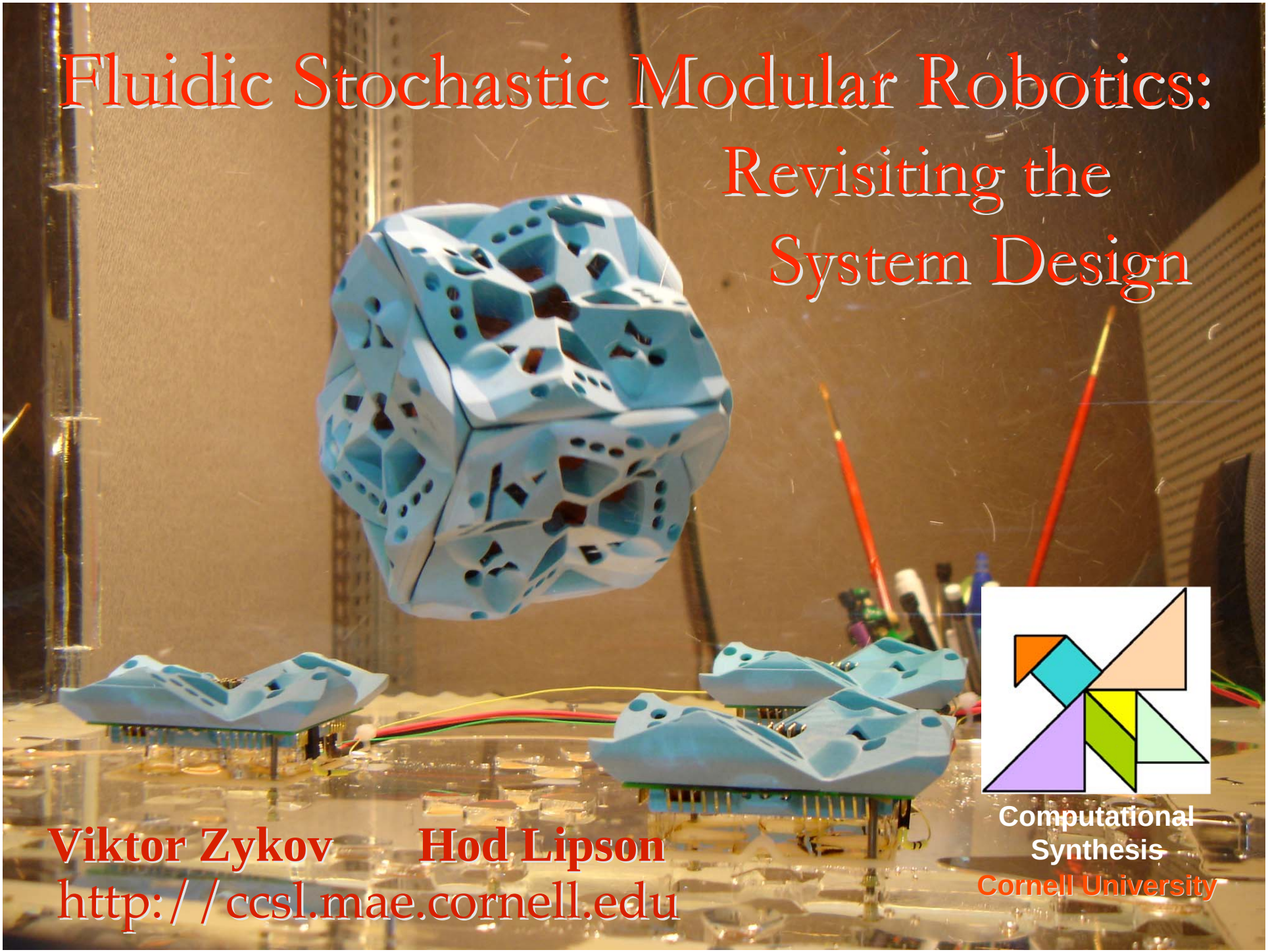
Fluidic Stochastic Modular Robotics: Revisiting the System Design



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Computational Synthesis
Cornell University

Grand Challenges in the Area of Self-Reconfigurable Modular Robots

- **Self-repair and self-replication** one of the biggest challenges is to create practical algorithms that take advantage of these capabilities
- **Limited resources** modular robots are limited by power, size, torque and other resources
- **Scale** algorithmic and physical limitations make it difficult to scale to a large number of modules and to very small modules
  - >100 modules
  - <1cm modules
  - operate unattended for X days or recover from Y% damage
  - planning algorithm that will work on >1E6 units in real time
- **Hardware** the planning and control side of self-reconfigurable modular robots are far ahead of the hardware side

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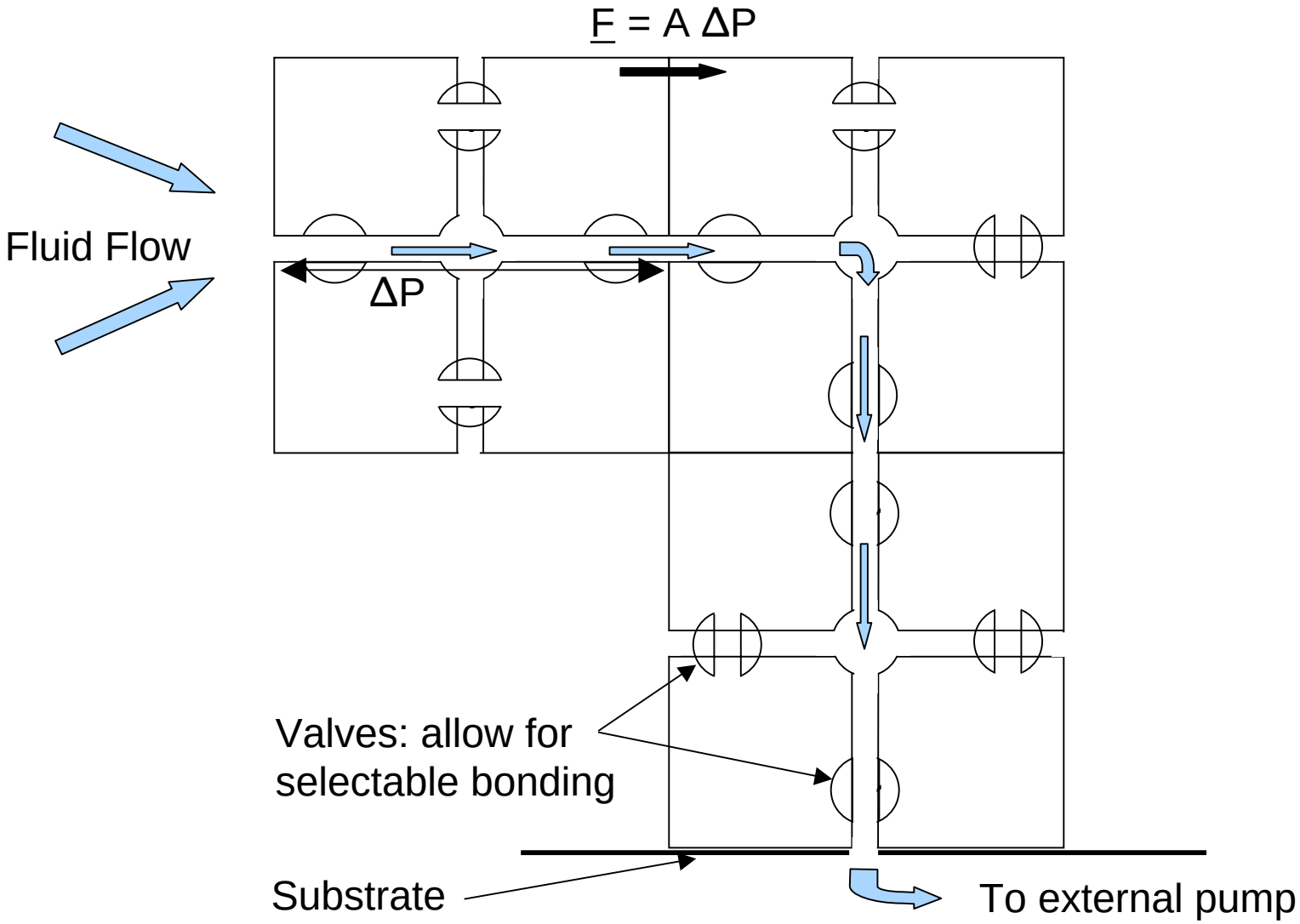
Our Proposal:
Circumvent Technological Challenges

