MULTICELLULAR MACHINES

A Bio-inspired approach to automated electromechanical design and fabrication

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

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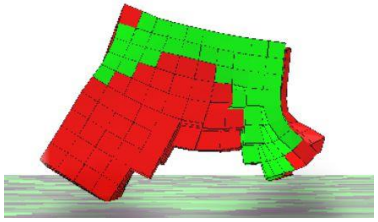
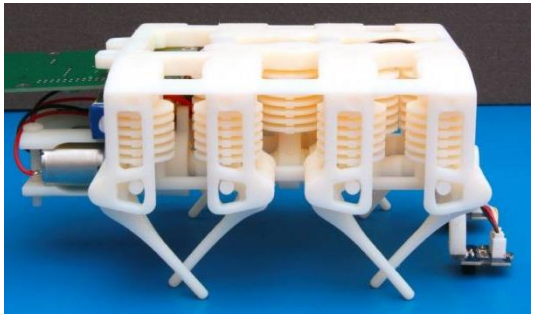
Research Vision:

- Automate the design and fabrication of customized robots
- Non-specialists specify desired behavior
  - robots “walk out of the printer”

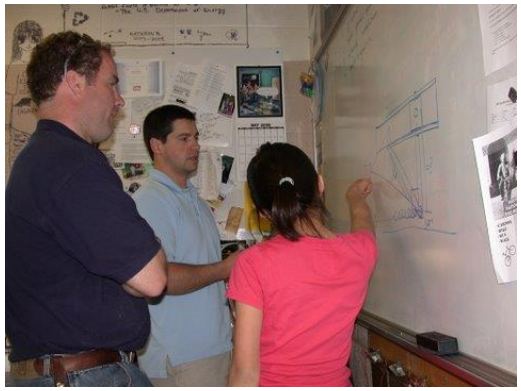
Spec: “run as fast as possible”



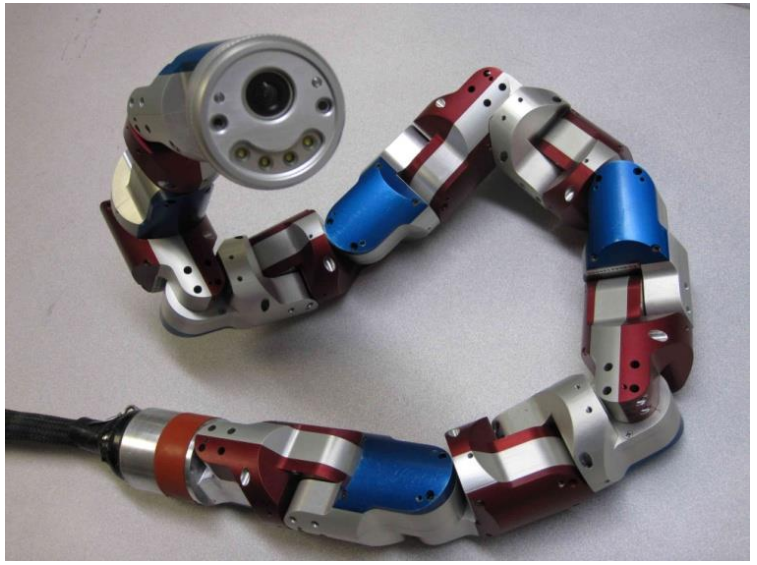


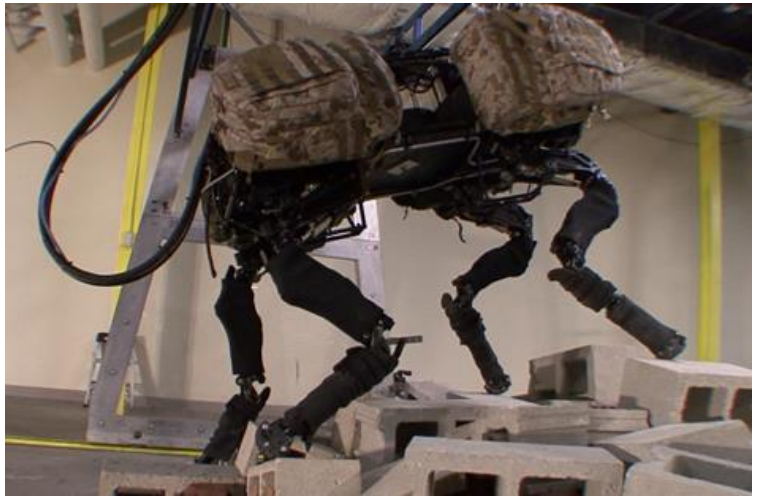
Research Vision:

- Automate the design and fabrication of customized robots
- Democratize electromechanical engineering
  - make it accessible, fun!



Highlights of robots designed and fabricated by people





•Raibert, Marc, et al. "**Bigdog**, the rough-terrain quadruped robot." *Proceedings of the 17th World Congress*. 2008.

•Raibert, Marc. "Dynamic legged robots for rough terrain." Humanoid Robots (Humanoids), *2010 10th IEEE-RAS International Conference on*. IEEE, 2010.

•Wright, Cornell, et al. "Design and architecture of the unified modular snake robot." *Robotics and Automation (ICRA), 2012 IEEE International Conference on. IEEE*, 2012.

•Yamauchi, Brian M. "**PackBot**: a versatile platform for military robotics." *Defense and Security. International Society for Optics and Photonics*, 2004.

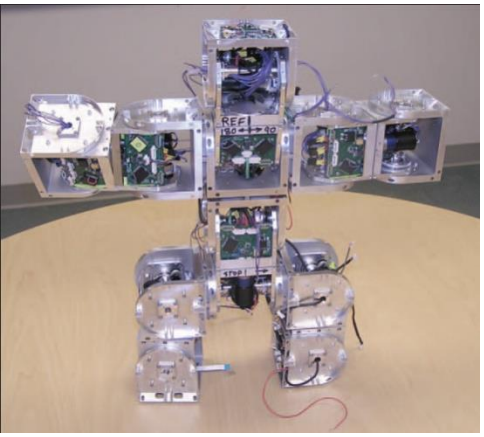
•Ulbrich, Peter, et al. "**I4Copter**: An adaptable and modular quadrotor platform." *Proceedings of the 2011 ACM Symposium on Applied Computing*.

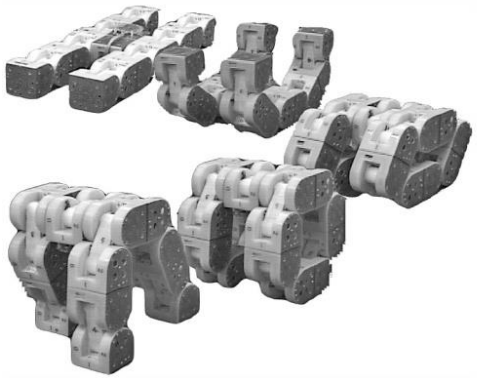
Current Robotic Design Paradigm

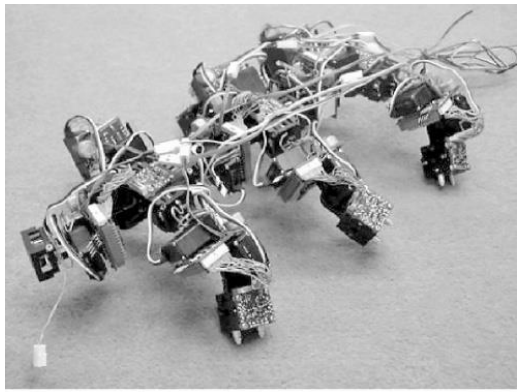
Robots are complex systems that require large human development efforts that are slow and costly!

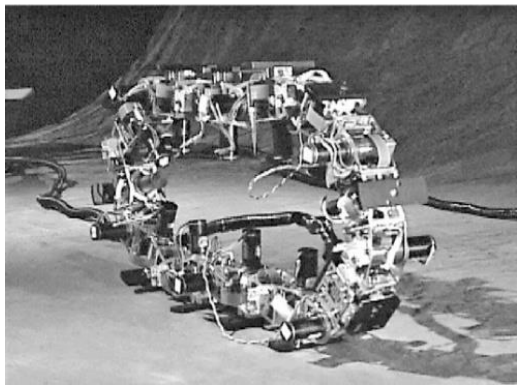
- Expertise in many disciplines; specialized domain knowledge
- Sourcing: specialized materials; disparate suppliers; custom parts
- Fabrication: manual assembly, or high startup cost
- Arbitrary design space

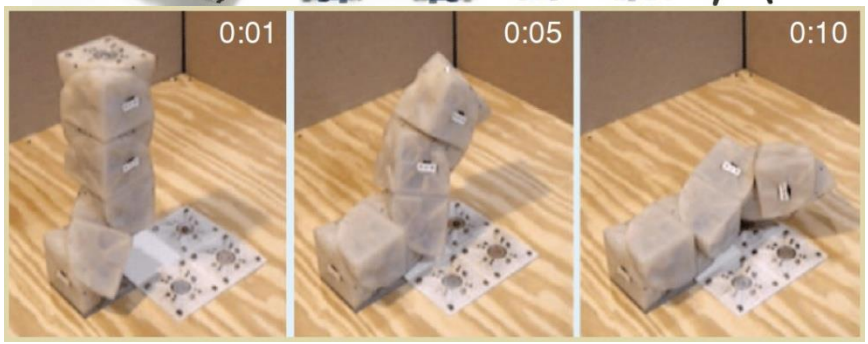
Modular Robots











Refs (Top-Bot, L-R):

•Salemi, Behnam, Mark Moll, and Wei-Min Shen. "SUPERBOT: A deployable, multi-functional, and modular self-reconfigurable robotic system." *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*. IEEE, 2006.

•Murata, S.; Yoshida, E.; Kamimura, A.; Kurokawa, H.; Tomita, K. & Kokaji, S. "M-TRAN: self-reconfigurable modular robotic system" Mechatronics, IEEE/ASME Transactions on, 2002, 7, 431-441

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•Jorgensen, M. W., Ostergaard, E. H., & Lund, H. H. (2004, September). Modular ATRON: Modules for a self-reconfigurable robot. In *Intelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on* (Vol. 2, pp. 2068-2073). IEEE.

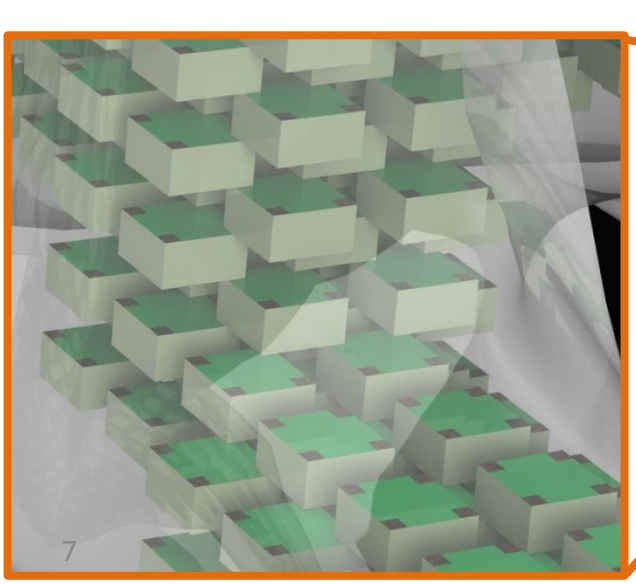
•Yim, Mark, David G. Duff, and Kimon D. Roufas. "PolyBot: a modular reconfigurable robot." *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on*. Vol. 1. IEEE, 2000.

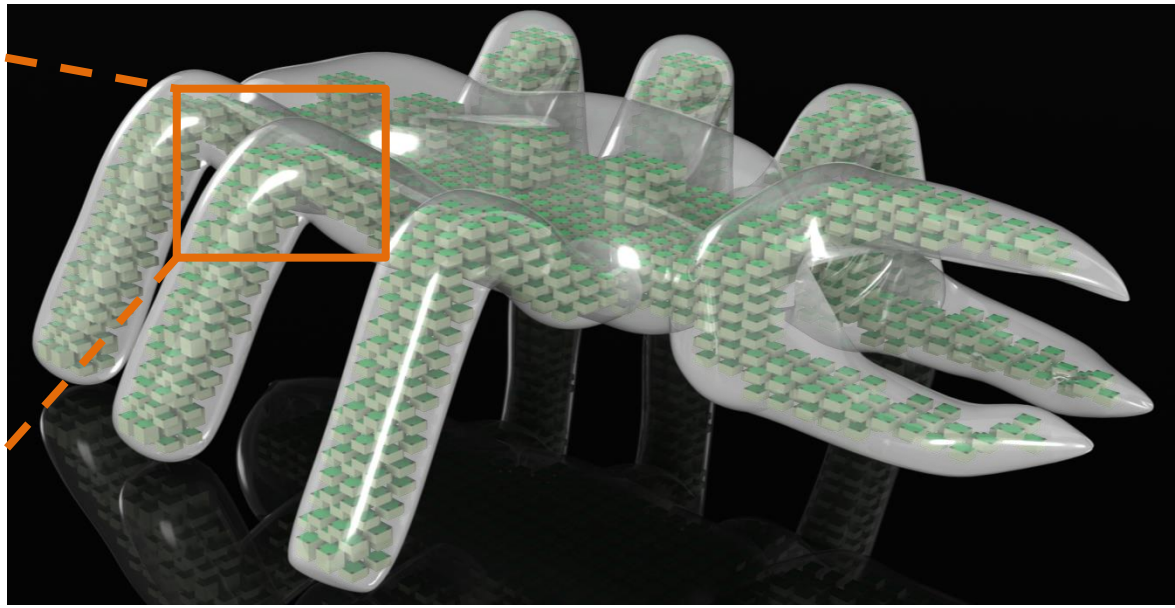
•Zykov, V.; Phelps, W.; Lassabe, N. & Lipson, H. "Molecubes extended: Diversifying capabilities of open-source modular robotics" IROS-2008 Self-Reconfigurable Robotics Workshop, 2008

•Zykov, V.; Mytilinaios, E.; Adams, B. & Lipson, H."Self-reproducing machines" Nature, 2005, 435, 163-164

Multicellular Machines

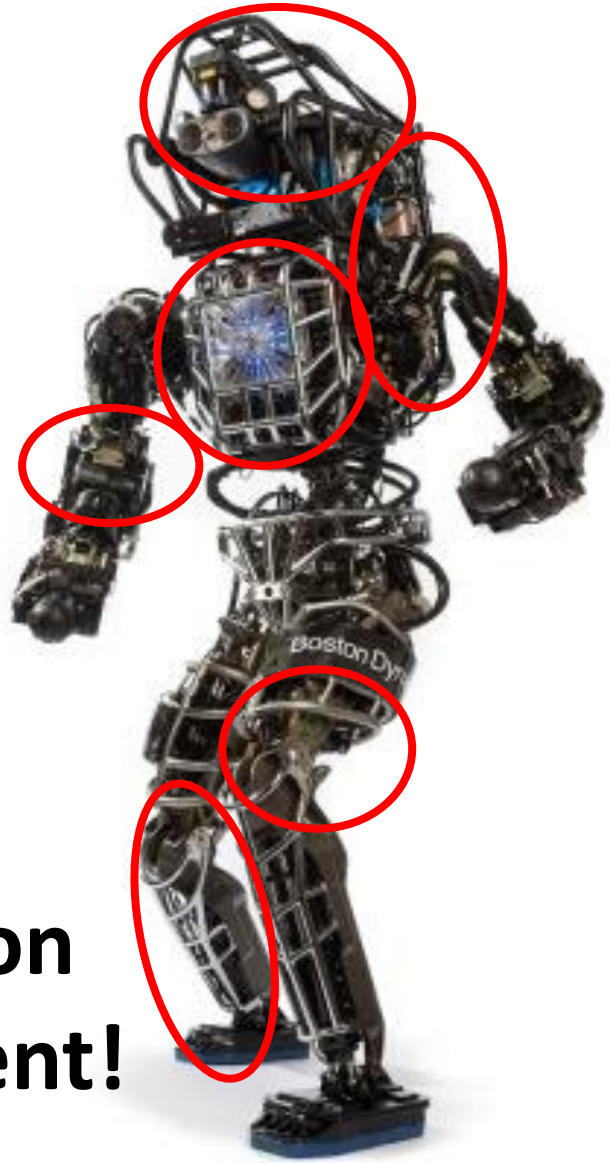
- Composed of heterogeneous modules (cells)
- Cell placement, orientation impacts behavior
- Specific cells perform specific tasks (computation, actuation, sensing, structural)
- Cellular framework enables automated design & fabrication





