MULTICELLULAR MACHINES

A Bio-inspired approach to automated electromechanical design and fabrication

(How to rapidly design and build robots from many different modules)

Robert MacCurdy
Postdoctoral Associate, MIT/CSAIL
Research Vision:

• Automate the design and fabrication of customized robots

• Non-specialists specify desired behavior
  • robots “walk out of the printer”
Research Vision:

- Automate the design and fabrication of customized robots
- Democratize electromechanical engineering
  - make it accessible, fun!
Highlights of robots designed and fabricated by people

Current Robotic Design Paradigm

Robots are complex systems that require large human development efforts that are slow and costly!

- Expertise in many disciplines; specialized domain knowledge
- Sourcing: specialized materials; disparate suppliers; custom parts
- Fabrication: manual assembly, or high startup cost
- Arbitrary design space
Modular Robots

Refs (Top-Bot, L-R):
Multicellular Machines

- Composed of heterogeneous modules (cells)
- Cell placement, orientation impacts behavior
- Specific cells perform specific tasks (computation, actuation, sensing, structural)
- Cellular framework enables automated design & fabrication
Components required by robots

- Signals & sensing
- Low-level control
- High-level commands/behavior
- Structure/mechanisms
- Actuation
- Energy

Design & Fabrication Automation tools needed for each component!
Automation tools in Design and Fabrication
(common in *electrical* engineering)

- Performance checking (SPICE)
- Layout (auto-routers)
- Circuit synthesis (VHDL-synthesis)
- Fabrication (PCB fab, PCB assembly)

Equivalent tools needed for *Electromechanical systems* design and fabrication
Components required by robots (my to-do’s!)

• Signals & sensing

• Low-level control

• High-level commands/behavior

• Structure/mechanisms

• Actuation

• Energy

Develop Design & Fabrication Automation tools for each component
Components required by robots (my to-do’s!)

- Signals & sensing
- Low-level control
- High-level commands/behavior
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“Nervous System”

“Body”

Develop Design & Fabrication Automation tools for each component
### Multicellular Machines (selected contributions)

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<thead>
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<td>(Structure &amp; mechanisms)</td>
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<td>![Body Image]</td>
<td>![Nervous System Image]</td>
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#### Design Automation

- **Netlist**: (ButtonA, "T1"), (ButtonB, "T1")
- **Positions**: $|M| = 2 \times 1 \times 2 = 4$
- **Rotations**: $0 = \{R1, R2, R3, R4\}$
- **Uniqueness**: Crosses
- **Collision**: Crosses
- **Shorts**: Crosses
- **Connections**: Checkmark

#### Fabrication Automation

- [Image of fabricated multicellular machine]
Multicellular Machines (selected contributions)

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Netlist: (ButtonA, "T1"), (ButtonB, "T1")

- Positions: | = 2 x 1 x 2 = 4
- Rotations: O = [R1, R2, R3, R4]

- Uniqueness
- Collision
- Shorts
- Connections

![Image of Body and Nervous System](image-url)
How we (usually) build robots
What if building a robot could be as easy as pressing a button?
• Inkjet 3D printer: multiple materials deposited in one layer

• Photo-cured resins harden layer-by-layer
• Printable Hydraulics: introduce *non-curing* material

• Liquids are embedded in solid part

• No materials to purge; no holes to seal

• Print moving objects; *no assembly required*

---

Printable Hydraulics:
• Design actuated mechanical parts in a **voxelized space**
• Modular design: print materials = module types

• Bellows transducer building block: force ↔ pressure

• Sliding seals = bad

• Flexure allows motion; strain < 20%

• More folds = more displacement

• Larger diameter = more force
• 12 bellows + crankshaft + motor = simple walker!
• Tripod gait
• Quadrature drive via offset crank
Printing a gear pump using rigid plastic and liquid

3-hour print job
“Printable Hydraulics”

Contributions

• First 3D printed hydraulic system

• Automates fabrication of moving assemblies (robots)

• First step to robot “walking out of the printer!”

Multicellular Machines *(selected contributions)*

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<td><img src="image.png" alt="Netlist" /></td>
<td>![Image of a nervous system]</td>
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Netlist: *(ButtonA, "T1"), (ButtonB, "T1")*

- **Positions**: 2 x 1 x 2 = 4
- **Rotations**: 0 = {R1, R2, R3, R4}
  - R1: <!-- Image of a connection diagram -->
  - R2: <!-- Image of a connection diagram -->
  - R3: <!-- Image of a connection diagram -->
  - R4: <!-- Image of a connection diagram -->

- **Uniqueness**: x
- **Collision**: x
- **Shorts**: x
- **Connections**: ✔
Printable Viscoelastics

- Problem:
  - Given a desired (complex) elastic modulus and a bounding surface, find a satisfying placement (position and type) of modules

\[ E^*(\omega, P_i) = E'|_{1Hz} \ast (\omega^{n1} + i \ast \tan(\delta)|_{1Hz\omega^{n2}} \]
Printable Viscoelastics

• Solution:
  – Develop model relating liquid fraction to $E^*$
  – Algorithm uses model to populate module occupancy matrix
  – Voxelized design converted to printable files and fabricated using “Printed Hydraulics” approach
Impact Tests