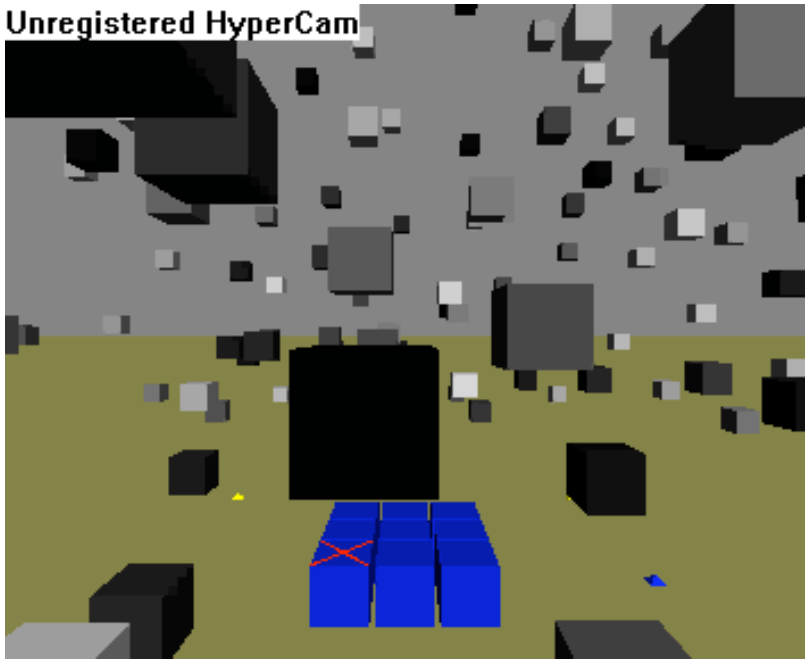
- Use only available technology to mass produce small-scale modular robots without batteries, motors, and power train:
  - instead of motors for individual module locomotion, use fluidic medium as external global actuator
  - instead of path planning for deterministic reconfiguration:
    - only deterministically control attachment/detachment of each module
    - for module repositioning, rely on globally directed fluid motion driving the modules
  - instead of carrying a battery on board, only activate units externally when they become a part of a global modular structure

Scalable System Concept (P. White et al, 2005)



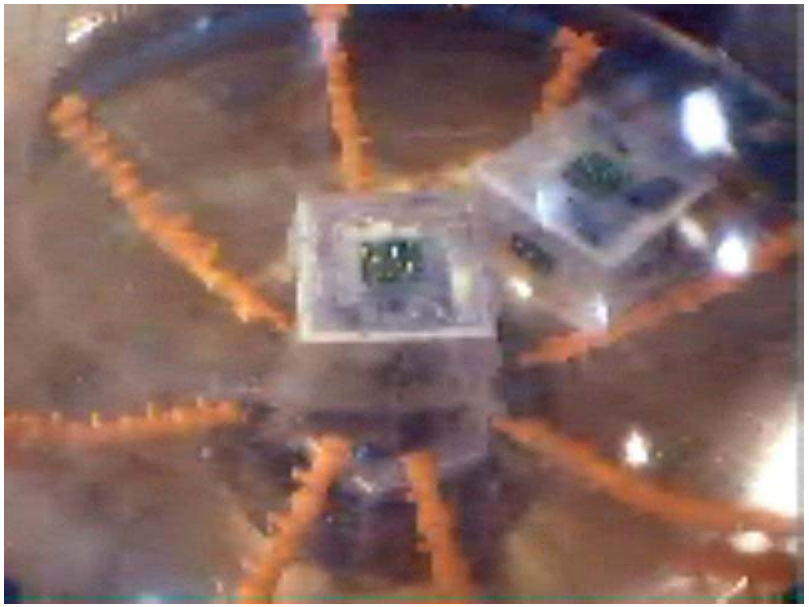
RSS'05 Progress Report

- We presented a simulation that allowed us to explore:
  - the factors that govern the rate of assembly and reconfiguration:
    - the shape of the target structure
    - the use of reconfiguration (rejection capability)
  - the effects of larger quantities of modules on the system



RSS'05 Progress Report

- We introduced a three-dimensional stochastic modular robotic system
  - in two implementations
  - scalable to microscale



Prototype I Problems

- Permanent magnets create undesired bonds
- Electromagnets require local power storage
- Viscous medium requires high actuation power
- Electromagnetic bonding and actuation does not scale