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

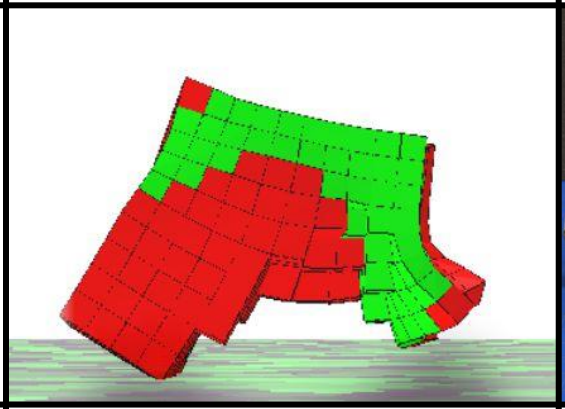
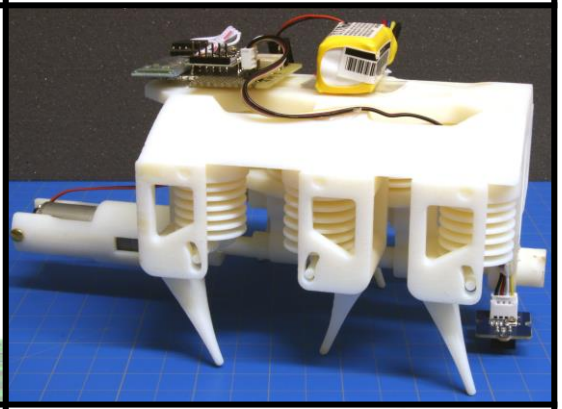
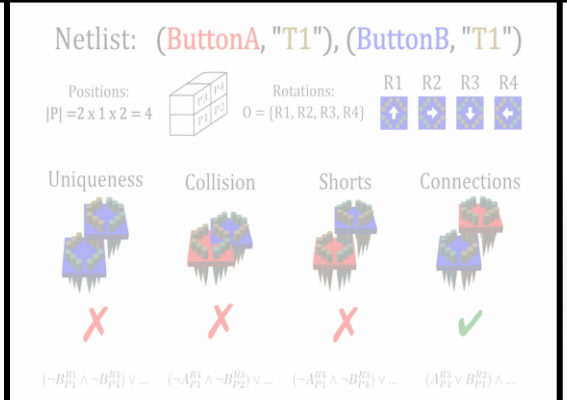
"Nervous System"

- **Structure/mechanisms**
- Actuation
- Energy

"Body"

Develop Design & Fabrication Automation tools for each component

Multicellular Machines (selected contributions)

	Design Automation	Fabrication Automation
Body (Structure & mechanisms)		
Nervous System (Signals & sensing)		

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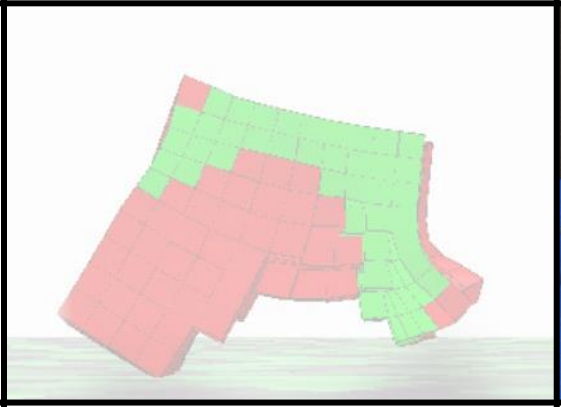
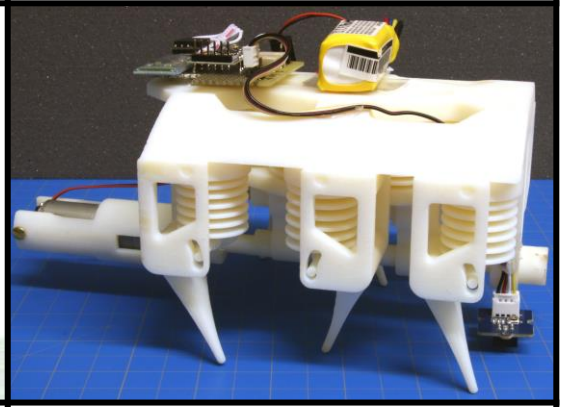
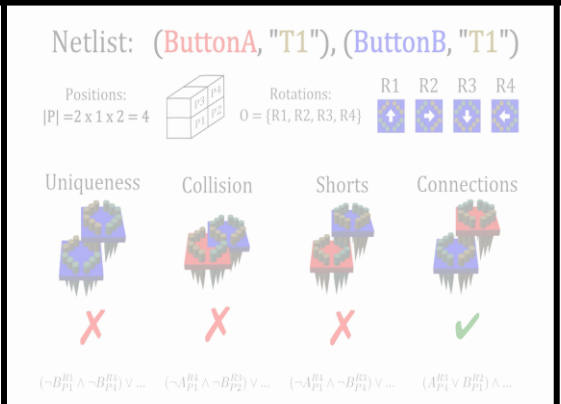
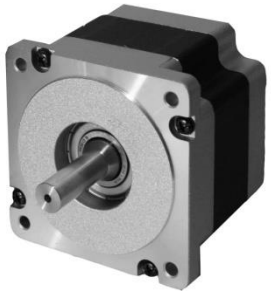
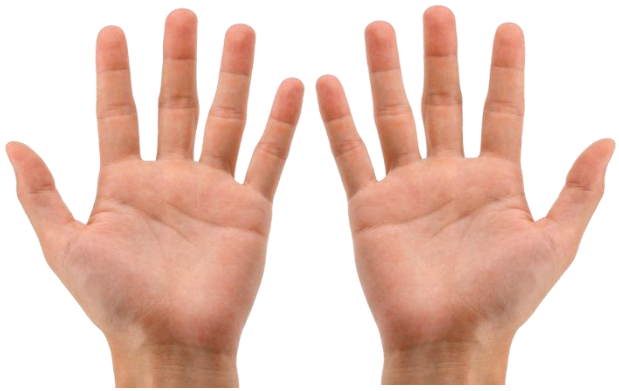
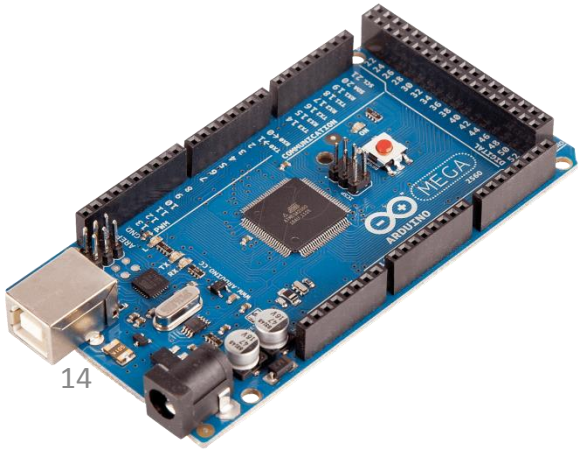
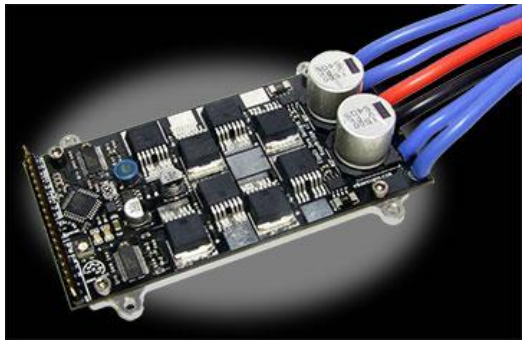
Body (Structure & mechanisms)		
Nervous System (Signals & sensing)		

How we (usually) build robots

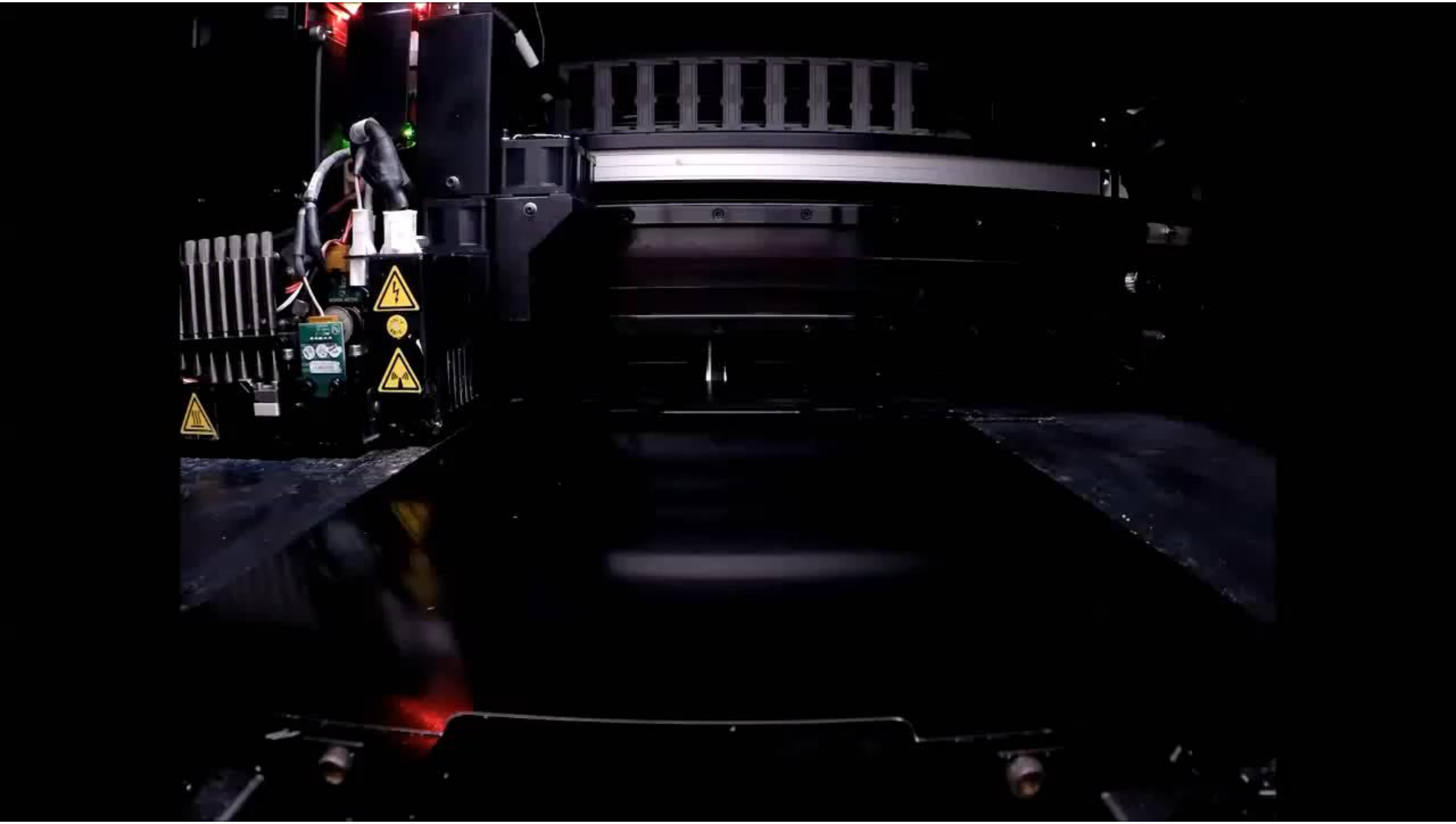




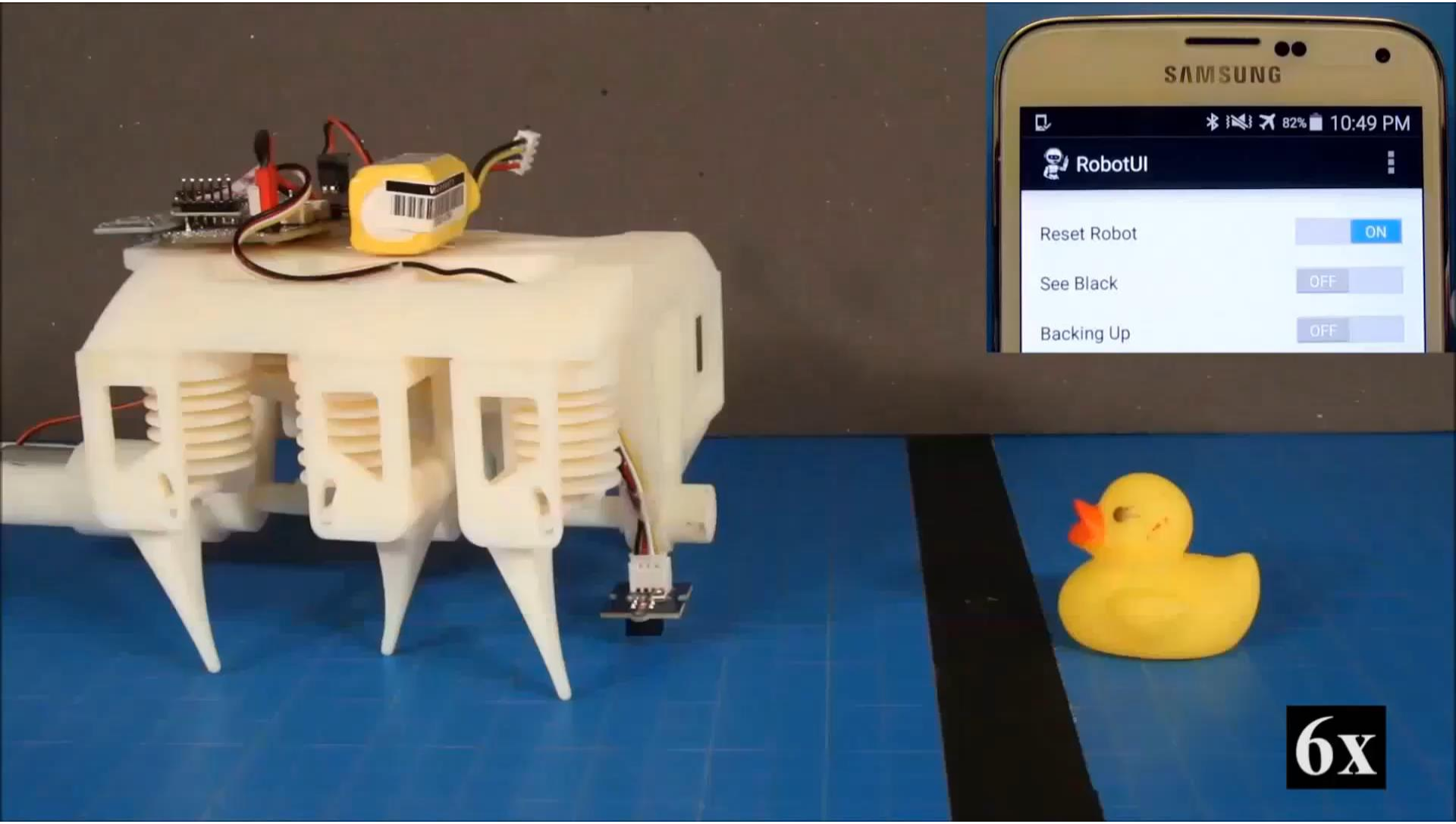




What if building a robot could be as easy as pressing a button?

