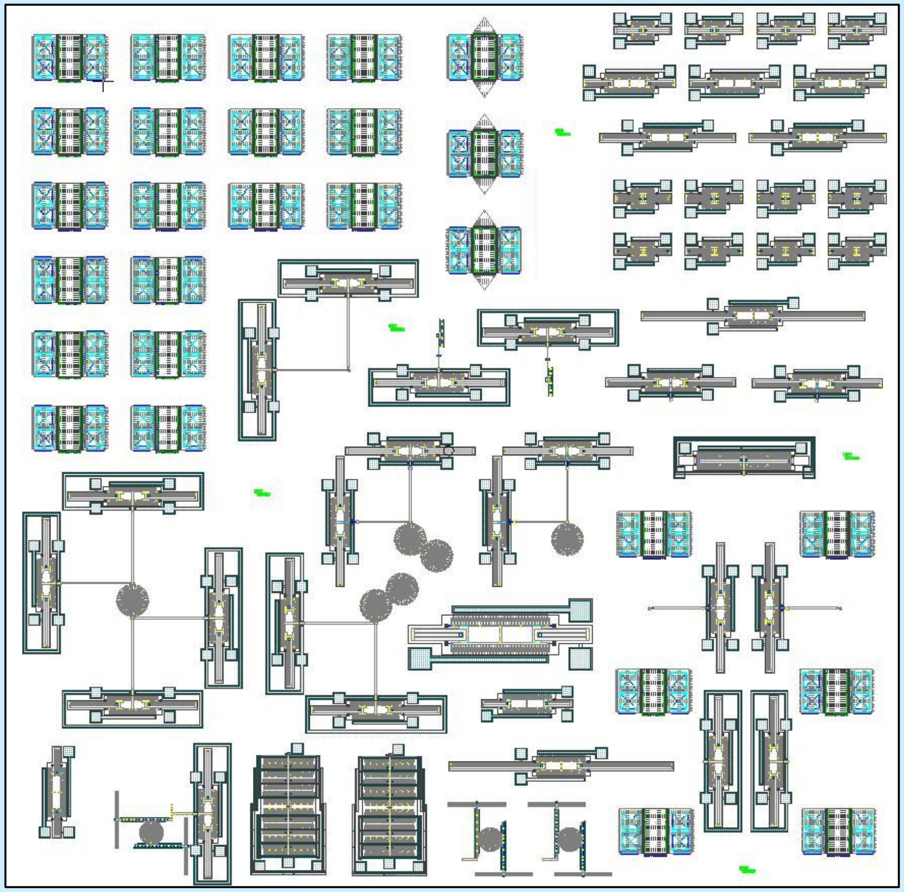
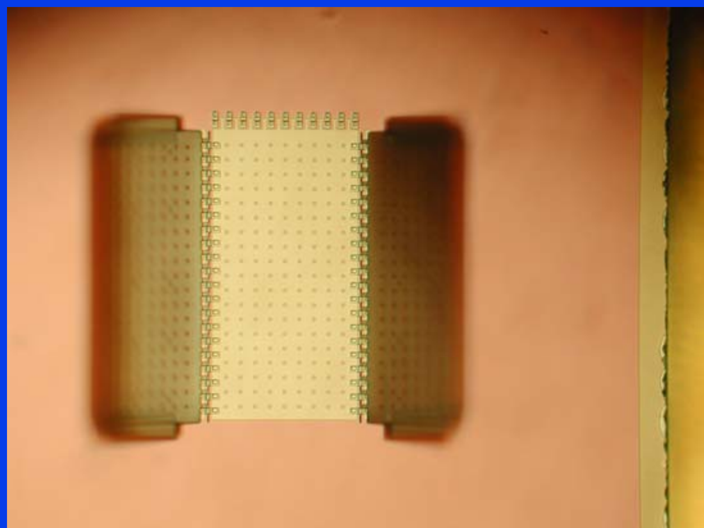
Fabrication and Testing

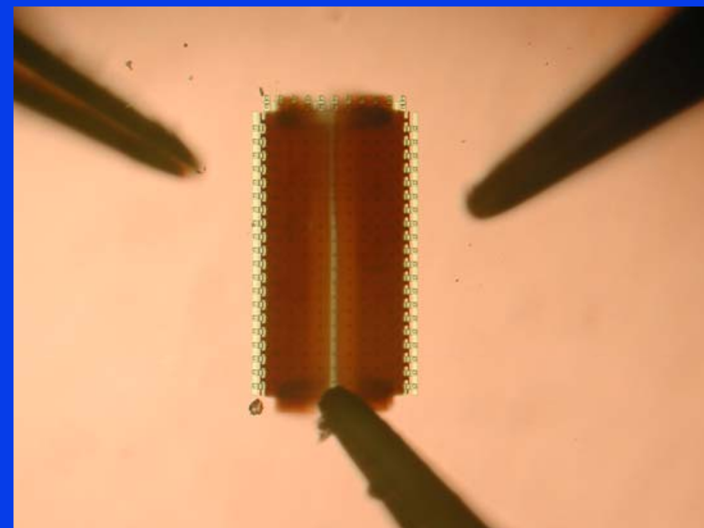
- Later design iterations built upon our first efforts
  - Refined and improved components
  - Designed new devices
  - Began combining and integrating previously fabricated devices