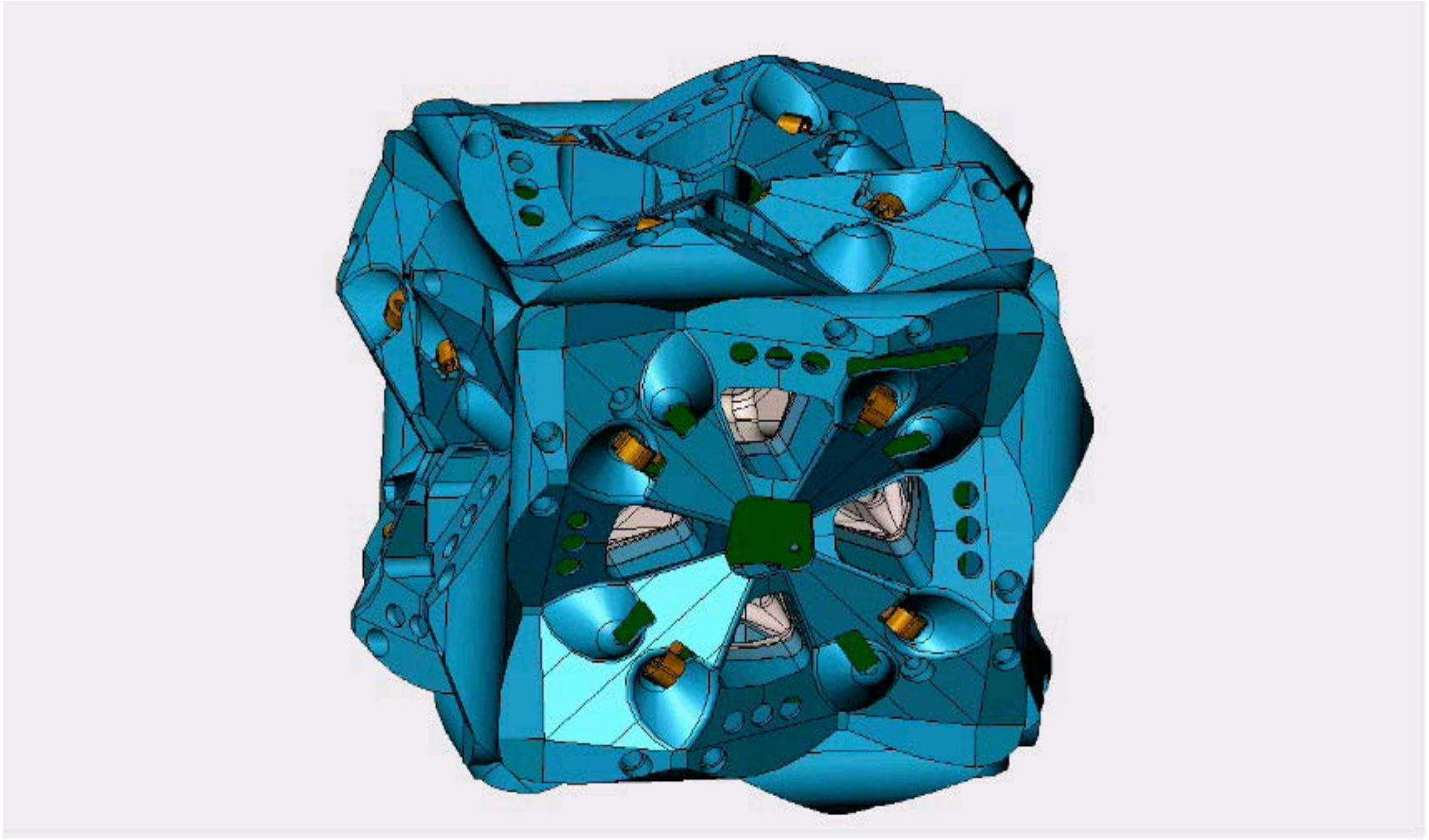
Prototype II Problems

- Very high module volume (2.2 liter vs. 1.0 liter) leads to
- High module inertia in neutral buoyancy environment
- Experiment speed reduction to prevent inertial module misalignment with the flow through valves
- Very large experimental installation for multi-module reconfiguration

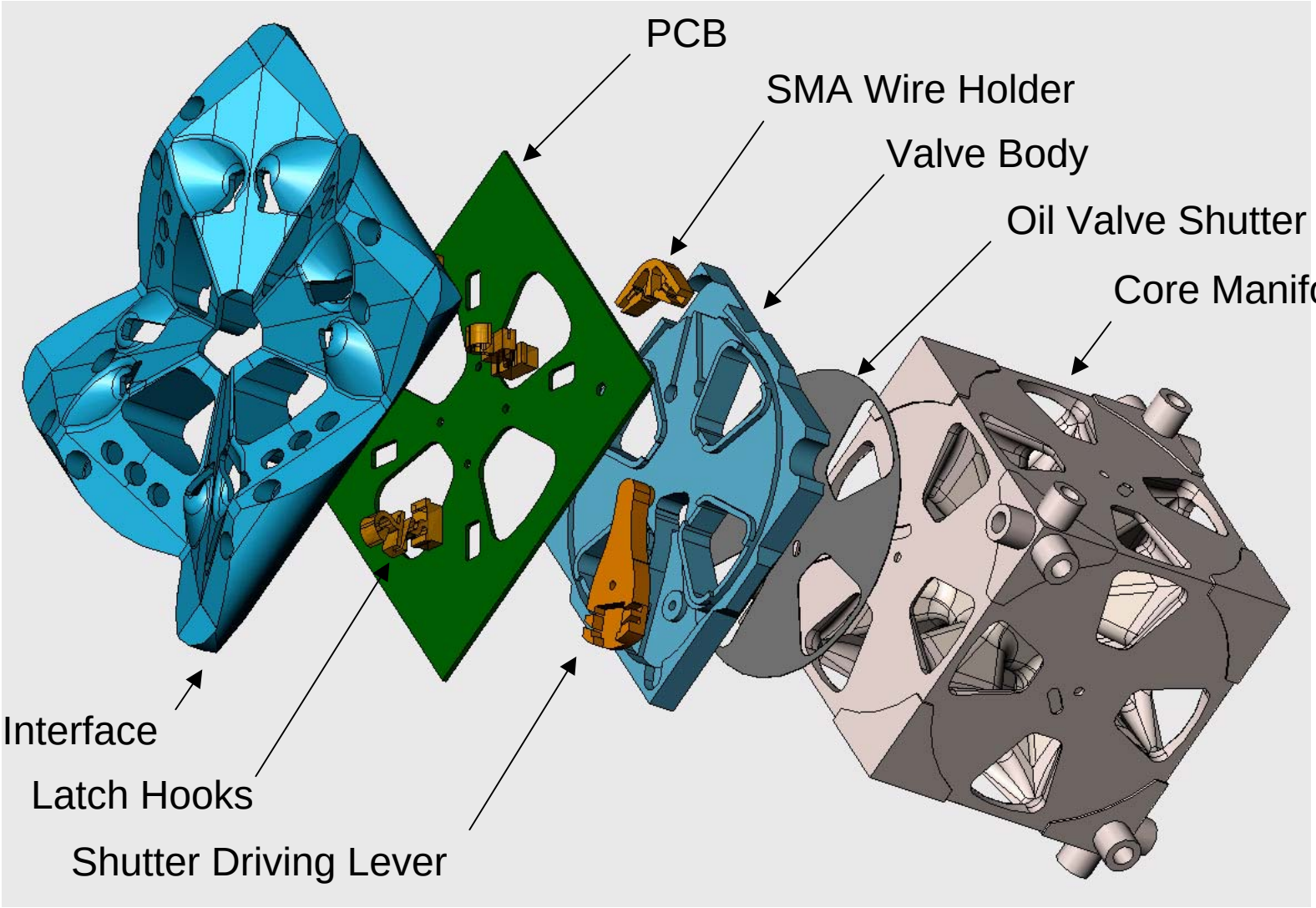
Revised Design Requirements

- All technology must be available for small-scale implementations
- Individual modular robots must:
  - be able to move freely in 3D within the fluidic medium
  - predictably and passively align and attach on contact
  - be able to receive and share electrical power with other modules and the substrate when attached
  - have means of communication with other modules/main controller
  - identify their position and orientation once attached to the structure
  - have means to control the fluid flow within the system
  - have ability to attach, passively bond to, and detach from the structure when commanded
  - be manufacturable in series of tens
- The substrate must:
  - attract the dormant modules floating with the fluid
  - be geometrically compatible with the modular robots
  - provide the modular robots with the electric power ..
  - and communication with the main controller