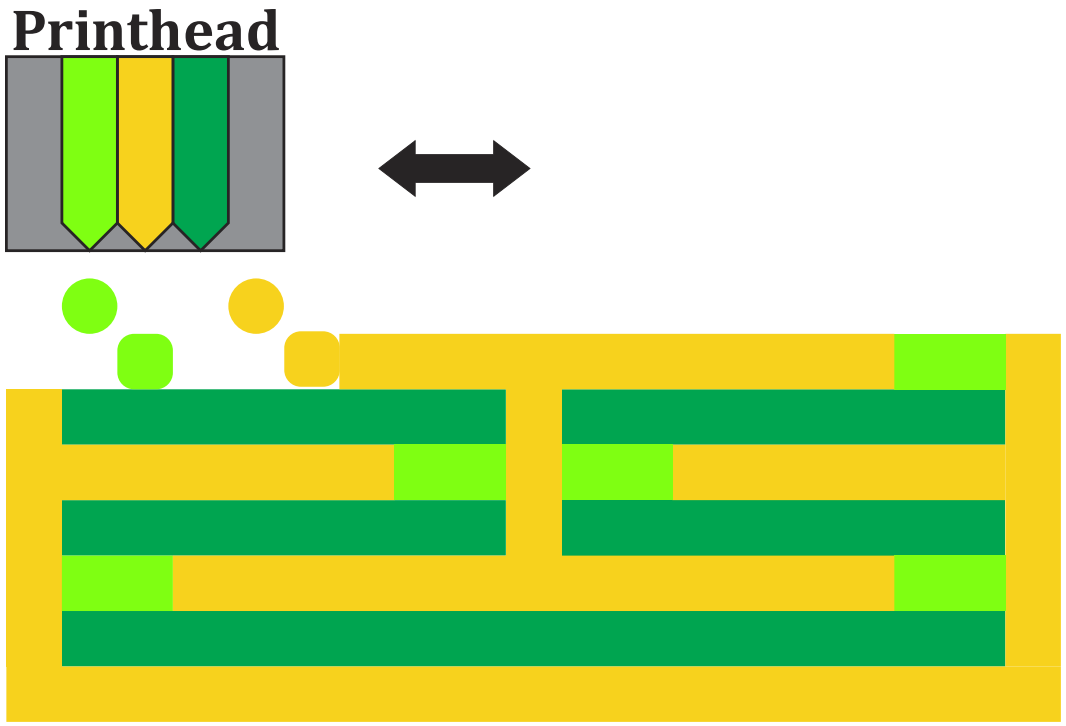


MacCurdy, Katzschmann, Kim, and Rus. Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids and Liquids. *ICRA 2016*

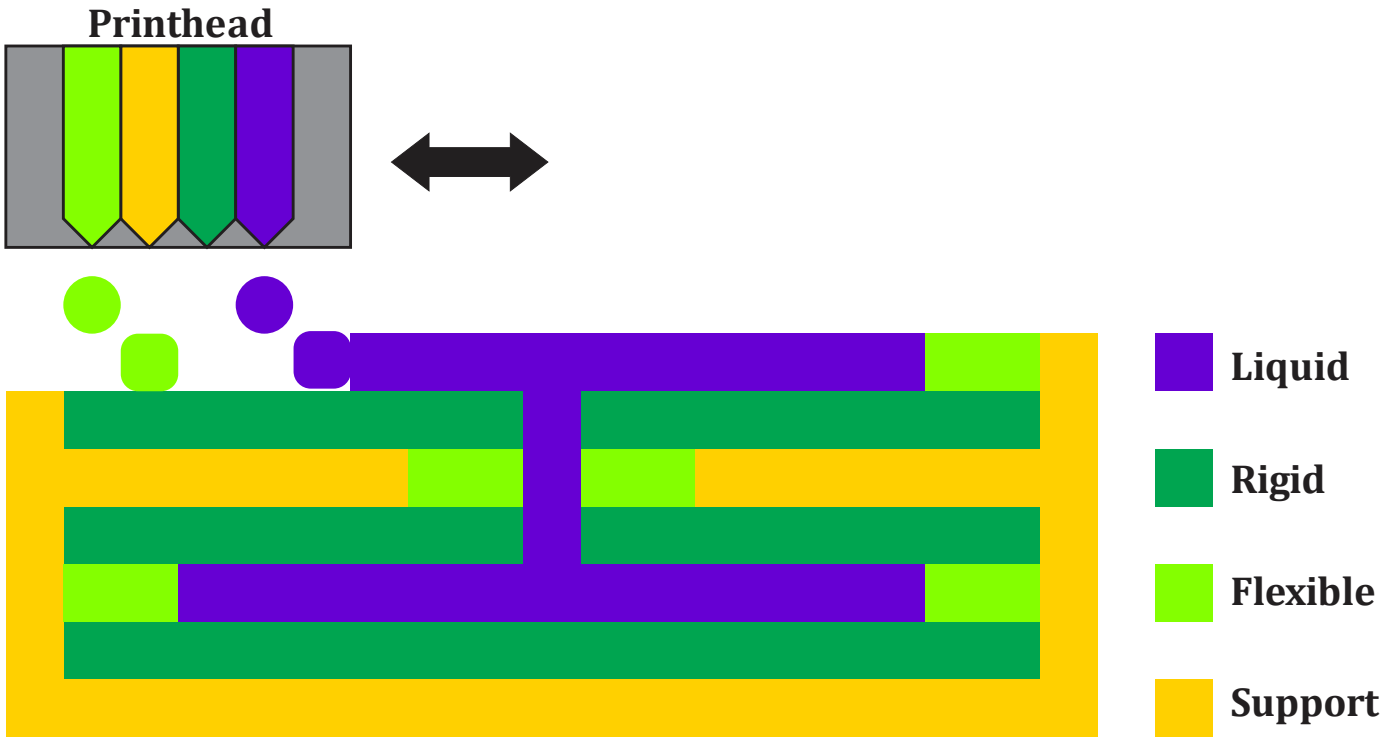


MacCurdy, Katzschmann, Kim, and Rus. Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids and Liquids. *ICRA 2016*

- Inkjet 3D printer: multiple materials deposited in one layer
- Photo-cured resins harden layer-by-layer



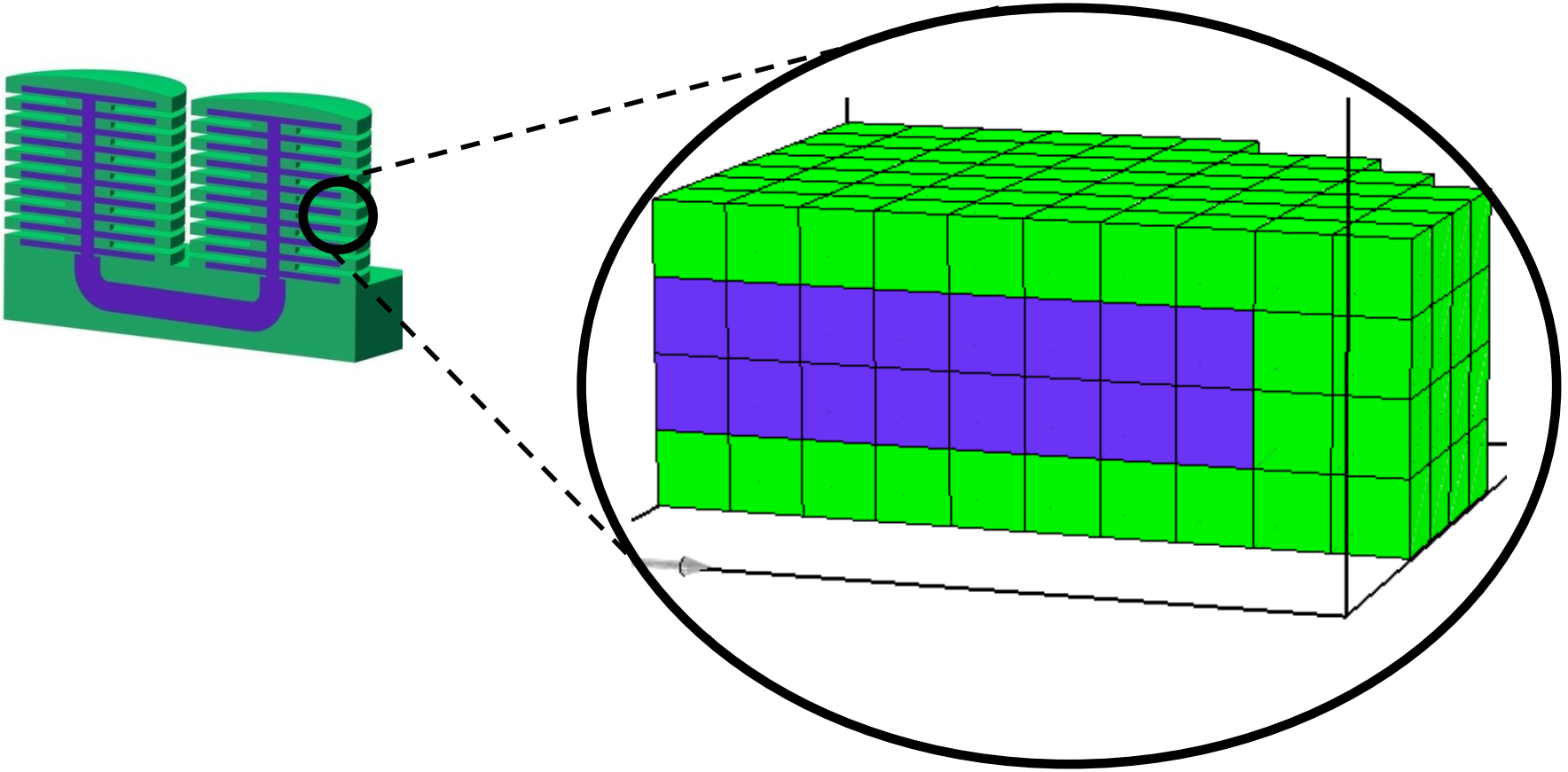
- Printable Hydraulics: introduce *non-curing* material
- Liquids are embedded in solid part
- No materials to purge; no holes to seal
- Print moving objects; no assembly required



MacCurdy, Katzschmann, Kim, and Rus. Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids and Liquids. *ICRA 2016*

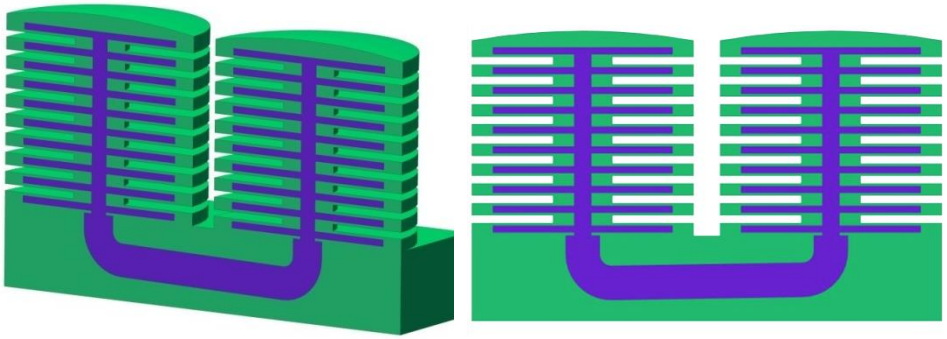
Printable Hydraulics:

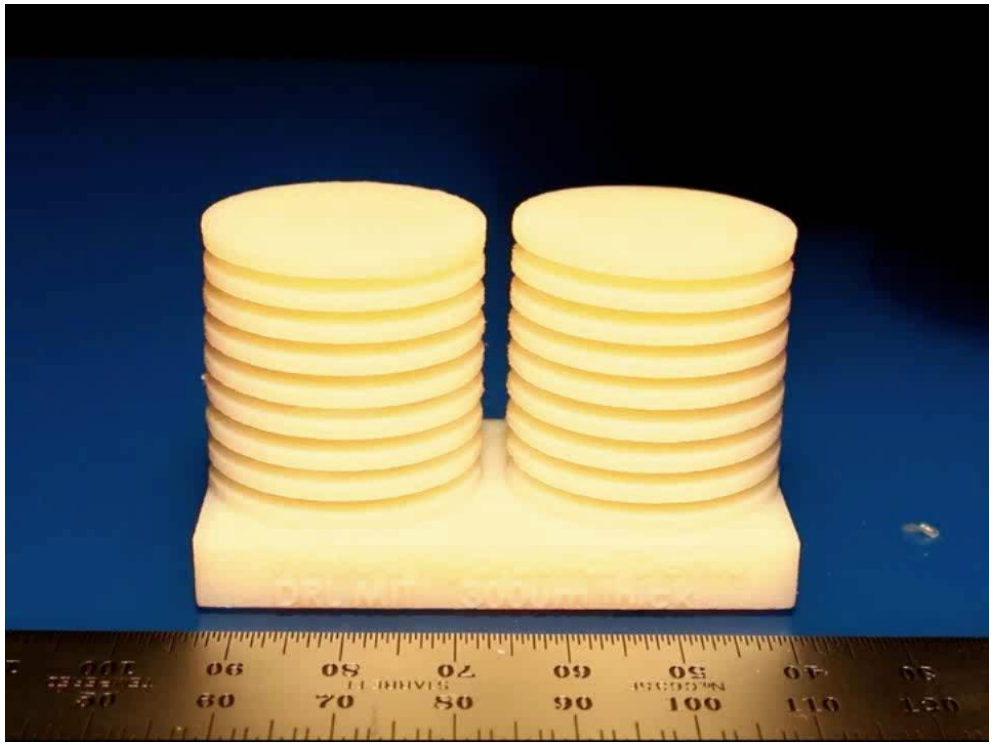
- Design actuated mechanical parts in a voxelized space
- Modular design: print materials = module types



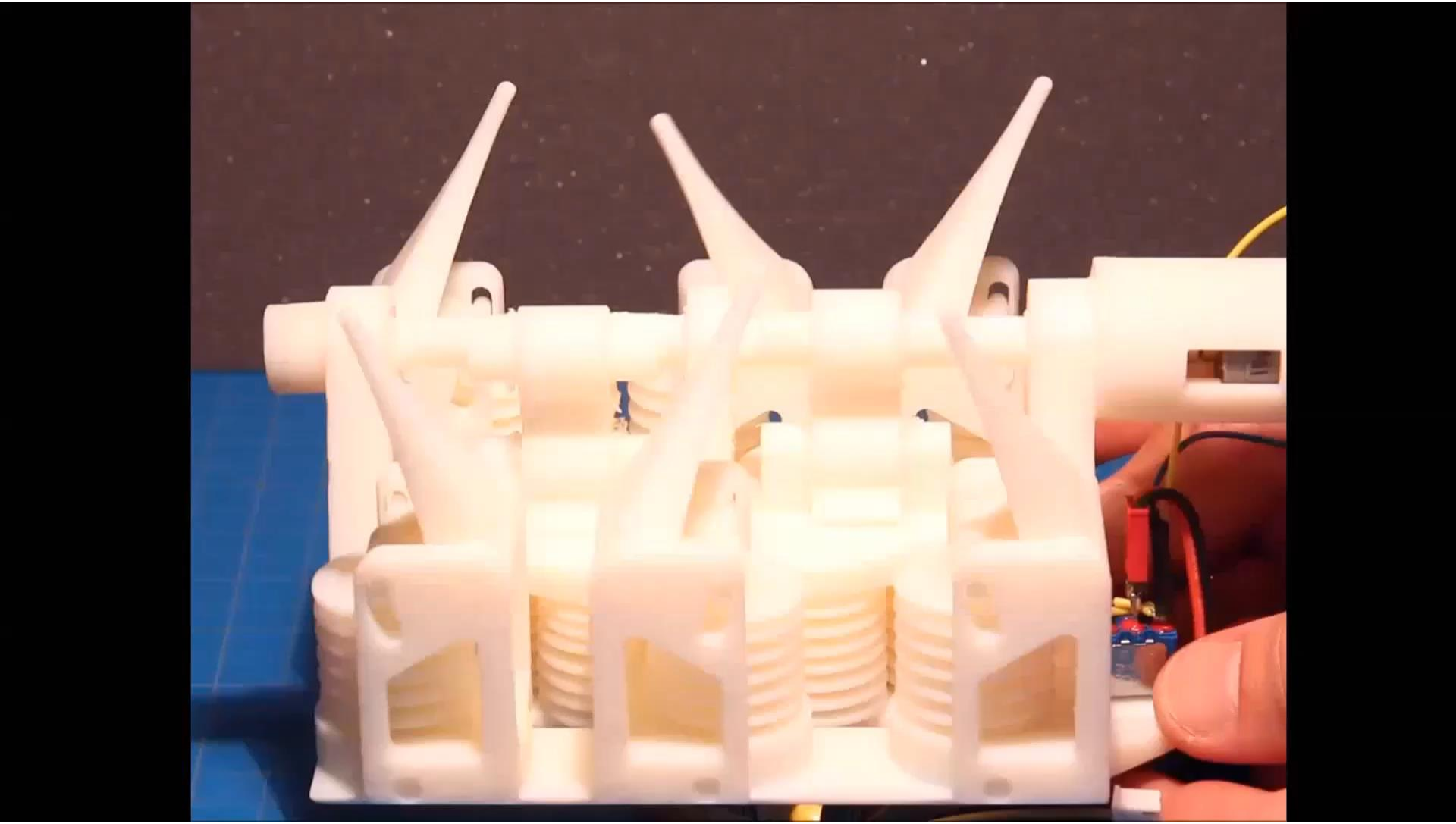
MacCurdy, Katzschmann, Kim, and Rus. Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids and Liquids. *ICRA 2016*

- Bellows transducer building block: force ⇔ pressure
- Sliding seals = bad
- Flexure allows motion; strain < 20%
- More folds = more displacement
- Larger diameter = more force

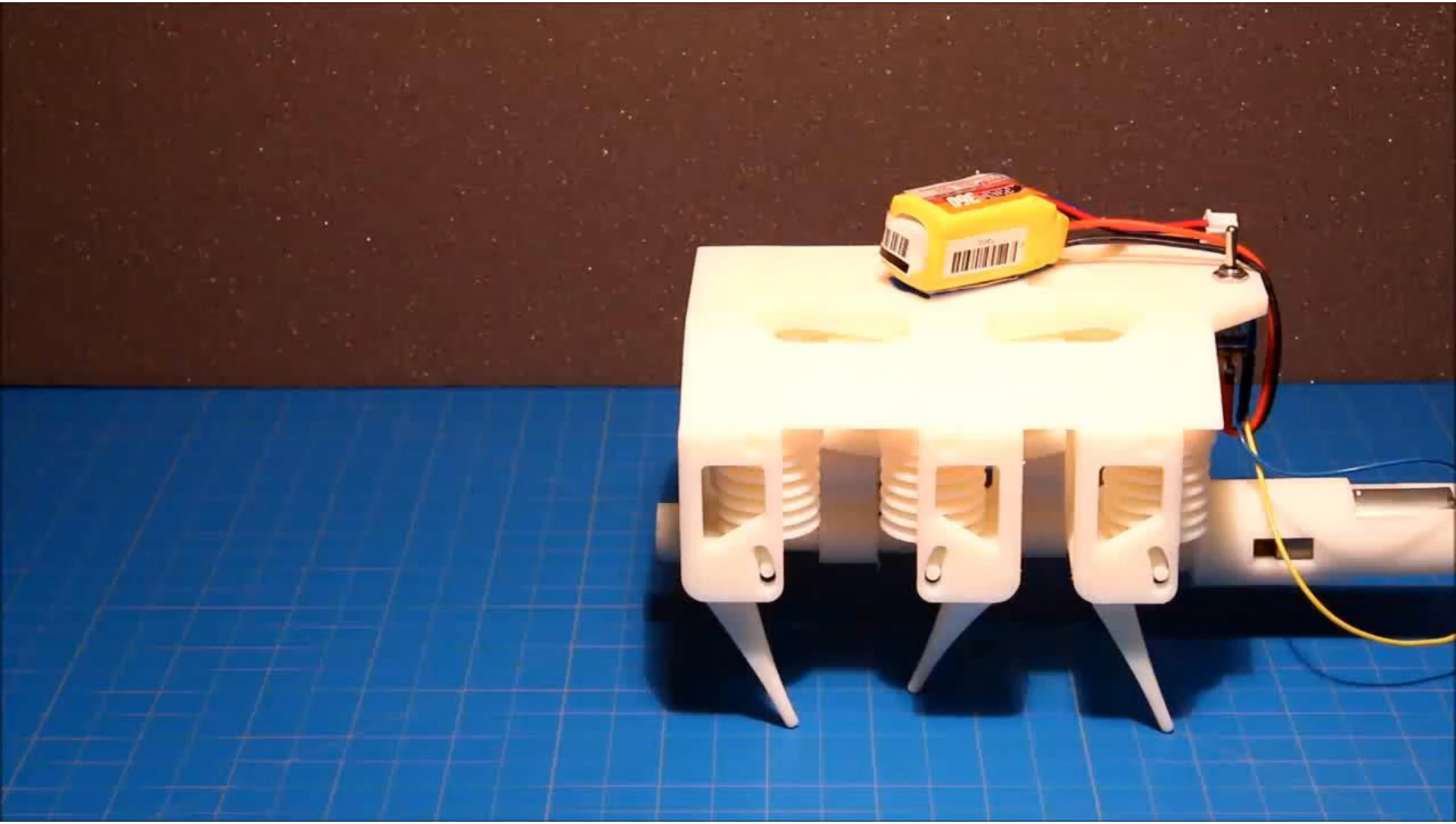




- 12 bellows + crankshaft + motor = simple walker!