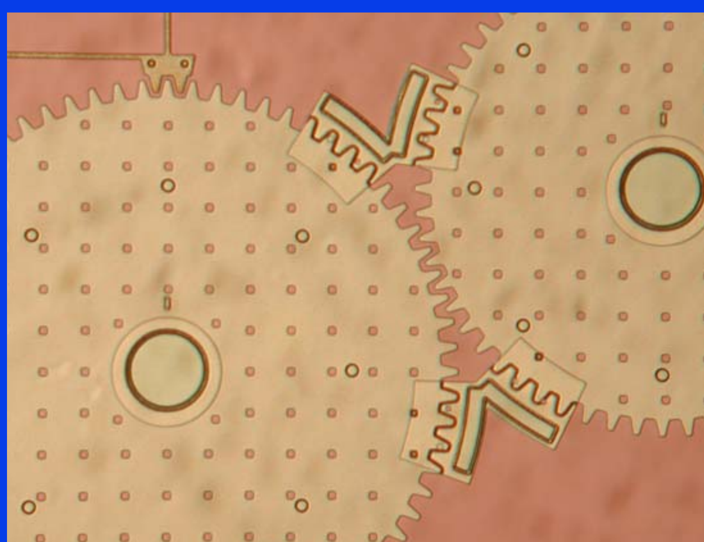


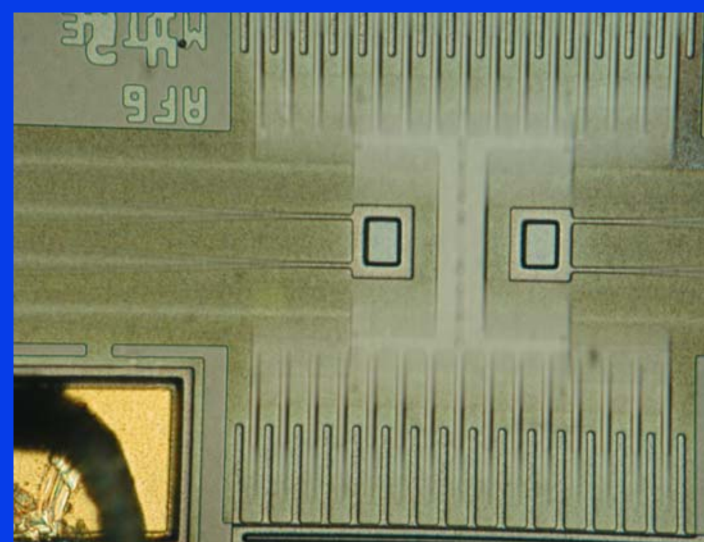


Selected Devices from Testing









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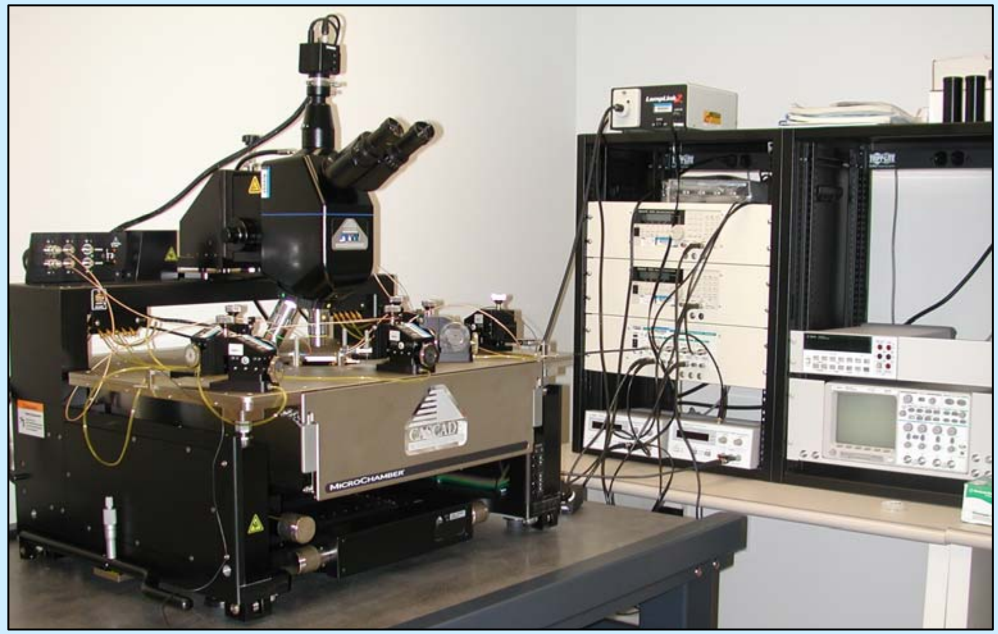
Fabrication and Testing

- 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

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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)

MITRE

Acknowledgements

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

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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

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