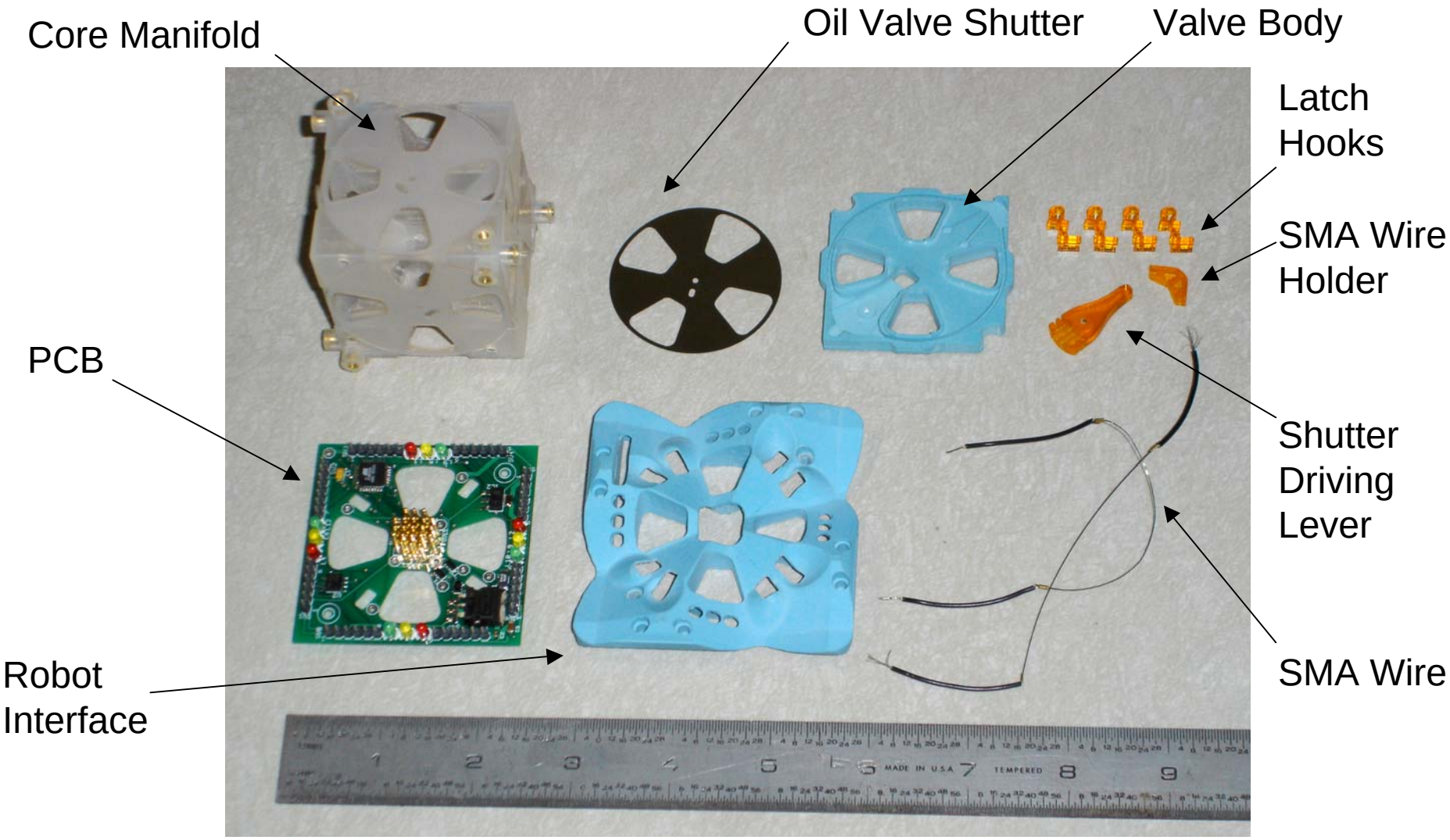
Re-Design, Version 3



Re-Design, Version 3



Re-Design, Version 3



Module Motion in 3D: Buoyancy

- Electrically non-conductive fluid
- Neutral buoyancy environment

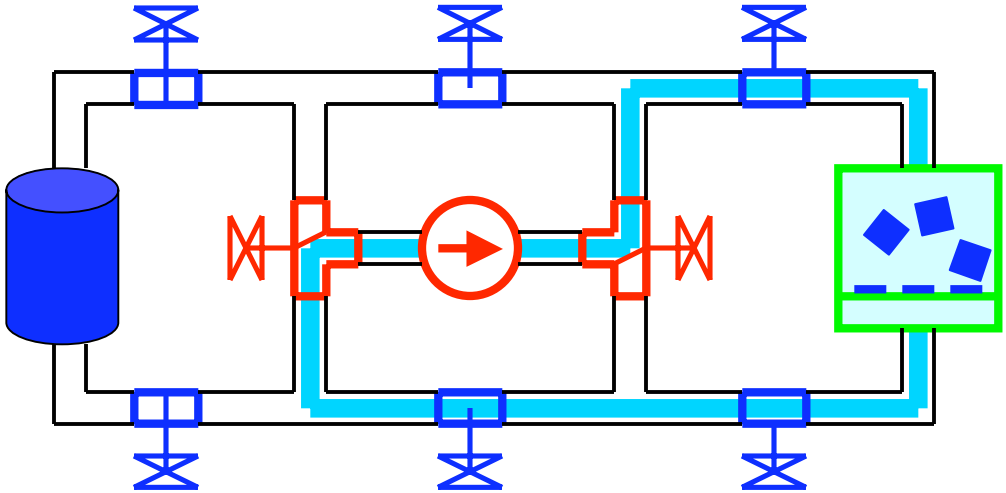
Buoyancy balance per 1/6 cube

Part	Weight, grams	Oil Displaced, grams	Buoyancy
Interface	11.5	12.9	+ 3.7
Valve Body	5.3	5.9	+ 1.2
1/6 Core	5.9	8.4	+ 2.6
Steel Parts	1.7	0.2	- 1.2
PCB	11.4	4.9	- 6.5
Total per 1/6 cube			- 0.2