- Tripod gait
- Quadrature drive via offset crank

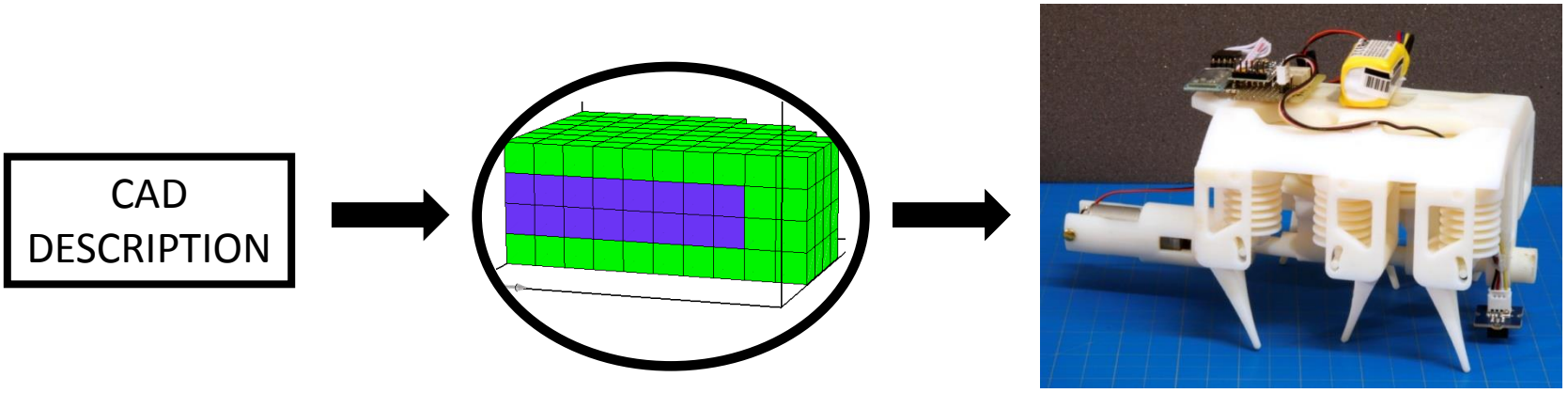



Printing a gear pump using rigid plastic and liquid
3-hour print job

“Printable Hydraulics”

Contributions

- First 3D printed hydraulic system
- Automates fabrication of moving assemblies (robots)
- First step to robot “walking out of the printer!”



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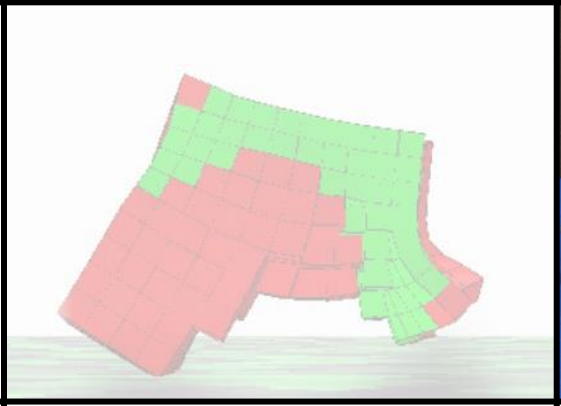
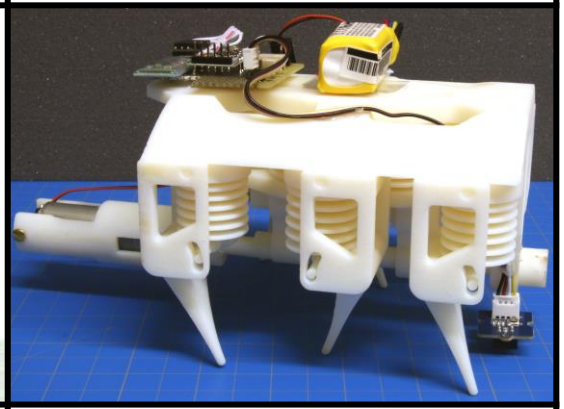
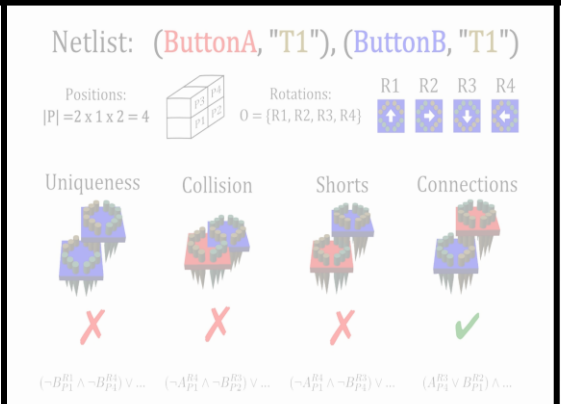
Body (Structure & mechanisms)		
Nervous System (Signals & sensing)		

Printable Viscoelastics

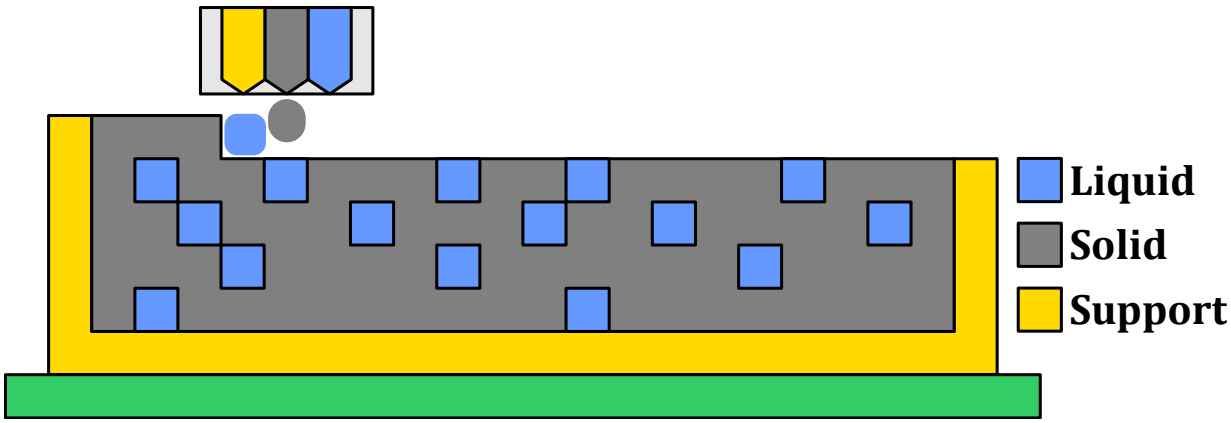
$$E^*(\omega, P_l) = E'|_{1Hz} * (\omega^{n_1} + i * tan(\delta)|_{1Hz}\omega^{n_2})$$

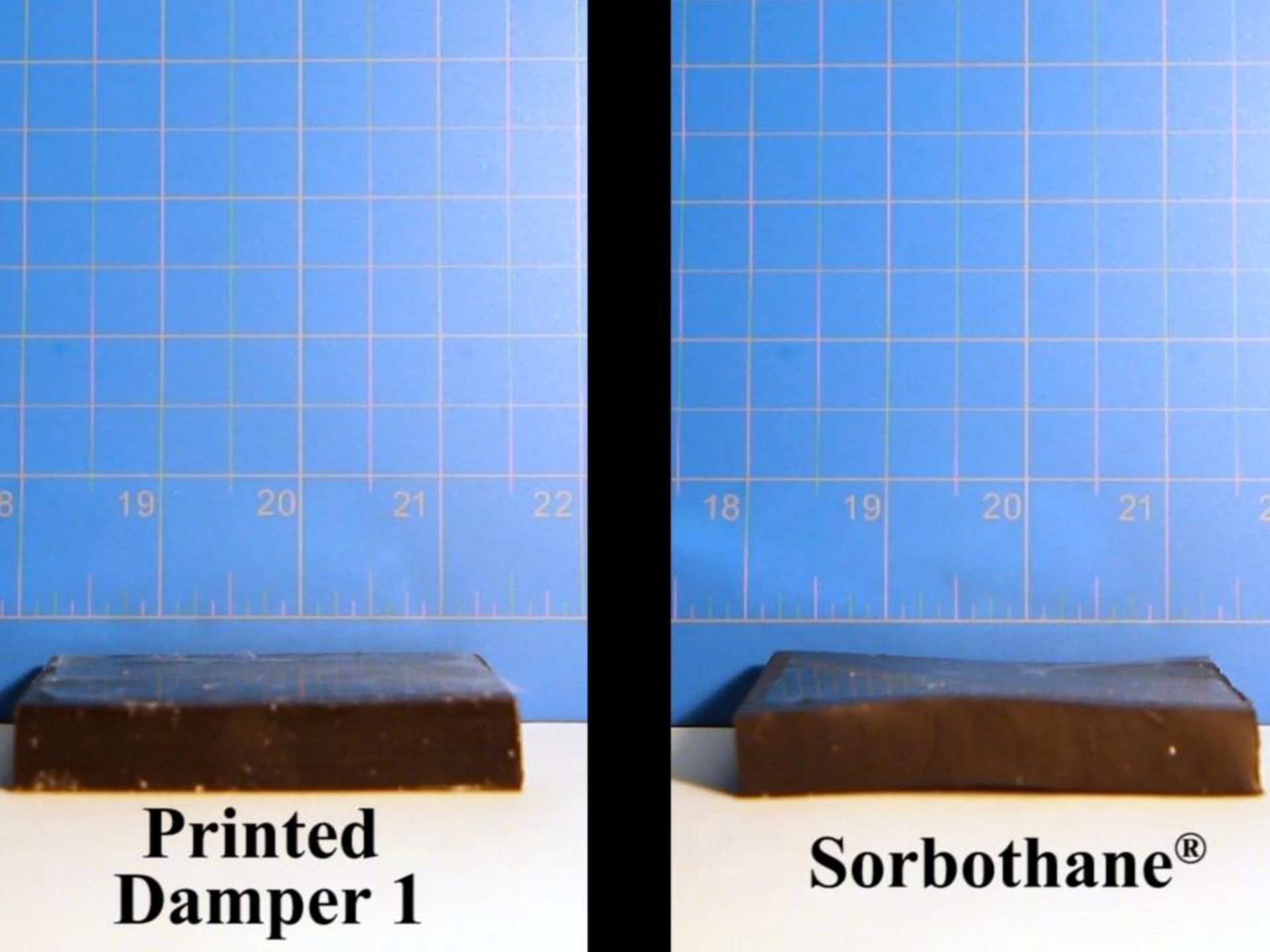
- Problem:
  - Given a desired (complex) elastic modulus and a bounding surface, find a satisfying placement (position and type) of modules

Printable Viscoelastics

$$E^*(\omega, P_l) = E'|_{1Hz} * (\omega^{n_1} + i * tan(\delta)|_{1Hz}\omega^{n_2})$$

- 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

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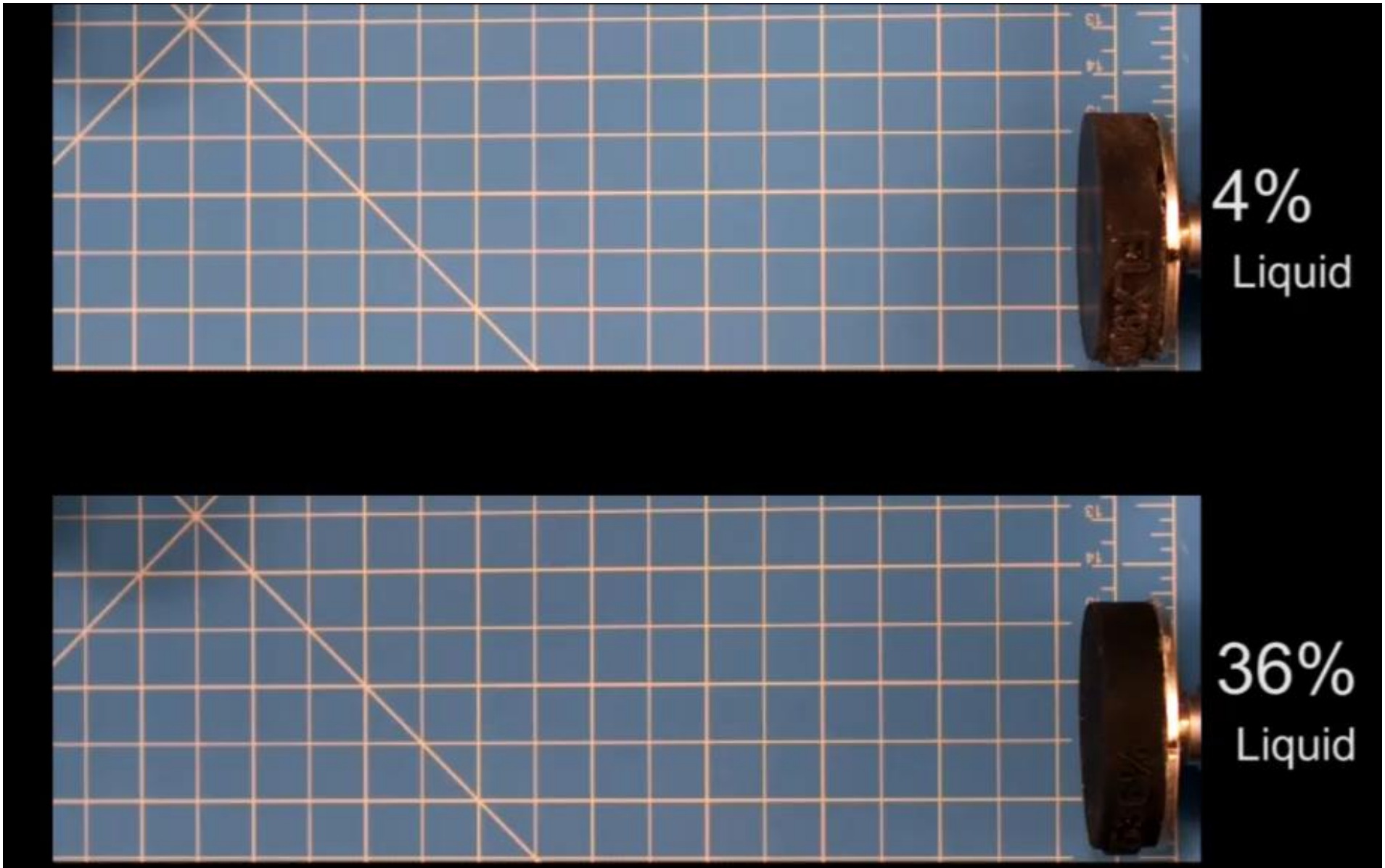
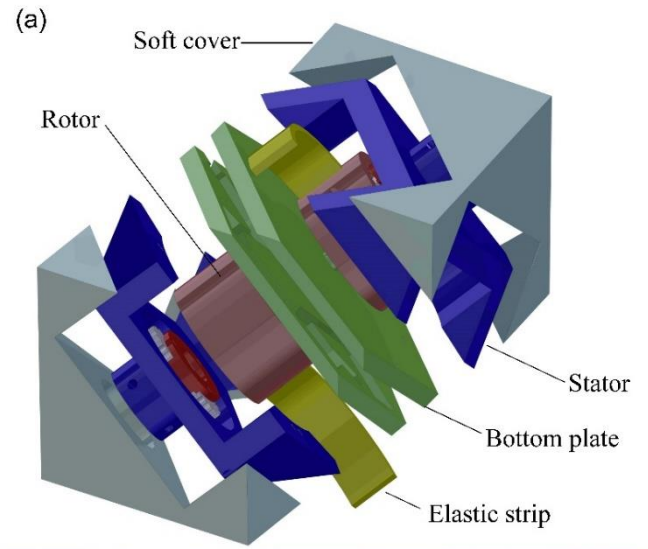
Sorbothane®