- Measure velocity change & transmitted force
Improving a soft 3D-printed jumping robot

“Printable Viscoelastics”

Contributions

• 3D printed components with prescribed viscoelastic properties

• Elasticity & damping “programmed” by design file & can vary continuously throughout part

\[
E^*(\omega, P_l) = E'_1 \omega^n (\omega^n + i \tan(\delta)) \omega^n
\]

MacCurdy, Lipton, Li, and Rus. Printable Programmable Viscoelastic Materials for Robots. *IROS 2016*
**Multicellular Machines** *(selected contributions)*

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Netlist: *(ButtonA, "T1"), (ButtonB, "T1")*

- **Positions:** 2 x 1 x 2 = 4
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- **Uniqueness:** ✗
- **Collision:** ✗
- **Shorts:** ✗
- **Connections:** ✔
Limitations in Printed Electronics

• 2 key challenges:
  – Printing conductors;   Printing semiconductors

• Best printed conductors:
  – Research: nearly same conductivity as bulk, but expensive special processing req’d
  – Commercial: ~30x more resistive than bulk

• Best printed semiconductors:
  – Electron mobility: 0.85 vs 1450 cm²/Vs; Hole mobility: 23.7 vs 450 cm²/Vs
  – Feature size ~ 1-5 micron (difficult to achieve in low-cost printer)
    ▪ Low drain current (mobility)
    ▪ Low operating frequency (mobility & geometry)

• **Embed** discrete, interconnected cells for **electrical functionality**

• Circumvent material compatibility, process compatibility issues

• Leverages the best of high-volume semiconductor fab and short-lead 3D printing

• Could be commercialized rapidly
• “Digital Material”
• Self-alignment; allows assembly with low-precision machine
• Accuracy of overall assembly exceeds precision of assembler\(^1\)
  – 1m x 1m assembly will have ~ 80um of error

\[
\Delta = \varepsilon N^{0.1}
\]

“Fabricating circuits with Digital Materials”

Contribution:

• High-performance mixed-signal circuits via additive manufacturing


• MacCurdy, R. & Lipson, H. “Hybrid Printing: Modular 3D Printing of Integrated Electromechanical Systems” (*submitted*)

# Multicellular Machines (selected contributions)

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- **Design Automation**
  - **Body**: (Structure & mechanisms)
  - **Nervous System**: (Signals & sensing)

- **Fabrication Automation**
  - Netlist: (ButtonA, "T1"), (ButtonB, "T1")
  - Positions: \( A = 2 \times 1 \times 2 = 4 \)
  - Rotations: \( O = \{ R1, R2, R3, R4 \} \)
  - Checking:
    - Uniqueness: ✗
    - Collision: ✗
    - Shorts: ✗
    - Connections: ✓
Designing with a cellular framework presents its own challenges:

• Large numbers of modules (cells) – potentially Billions
• Individual elements have limited functionality
• Design approach differs from existing methods (no cellular CAD package - yet)
• Implementation strategies differ from existing methods – new intuition must be developed

Evolutionary algorithms inspired by biological development provide one possible solution
Morphogenic gradients play a key role in determining cell destiny during development.

Bicoid (Bcd) is the primary morphogenic determinant of patterning along the anterior-posterior axis in Drosophila ("Hox" genes)

CPPN algorithm is readily applied to 3D cell-based structures...

presence? material

voxel at (x,y,z)

... with interesting results

- First Prize: AAAI Video Competition, 2013
- Winner: Virtual Creatures Competition, GECCO 2014
“Evolving Body Plans”

Contribution: method to synthesize modular robot bodies from heterogeneous parts

Spec: “run as fast as possible”

- First Prize: AAAI Video Competition, 2013
- Winner: Virtual Creatures Competition, GECCO 2014
- Frequently compared to Karl Sims’ pioneering work
Components required by robots (future work)

- Signals & sensing
- High-level commands/behavior
- Low-level control
- Structure/mechanisms
- Actuation
- Energy

“Body”

“Nervous System”
Automated Biological & Ecological Sensing

- **Automate** the acquisition of ecological data to inform science and conservation
- Implement solutions that allow human efforts to **scale**
Automated Biological & Ecological Sensing

• Automate the acquisition of ecological data to inform science and conservation

• Implement solutions that allow human efforts to scale
Localization via existing tags

- Radio tracking of wildlife is a widely used technique, *but*...
  - Labor intensive
  - Few simultaneous tags
  - Only real-time if people can be out gathering data all the time
  - Short transmitter life: _mass_
Automatic Radio Tracking

• System is like “GPS in reverse”
• Transmitter on animal sends pseudo-noise sequence
• Receivers at fixed locations run matched-filter detectors and record time of Rx event

\[ Xcorr(l) = \text{IFFT}\{\text{Sig}(f)\text{Prn}(f)\} \]

• Position computed via Time of Arrival

\[ r^k = \left( t^{(k)}_{Rx(R)} - t^{(k)}_{Tx(R)} \right) c = \| P^{(k)} - x \| \]

Automatic Wildlife Radio Tracking

Current & Future Work

- Automatic Tracking & Telemetry Systems for Large-Scale Science ("Big data for small organisms")
Multicellular Machines: 
*How to rapidly design and build robots from many different modules*

WE WANT YOUR FEEDBACK

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