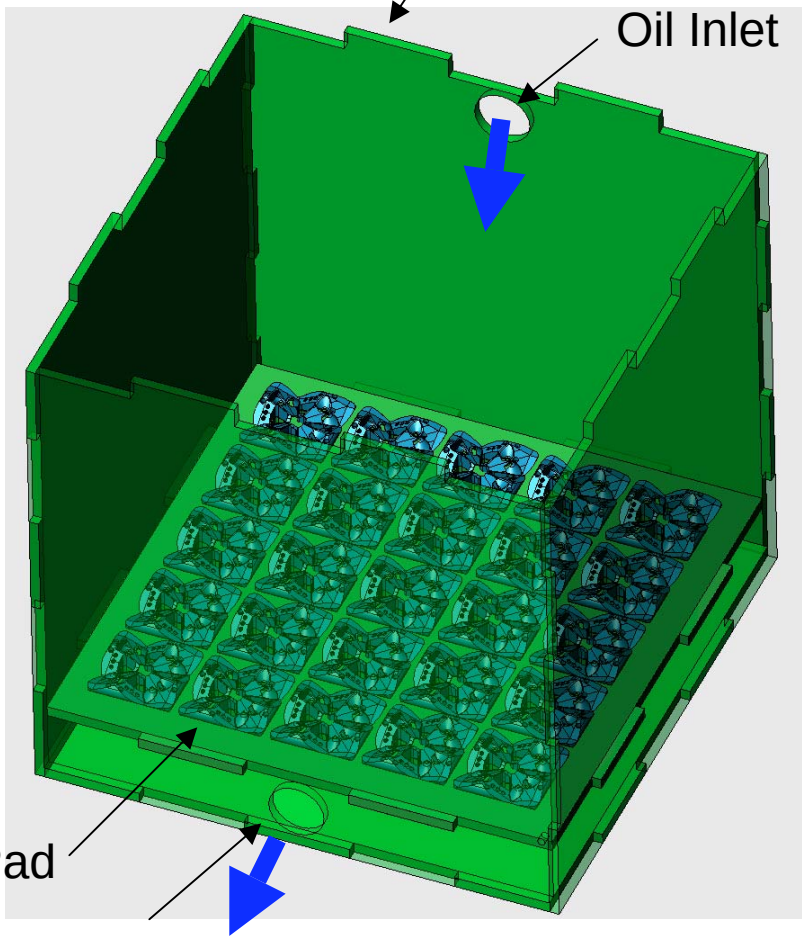
Module motion in 3D: Directed Flow

- Oil exchange rate: 50 gpm
- Reversible Flow

Forward Flow



Forward
Flow Rate
Adjustment



Module motion in 3D: Directed Flow

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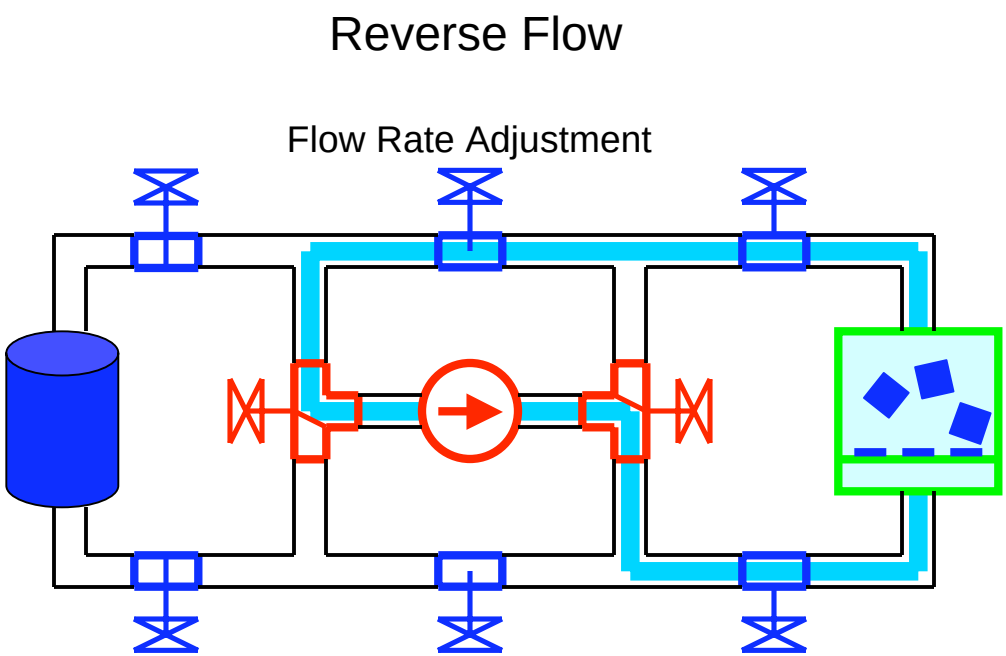

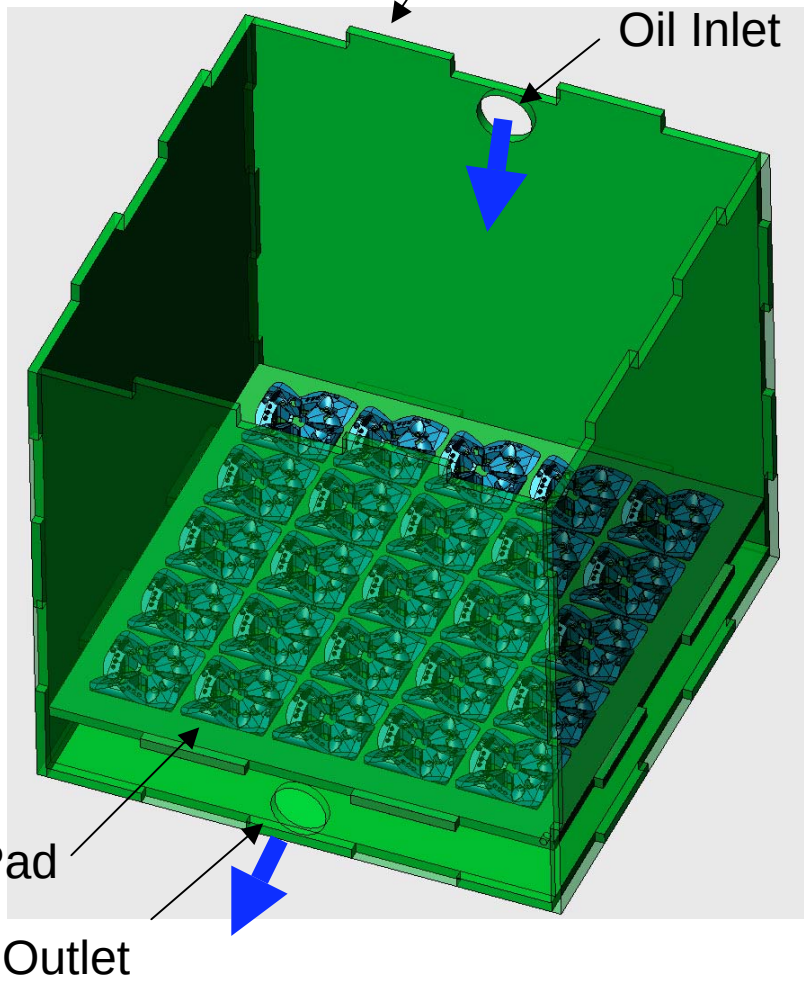

Module motion in 3D: Directed Flow

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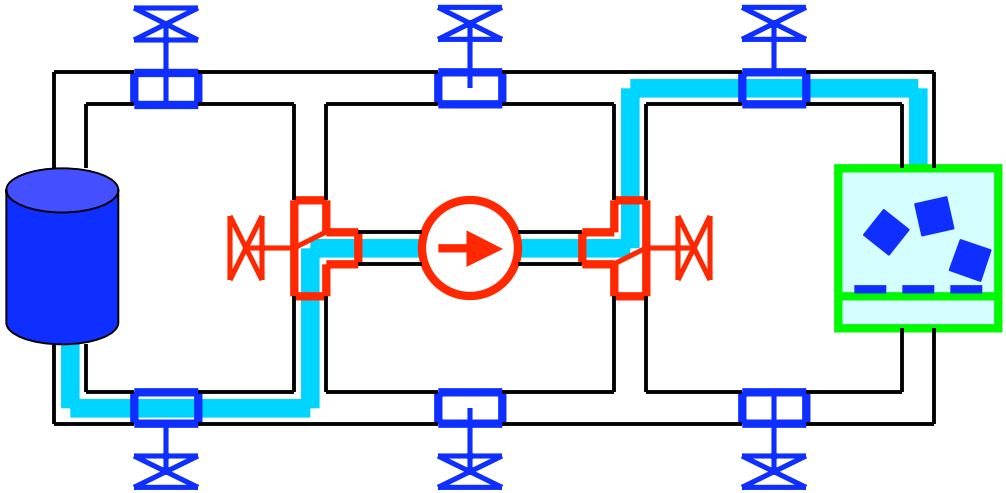
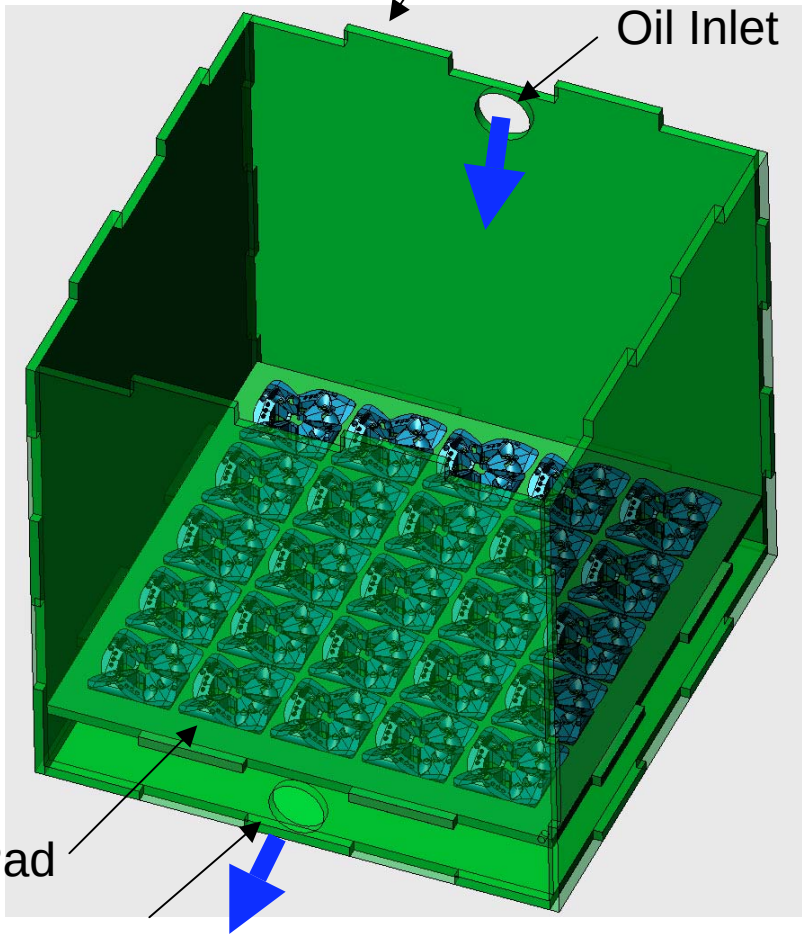
Filling Aquarium