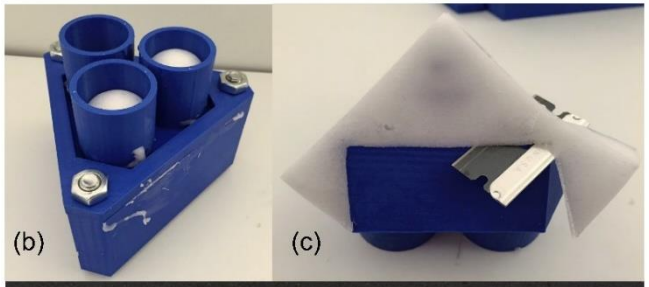
Impact Tests

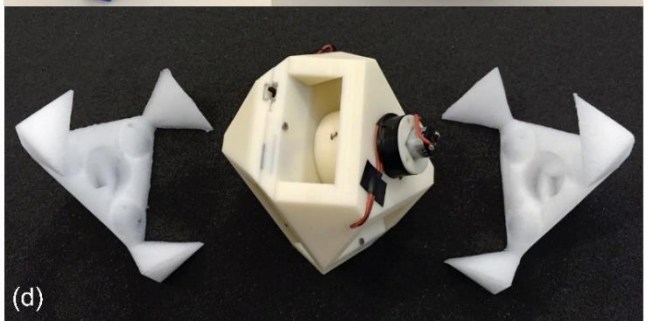
- Measure velocity change & transmitted force

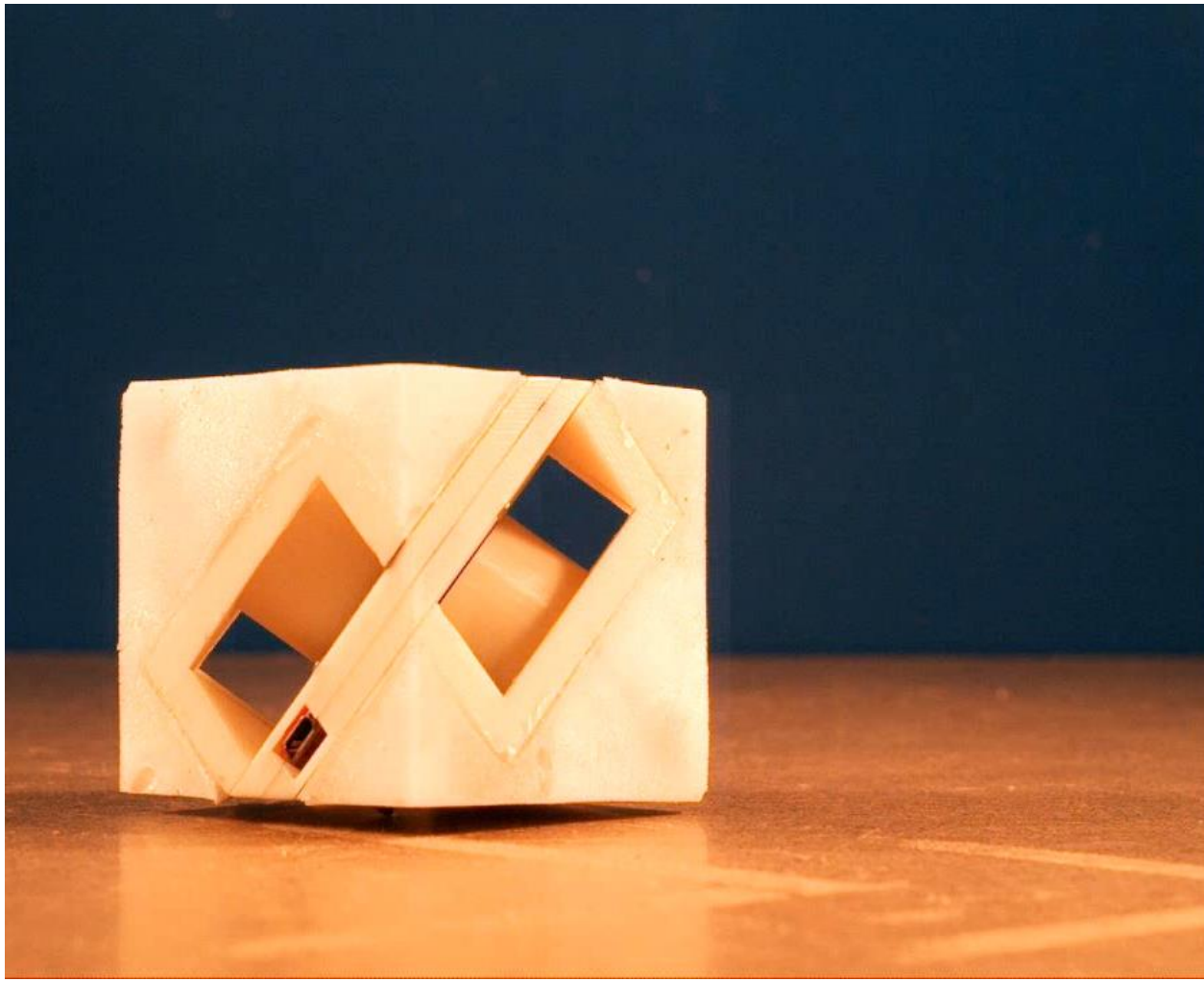


Improving a soft 3D-printed jumping robot

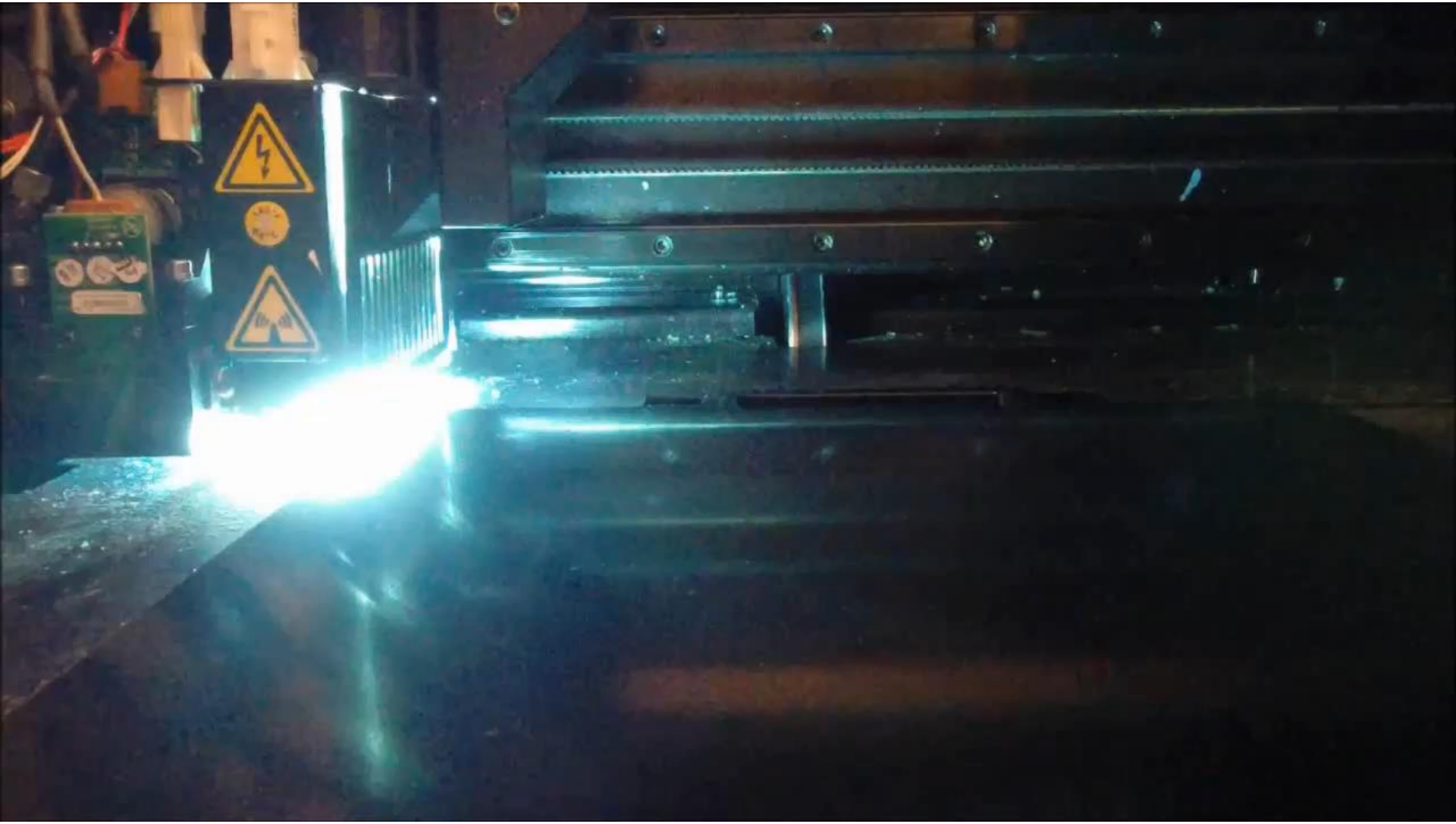


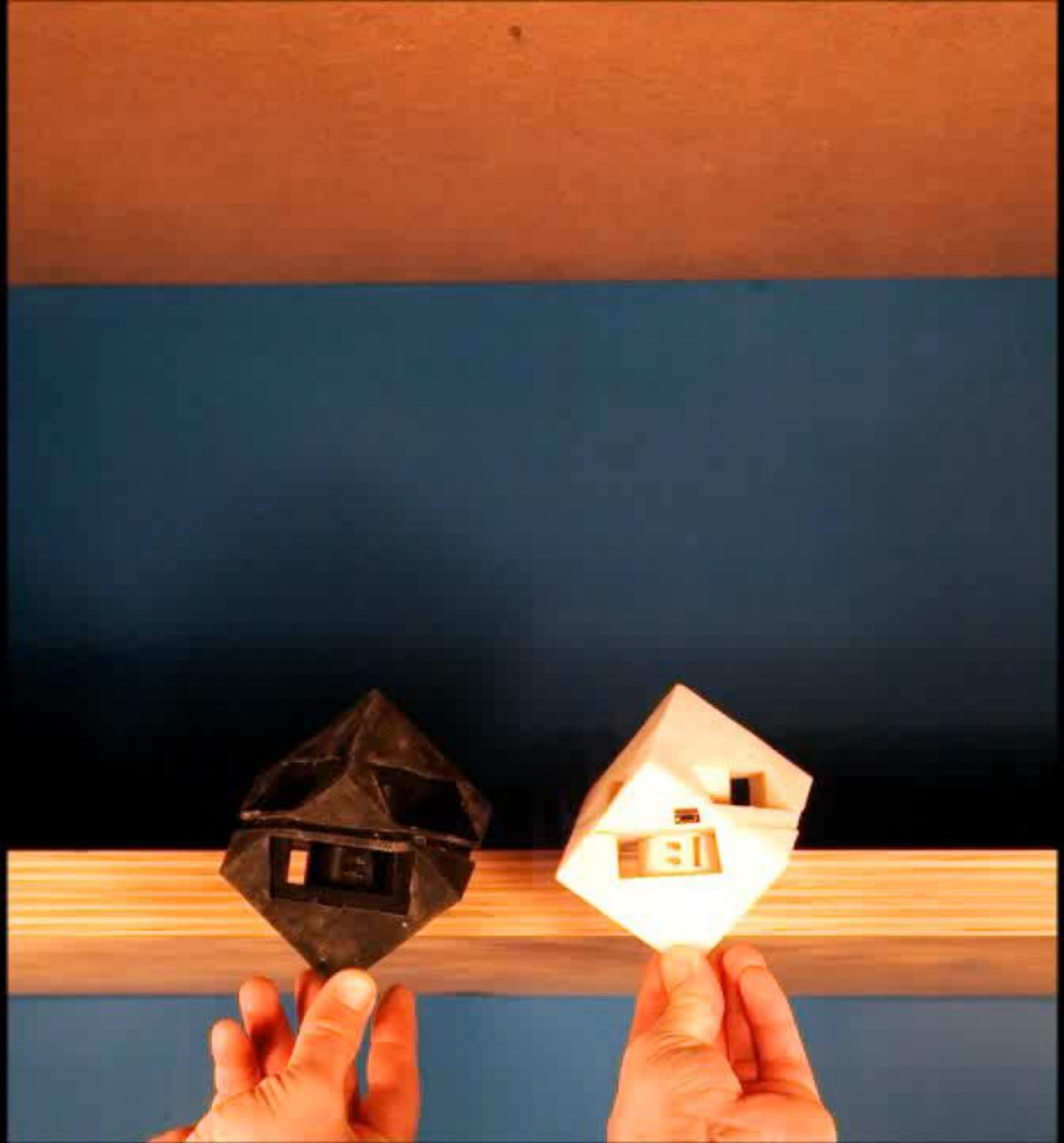


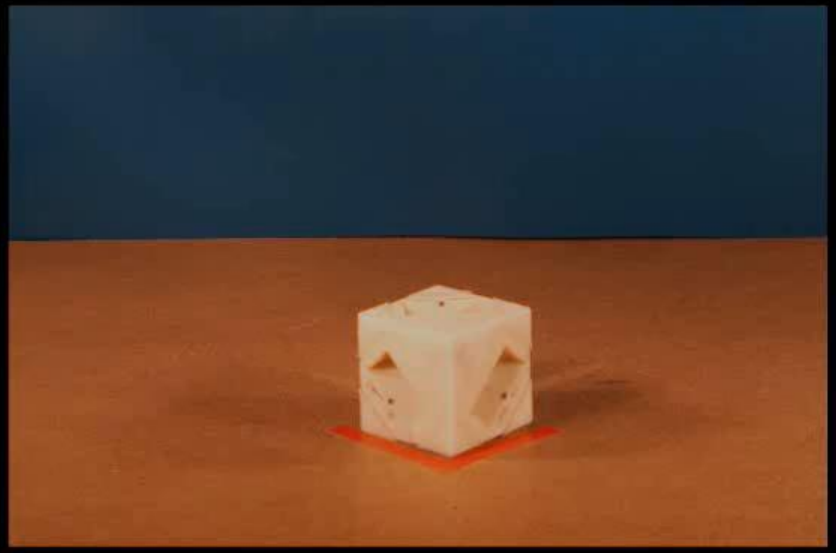


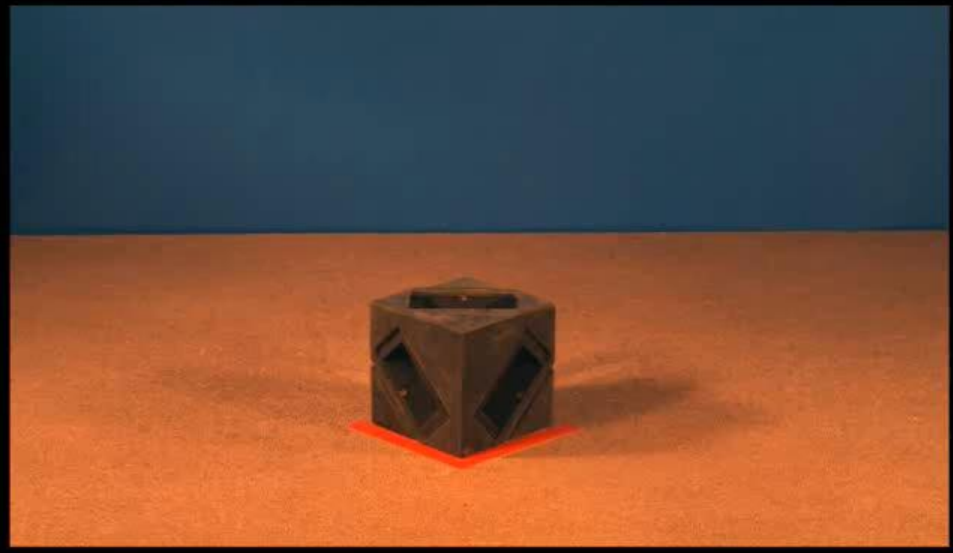


Li, S.; Katzschmann, R. ; Rus, D. A soft cube capable of controllable continuous jumping *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on,* **2015**, 1712-1717