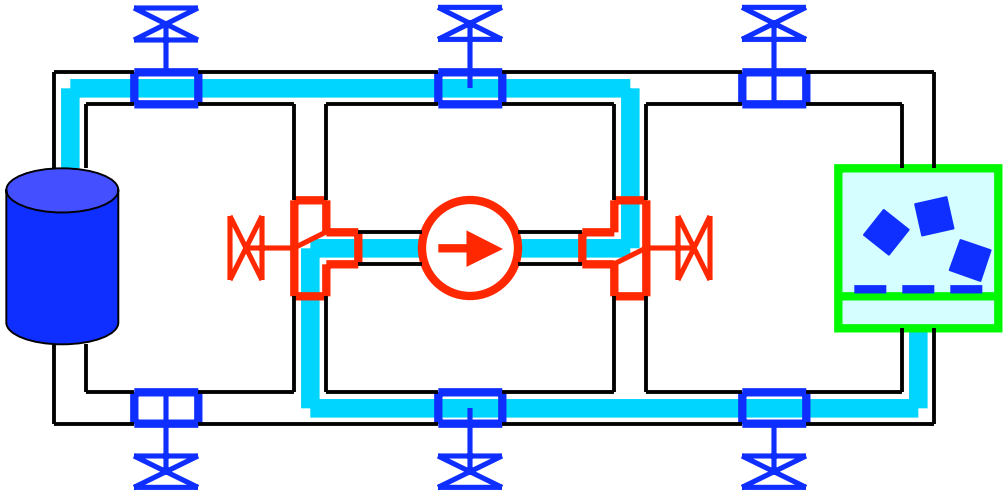


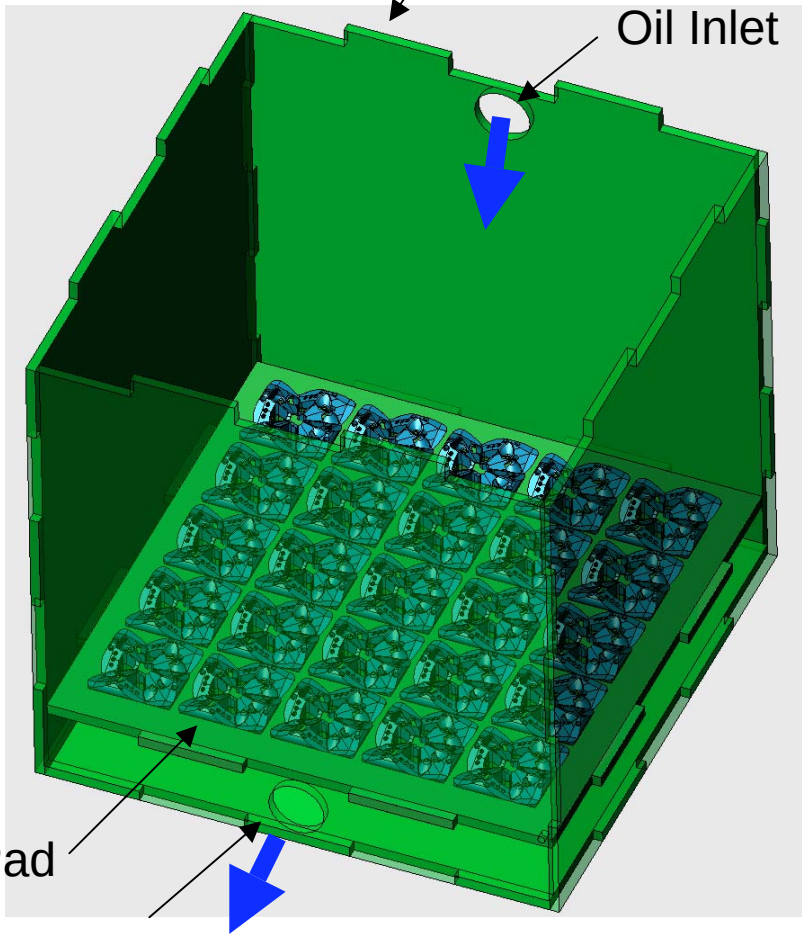


Module motion in 3D: Directed Flow

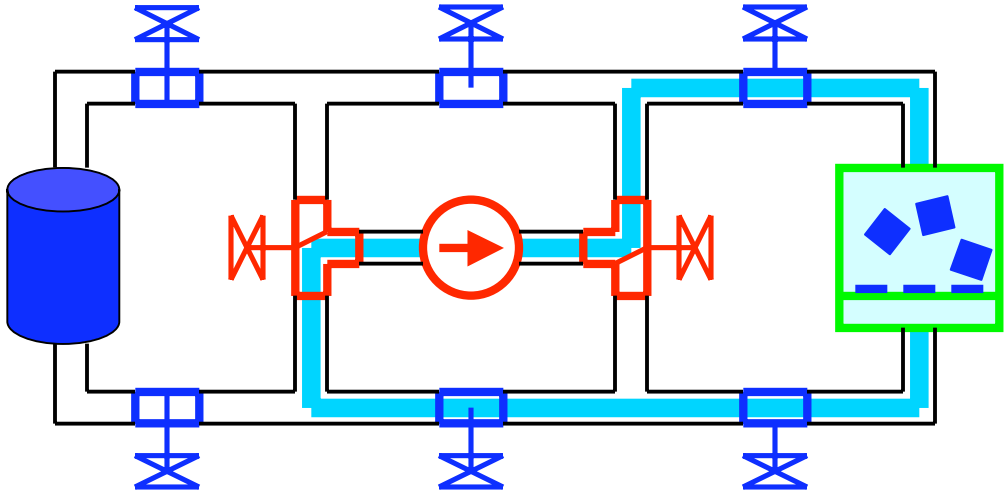
- Oil exchange rate: 50 gpm
- Reversible Flow

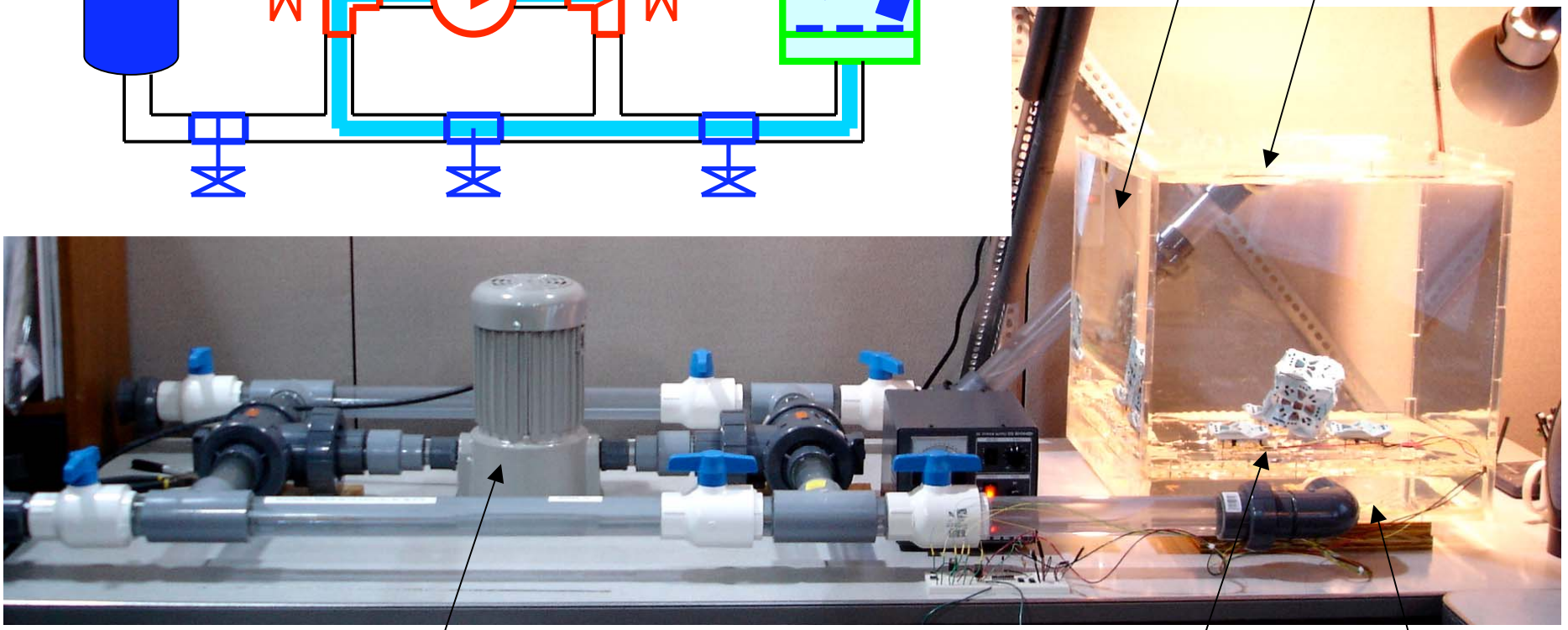
Draining Aquarium





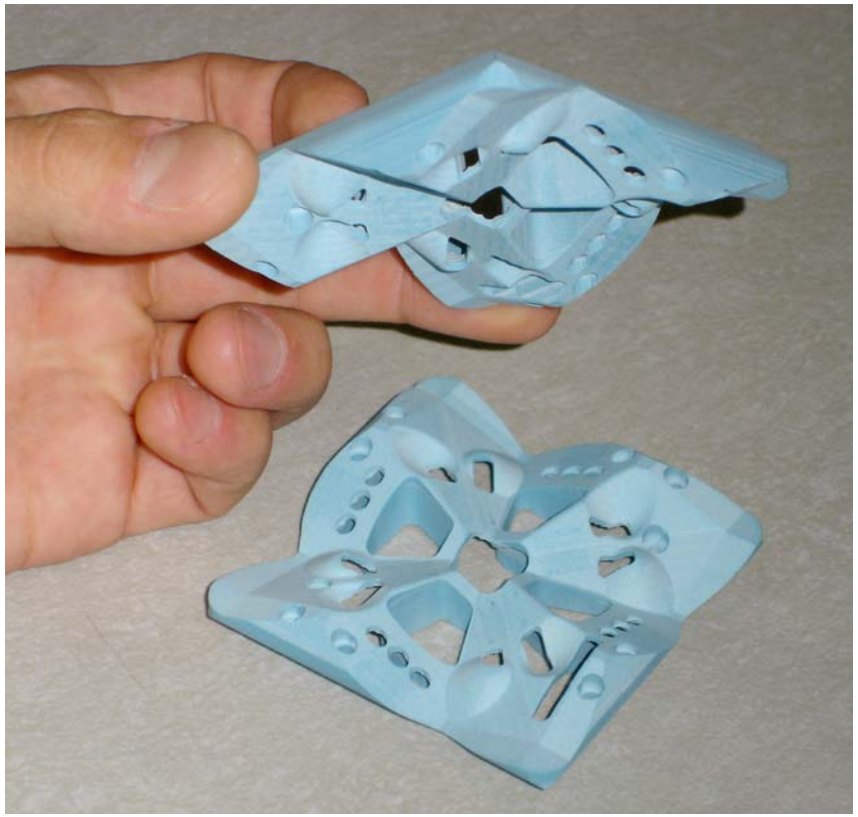
Module motion in 3D: Directed Flow

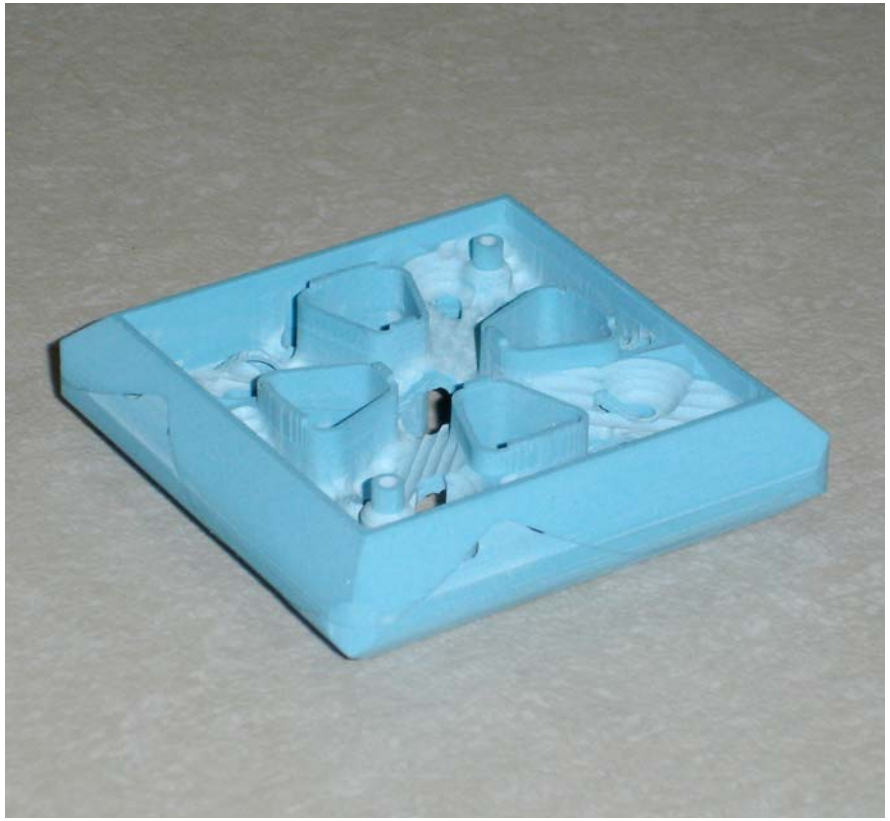




Passive Robot Alignment: Though Interface Geometry

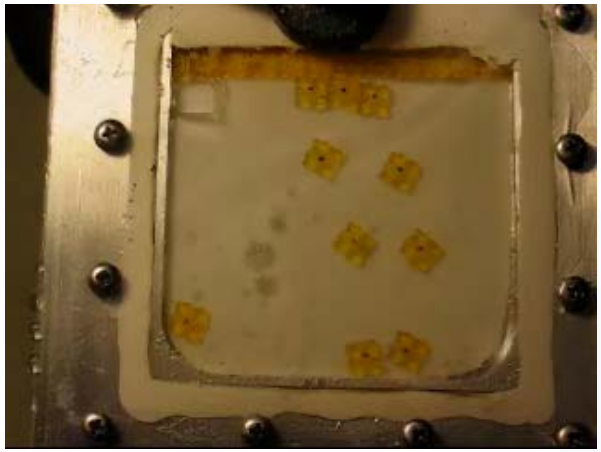
- Geometrical affinity of robot interfaces