“Printable Viscoelastics”

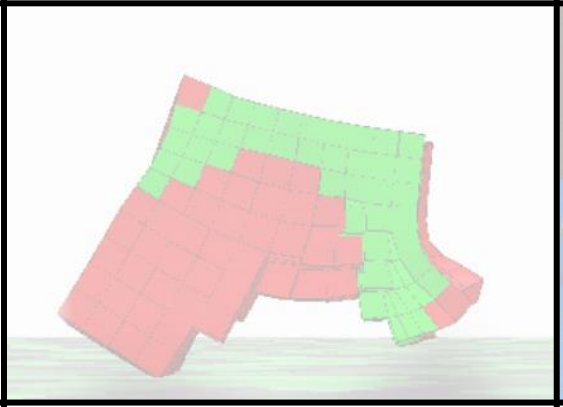
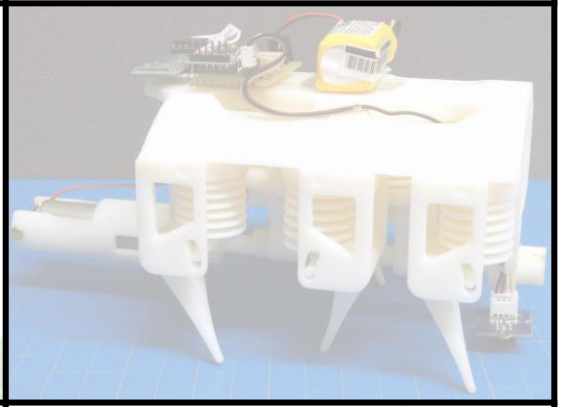
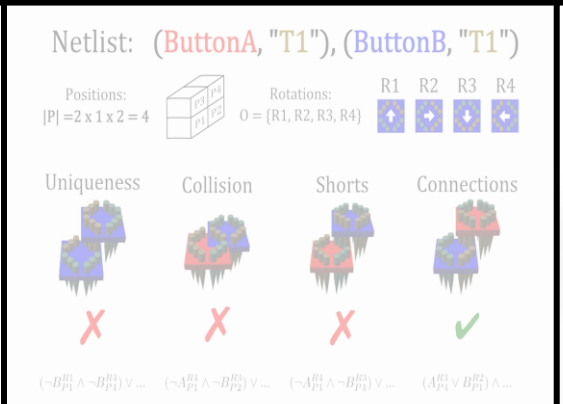
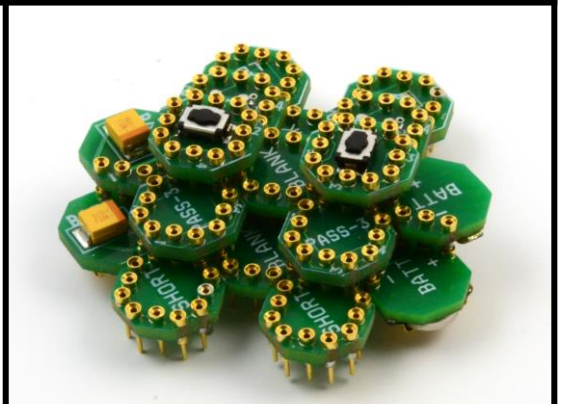
$$E^*(\omega, P_l) = E'|_{1Hz} * (\omega^{n_1} + i * tan(\delta)|_{1Hz}\omega^{n_2})$$

Contributions

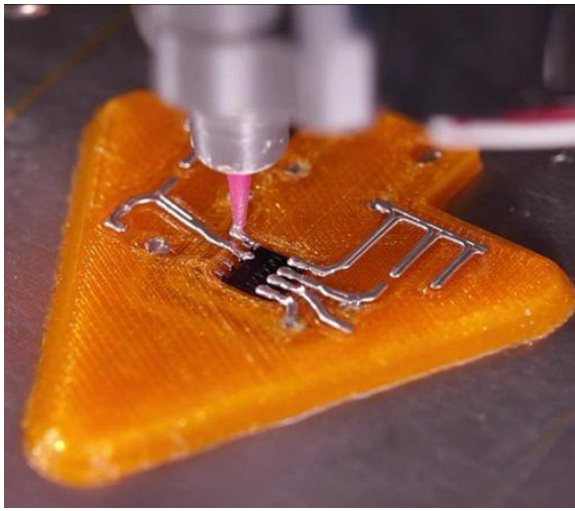
- **3D printed components with prescribed viscoelastic properties**
- **Elasticity & damping “programmed” by design file & can vary continuously throughout part**

MacCurdy, Lipton, Li, and Rus. Printable Programmable Viscoelastic Materials for Robots. *IROS 2016*

Multicellular Machines (selected contributions)

	Design Automation	Fabrication Automation
Body (Structure & mechanisms)		
Nervous System (Signals & sensing)		

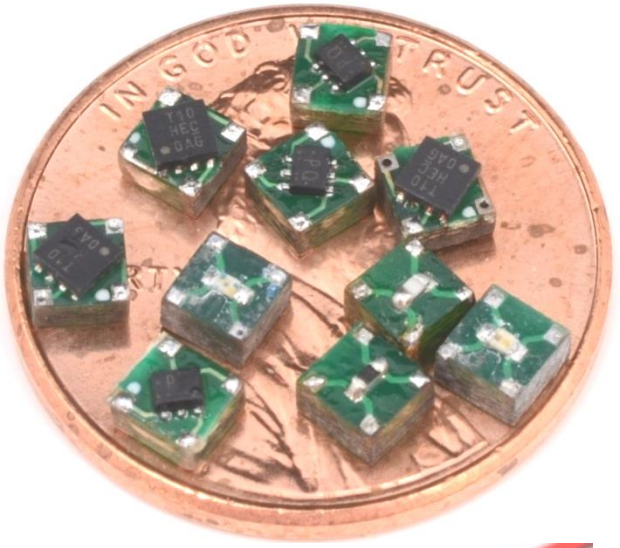
Limitations in Printed Electronics

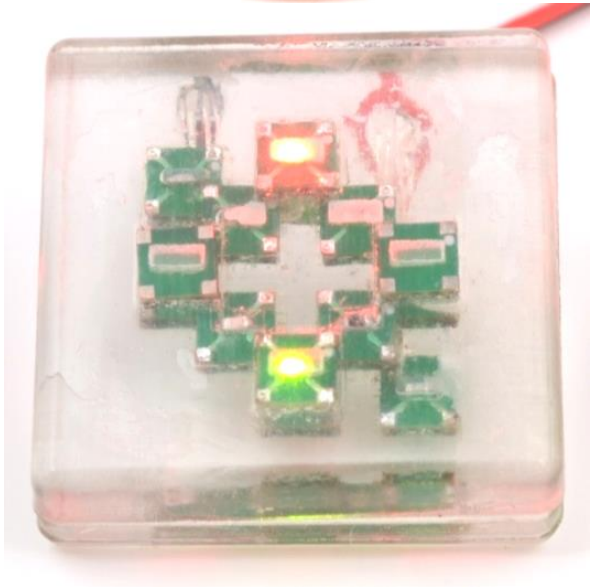


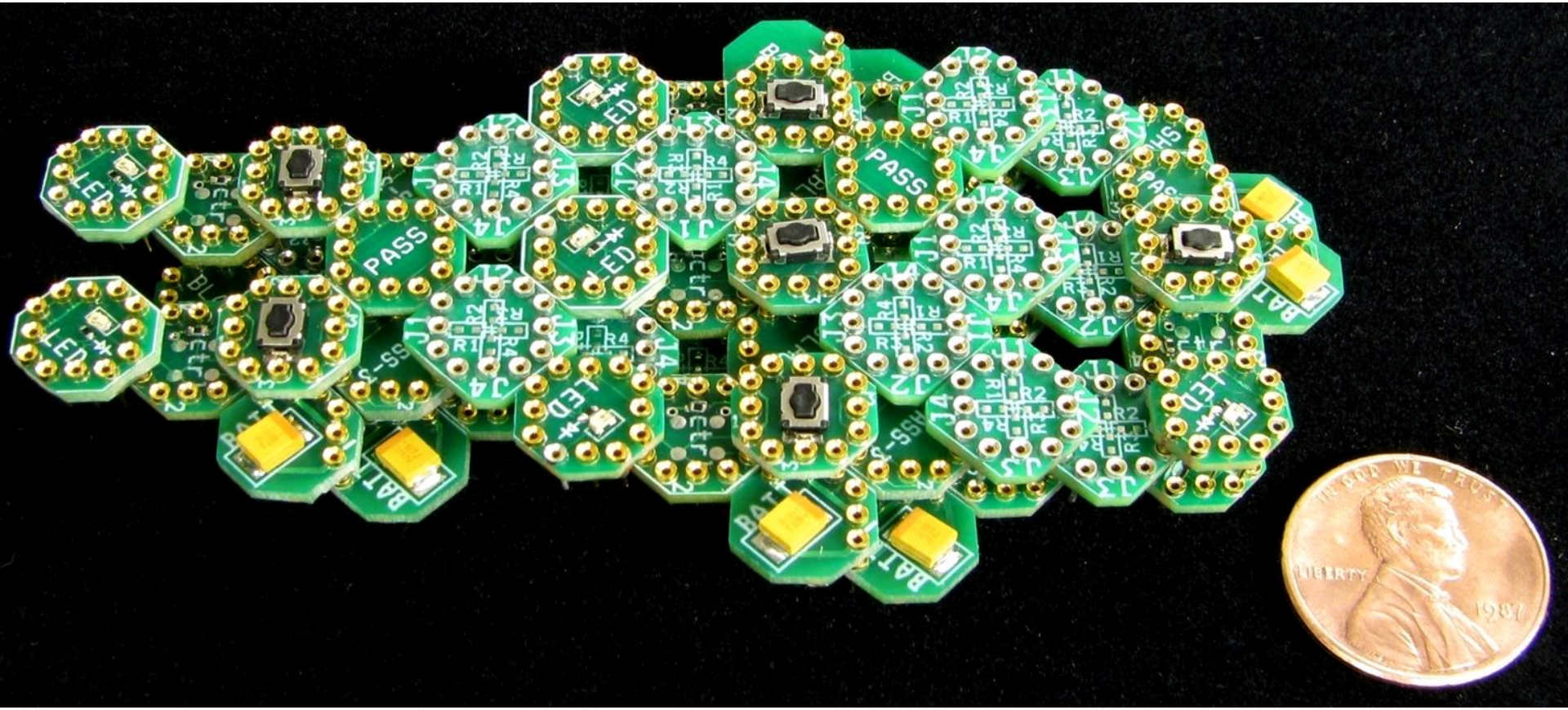
- 2 key challenges:
  - Printing conductors; Printing semiconductors
- Best printed conductors:
  - Research: nearly same conductivity as bulk, but expensive special processing req'd
  - Commercial: ~30x more resistive than bulk
- Best printed semiconductors:
  - Electron mobility: 0.85 vs 1450 cm^2/Vs; Hole mobility: 23.7 vs 450 cm^2/Vs
  - Feature size ~ 1-5 micron (difficult to achieve in low-cost printer)
    - Low drain current (mobility)
    - Low operating frequency (mobility & geometry)

1. Walker, S. B. & Lewis, J. A. "Reactive silver inks for patterning high-conductivity features at mild temperatures" *Journal of the American Chemical Society,* **2012***, 134*, 1419-1421
2. Tseng, H.-R.; et al "High-Mobility Field-Effect Transistors Fabricated with Macroscopic Aligned Semiconducting Polymers" *Advanced Materials,* **2014***, 26*, 2993-2998
3. Yan, H. et al "A high-mobility electron-transporting polymer for printed transistors" *Nature,* **2009***, 457*, 679-686

- 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



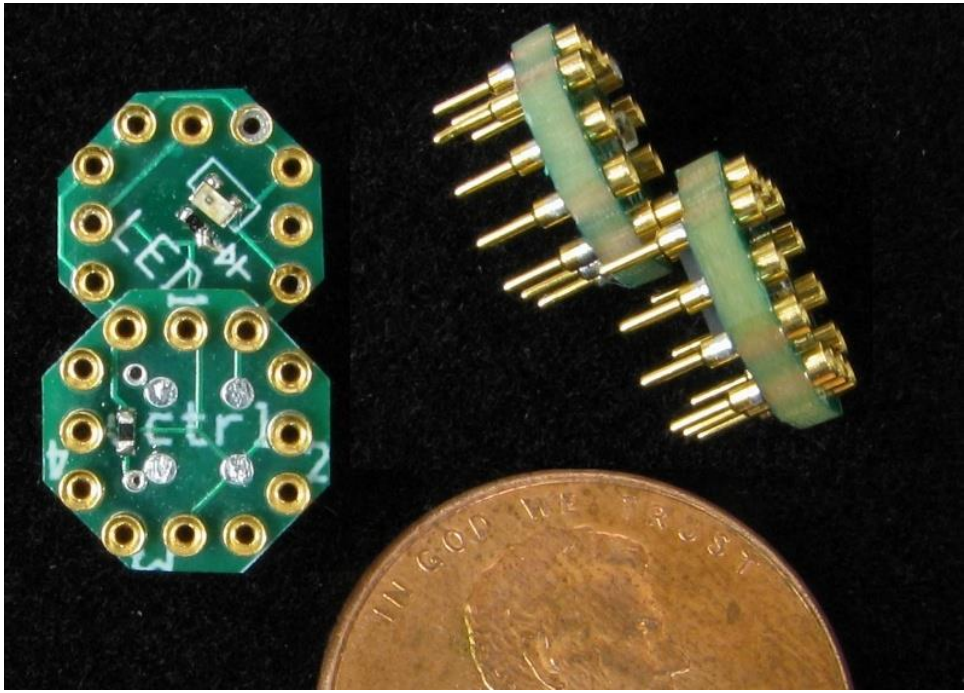




MacCurdy, R.; McNicoll, A. & Lipson, H. Bitblox: A Printable Digital Material for Electromechanical Machines. *International Journal of Robotics Research,* 2014, Vol. 33(10) pp1342–1360

- “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

$$\Delta = \varepsilon N^{0.1}$$



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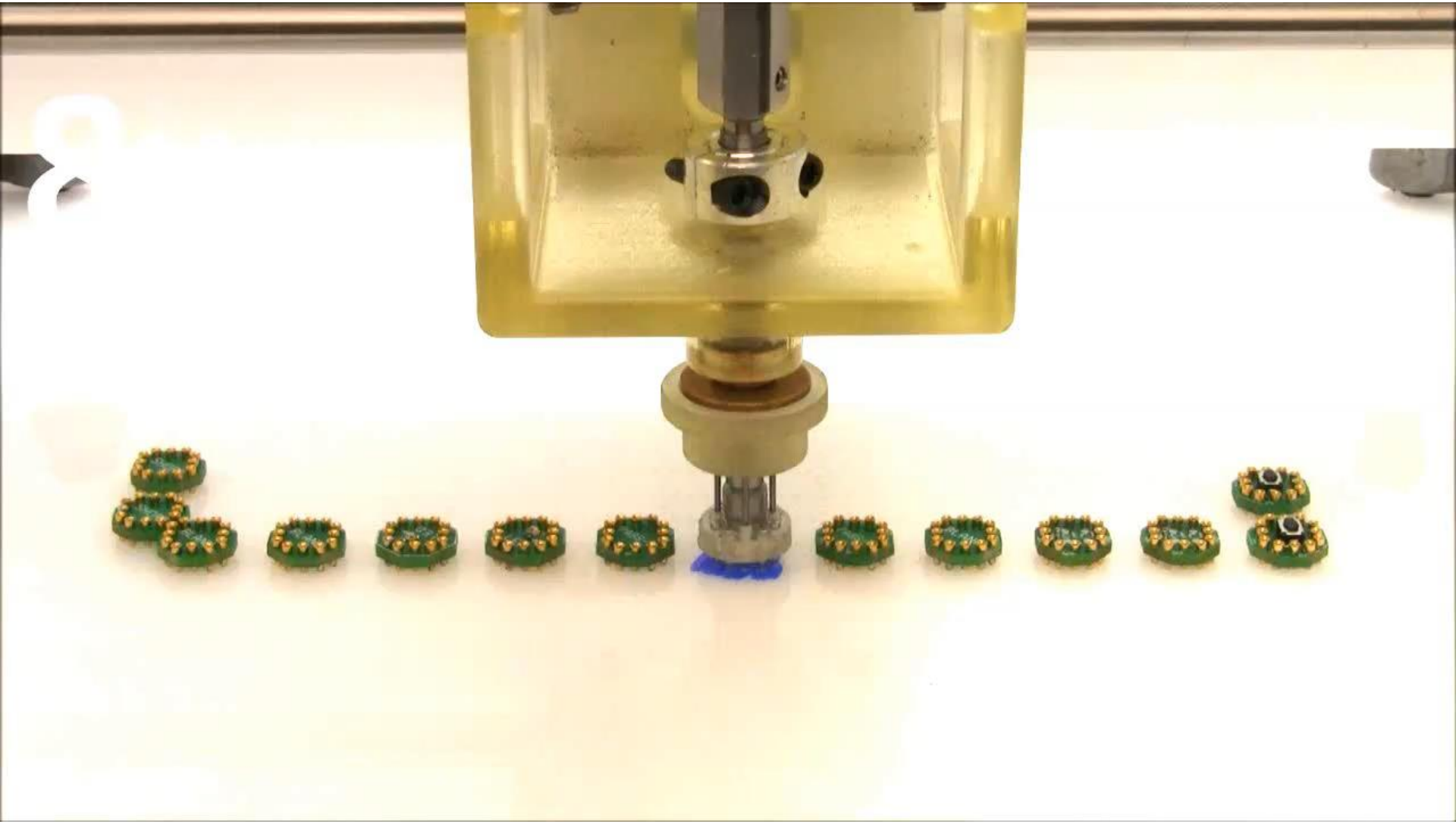
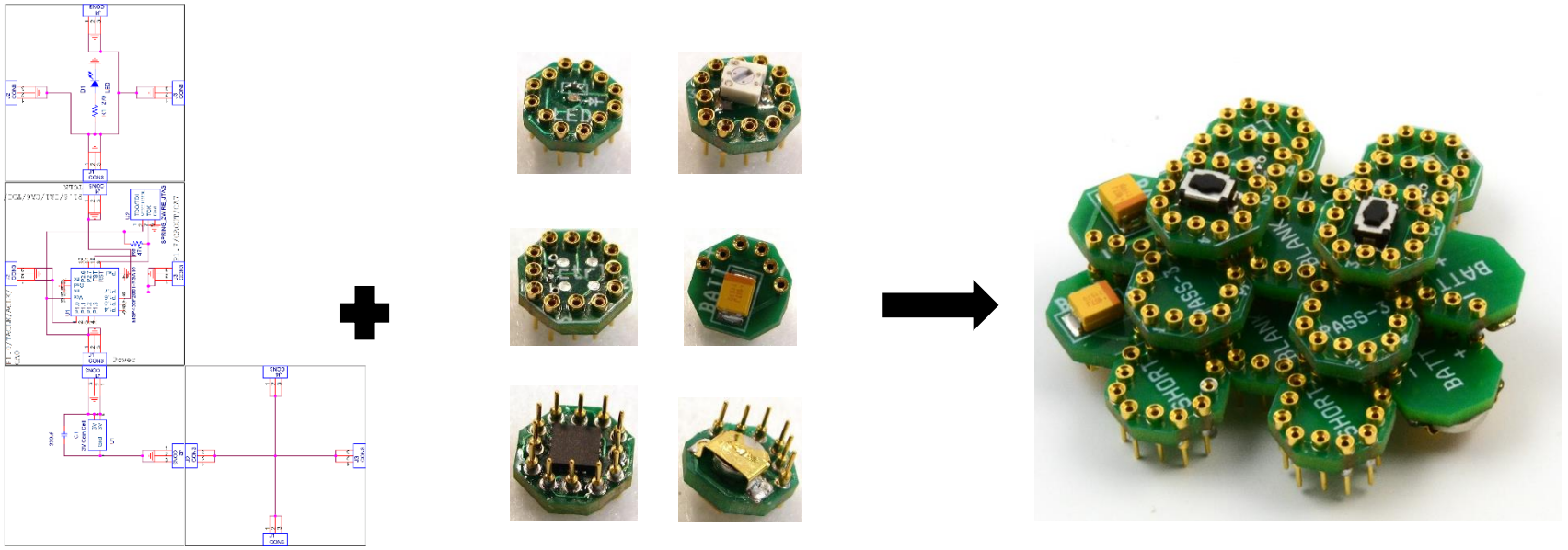


MacCurdy, R.; McNicoll, A. & Lipson, H. Bitblox: A Printable Digital Material for Electromechanical Machines. *International Journal of Robotics Research,* 2014, Vol. 33(10) pp1342–1360

“Fabricating circuits with Digital Materials”

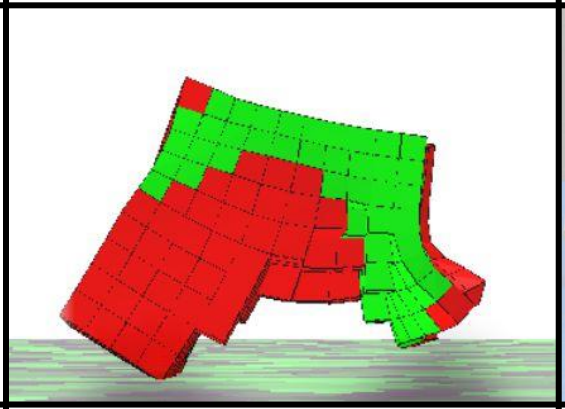
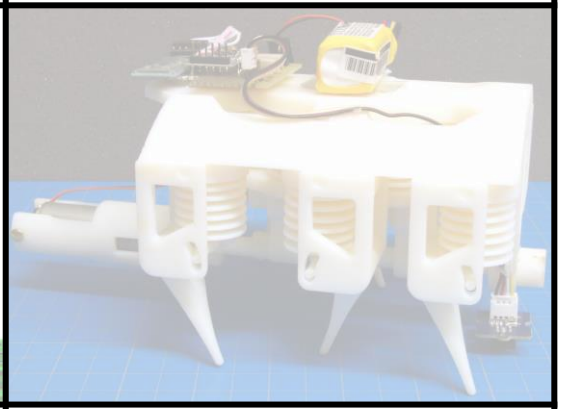
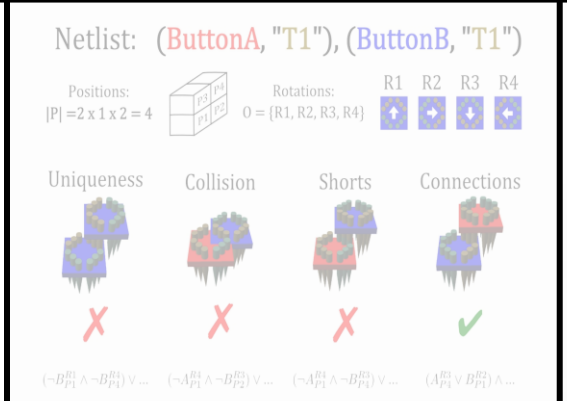
Contribution:

- **High-performance mixed-signal circuits via additive manufacturing**



- **MacCurdy, R.**; McNicoll, A. & Lipson, H. Bitblox: A Printable Digital Material for Electromechanical Machines. *International Journal of Robotics Research,* 2014, Vol. 33(10) pp1342–1360
- **MacCurdy, R.** & Lipson, H. “Hybrid Printing: Modular 3D Printing of Integrated Electromechanical Systems” (*submitted*)
- **MacCurdy, R.** ; Lipson, H. Hybrid printing of photopolymers and electromechanical assemblies. Solid Freeform Fabrication Symposium, Austin TX, Aug 4, 2014.

Multicellular Machines (selected contributions)

	Design Automation	Fabrication Automation
Body (Structure & mechanisms)		
Nervous System (Signals & sensing)		

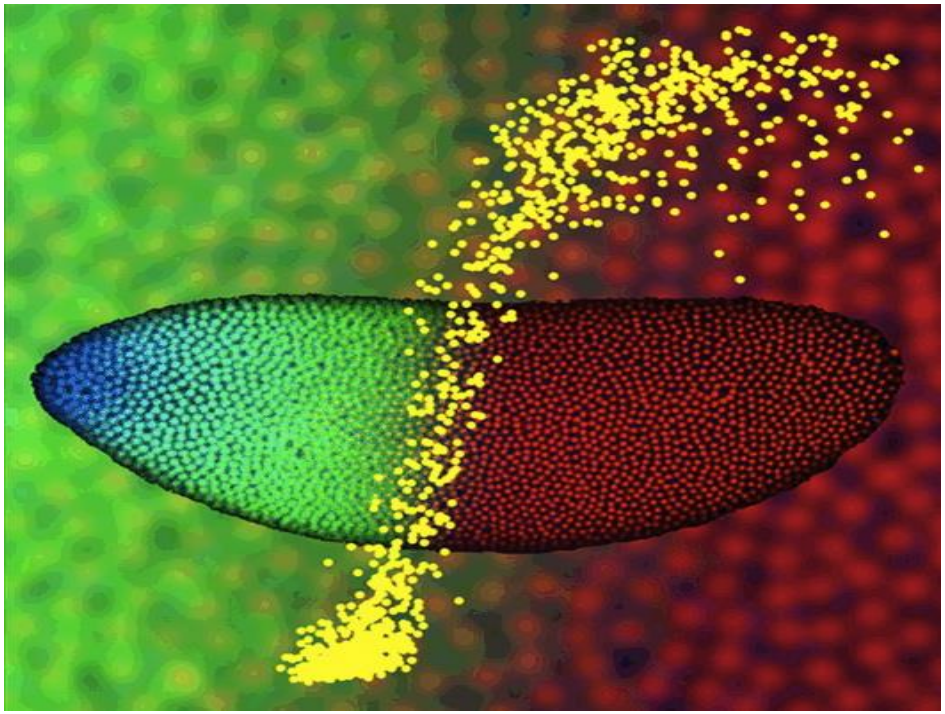
Designing with a cellular framework presents its own challenges:

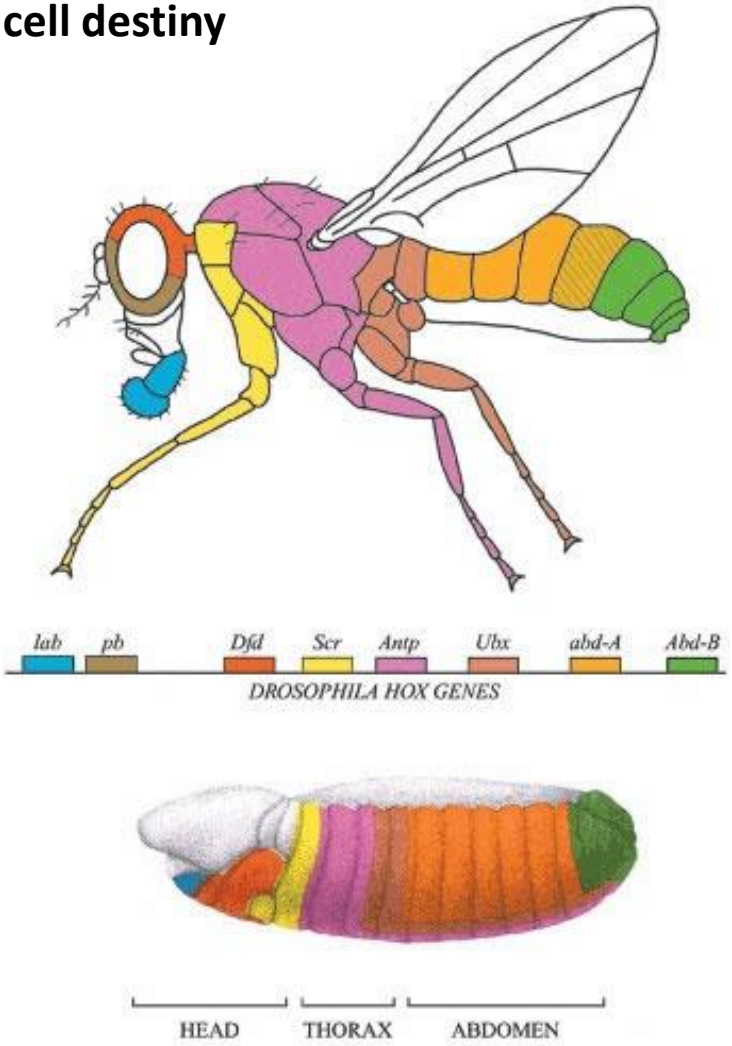
- Large numbers of modules (cells) – potentially Billions
- Individual elements have limited functionality
- Design approach differs from existing methods (no cellular CAD package - yet)
- Implementation strategies differ from existing methods – new intuition must be developed

Evolutionary algorithms inspired by biological development provide one possible solution

<u>Morphogenic gradients</u> 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)





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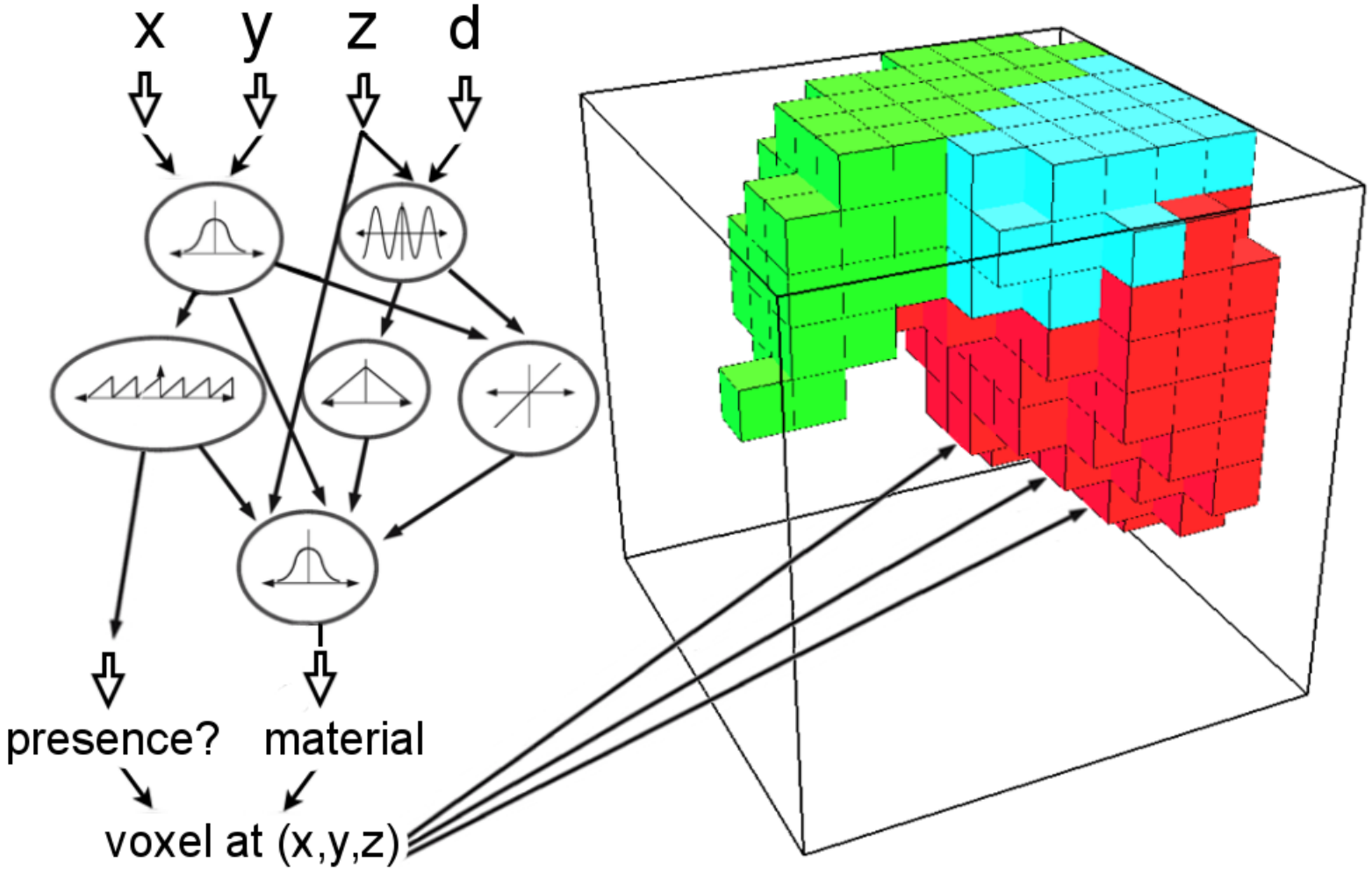
- Carroll, S. B. Endless forms most beautiful: The new science of evo devo and the making of the animal kingdom. *WW Norton & Company,* 2005

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



- Cheney, N.; **MacCurdy, R.**; Clune, J. & Lipson, H. Unshackling evolution: evolving soft robots with multiple materials and a powerful generative encoding. *ACM SIGEVOlution, ACM,* 2014*, 7*, 11-23
- Cheney, N.; **MacCurdy, R.**; Clune, J. & Lipson, H. Unshackling Evolution: Evolving Soft Robots with Multiple Materials and a Powerful Generative Encoding. *Proceedings of the conference on genetic and evolutionary computation (GECCO), 2013.*

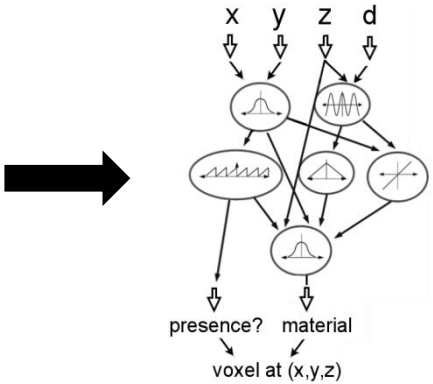
… with interesting results

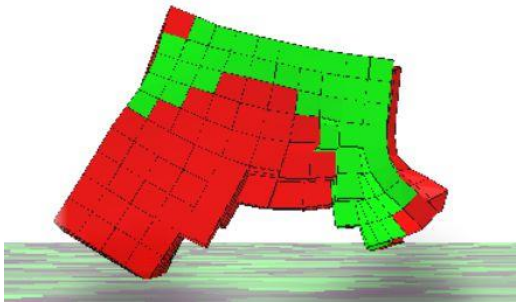
- First Prize: AAAI Video Competition, 2013
- Winner: Virtual Creatures Competition, GECCO 2014

“Evolving Body Plans”

Contribution: method to synthesize modular robot bodies from heterogeneous parts

Spec: “run as fast as possible”





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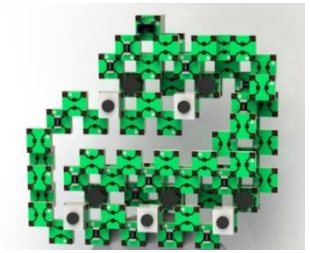
- First Prize: AAAI Video Competition, 2013
- Winner: Virtual Creatures Competition, GECCO 2014
- Frequently compared to Karl Sims’ pioneering work

Components required by robots (future work)

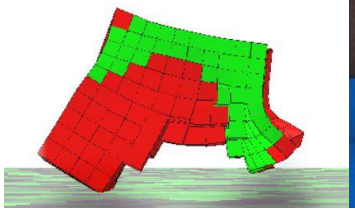
- **Signals & sensing**
- High-level commands/behavior
- Low-level control

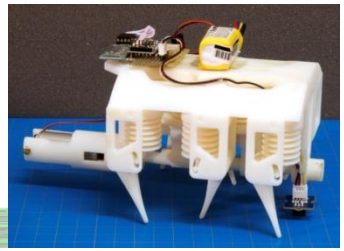
"Nervous System"



- **Structure/mechanisms**
- Actuation
- Energy

"Body"



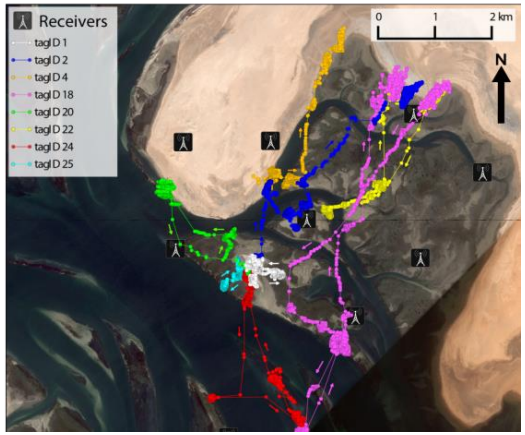


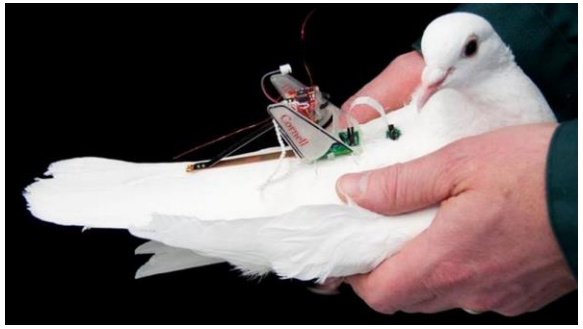
DESIGN AUTOMATION

FAB AUTOMATION

Automated Biological & Ecological Sensing

- Automate the acquisition of ecological data to inform science and conservation
- Implement solutions that allow human efforts to scale





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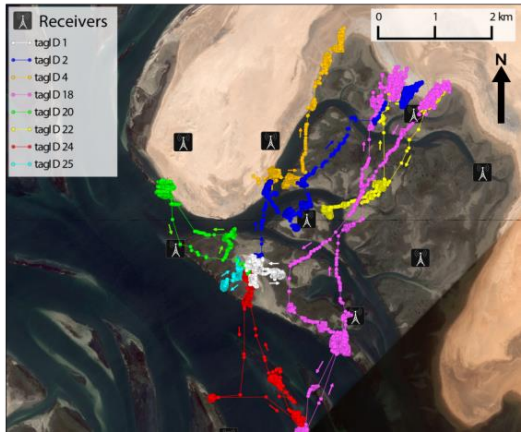


Localization via existing tags

- 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

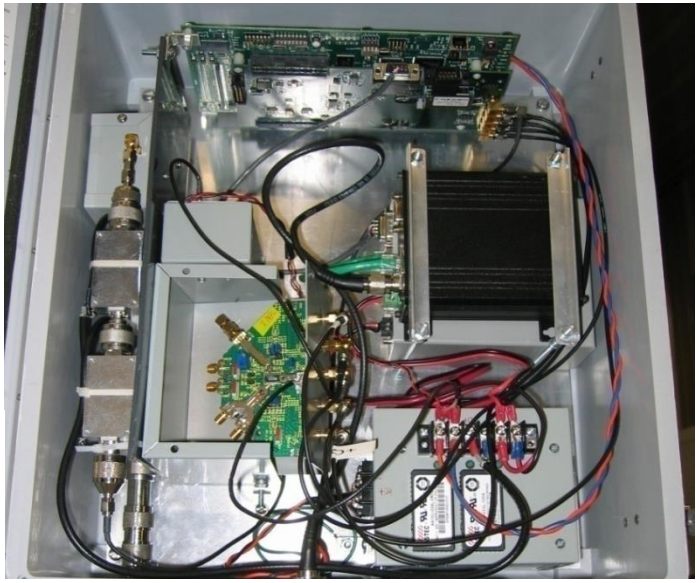
Automatic Radio Tracking

- 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

$$\mathrm{Xcorr}(l) = \mathrm{IFFT}\{Sig(f)Prn(f)\}$$

- Position computed via Time of Arrival

$$r^k = \left(t_{Rx(R)}^{(k)} - t_{Tx(R)}\right)c = \left\|\mathbf{P}^{(k)} - \boldsymbol{x}\right\|$$

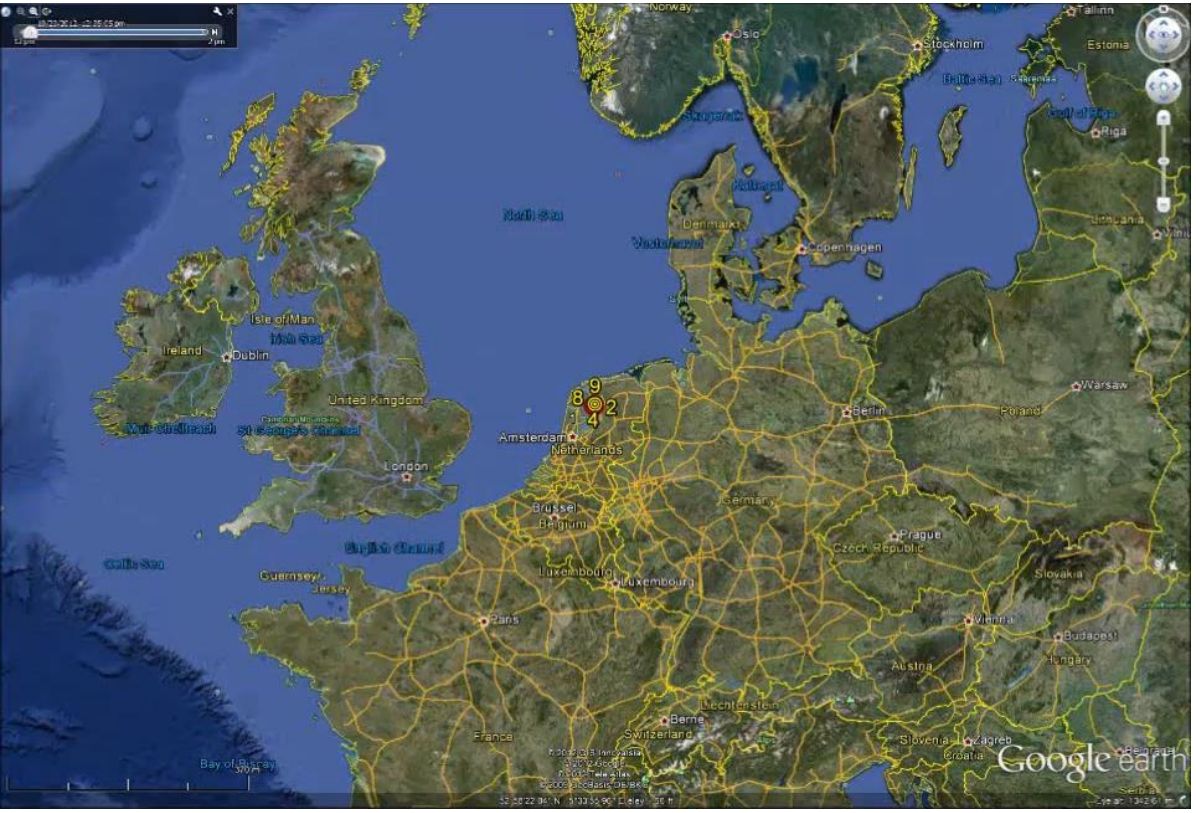


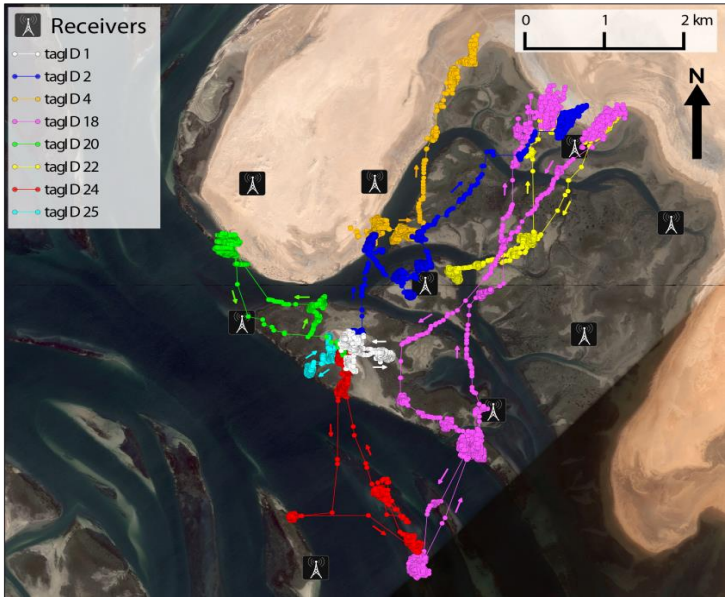
• **MacCurdy, R.**; Gabrielson, R. & Cortopassi, K. Automated Wildlife Radio Tracking. *Handbook of Position Location: Theory, Practice, and Advances, Wiley Online Library,* 2011, 1129-1167

• **MacCurdy, R.**; Gabrielson, R.; Spaulding, E.; Purgue, A.; Cortopassi, K. & Fristrup, K. Automatic animal tracking using matched filters and time difference of arrival. *Journal of Communications,* 2009*, 4*, 487-495.

• **MacCurdy, R.**; Gabrielson, R.; Spaulding, E.; Purgue, A.; Cortopassi, K. & Fristrup, K. Real-time, automatic animal tracking using direct sequence spread spectrum. *EuWiT 2008. European Conference on Wireless Technology,* 2008, 53-56

Automatic Wildlife Radio Tracking





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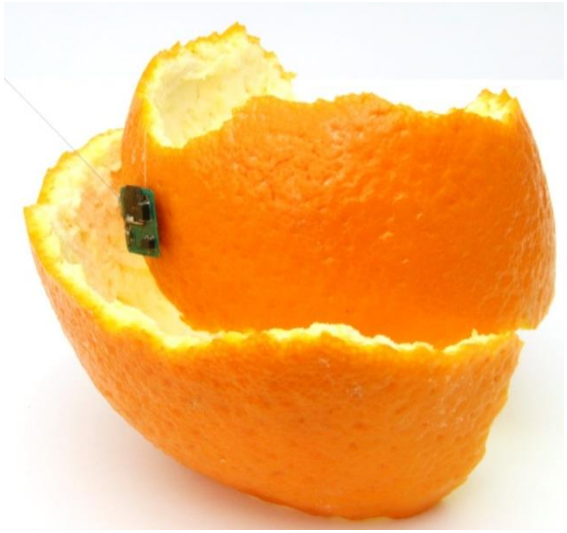
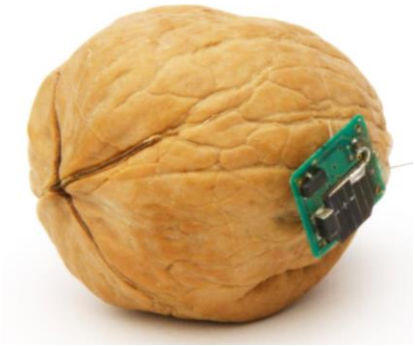
- Piersma, T.; **MacCurdy,** R. B.; Gabrielson, R. M.; Cluderay, J.; Dekinga, A.; Spaulding, E. L.; Oudman, T.; Onrust, J.; van Gils, J. A.; Winkler, D. W. & Bijleveld, A. I., Fine-scale measurements of individual movements within bird flocks: the principles and three applications of TOA tracking, *Limosa*, **2014**, 87, 156-167
- **MacCurdy**, Gabrielson, Cortopassi, "Automated Wildlife Radio Tracking - Chapter 33", Handbook for Position Location, **2011**, Wiley.
- **MacCurdy**, R., Gabrielson, R., Spaulding, E., Purgue, A., Cortopassi, K., Fristrup, K. "Automatic animal tracking using matched filters and TDOA", *Journal of Communications,* Vol 4, Issue 7, August **2009**, pp 487-495.

Current & Future Work

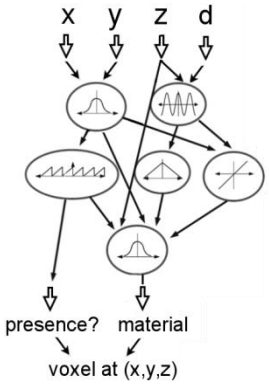
- Automatic Tracking & Telemetry Systems for Large-Scale Science (“Big data for small organisms”)





Multicellular Machines:

How to rapidly design and build robots from <u>many</u> different modules



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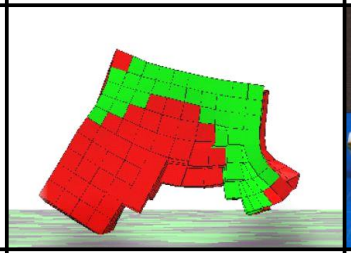
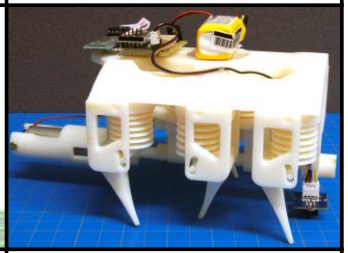
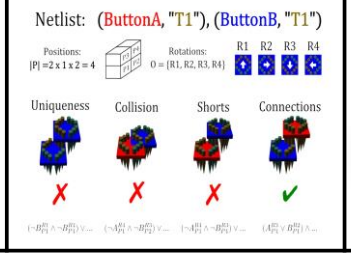
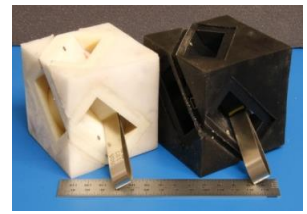
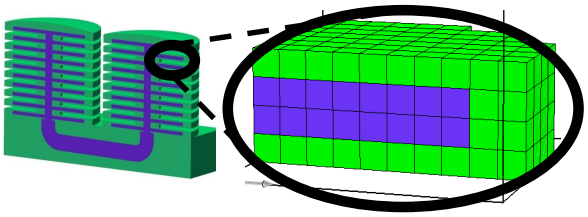
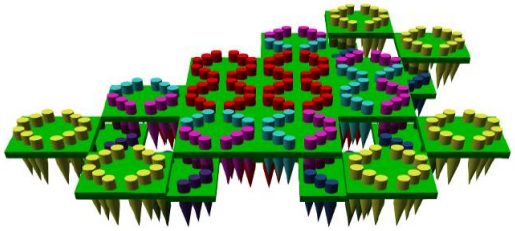
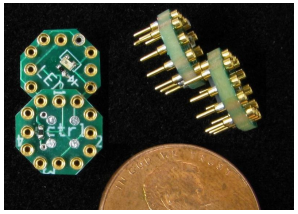
Body (Structure & mechanisms)		
Nervous System (Signals & sensing)		









Media Coverage: PBS, Scientific American, Discovery, The New York Times, The Economist, Wall Street Journal, Popular Science, ABC News, IEEE Spectrum, Wired, Quartz, Fast Company, nanoWerk, KurzweilAI, Engadget, Gismodo, Tech News Daily, Biotechnologia, EETimes, International Business Times, Live Science, CNET,…

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