- Exact passive alignment at four relative orientations

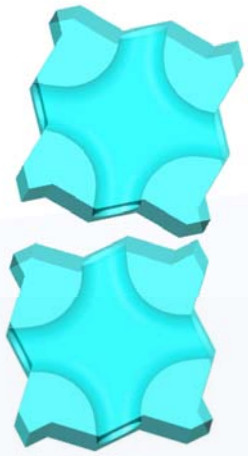


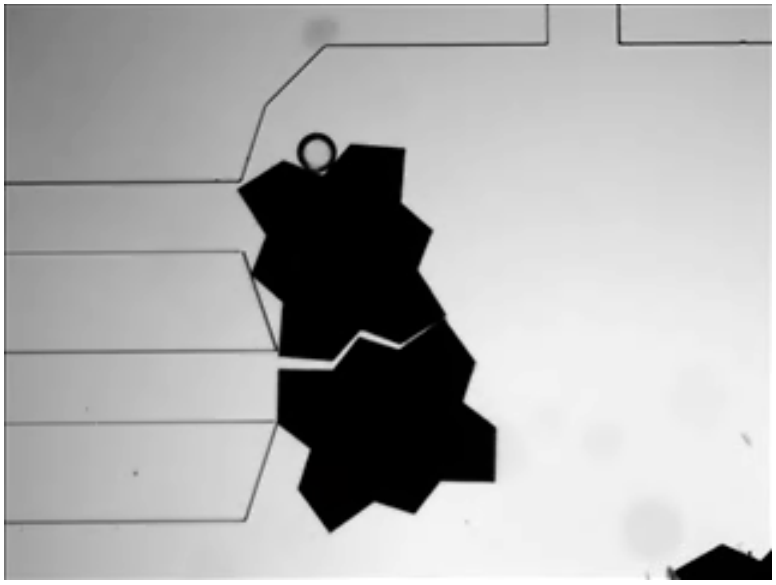


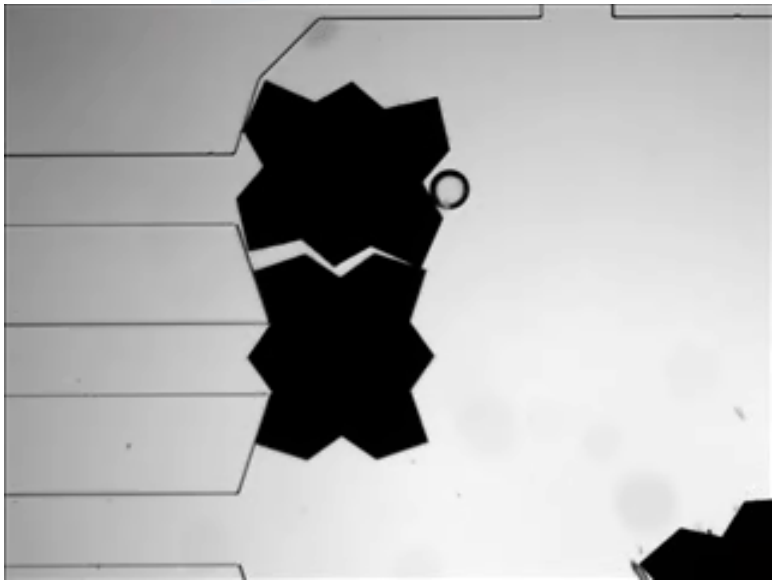
Passive Robot Alignment at Small Scales

- Meso-scale tiles, Hod Lipson (2005)
- Micro-scale tiles, Mike Tolley (2006)



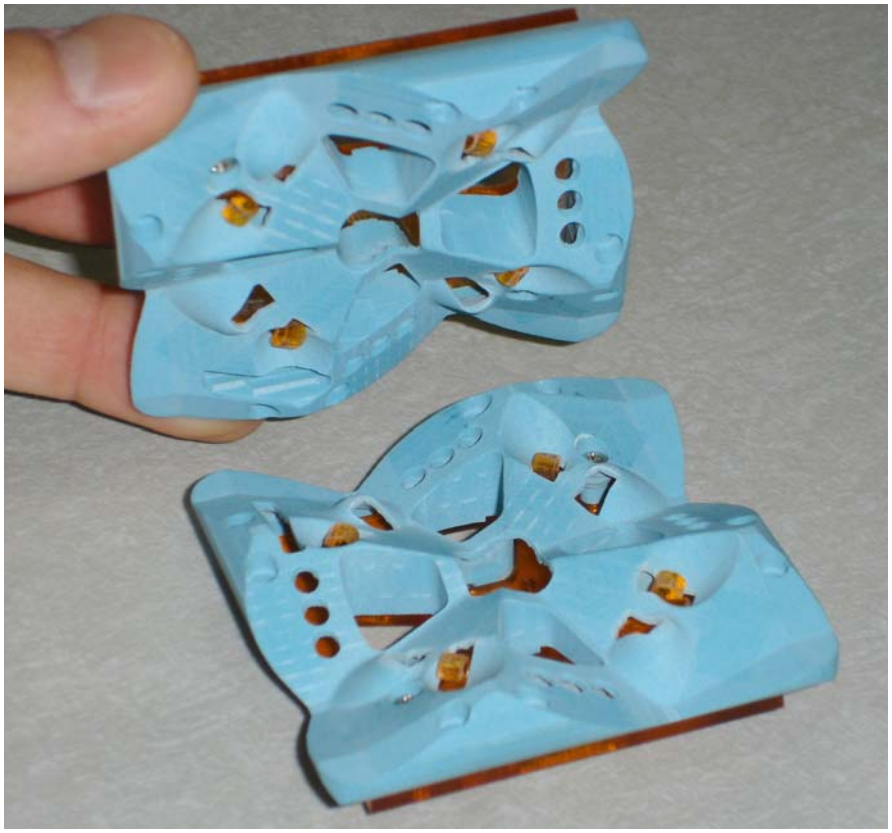


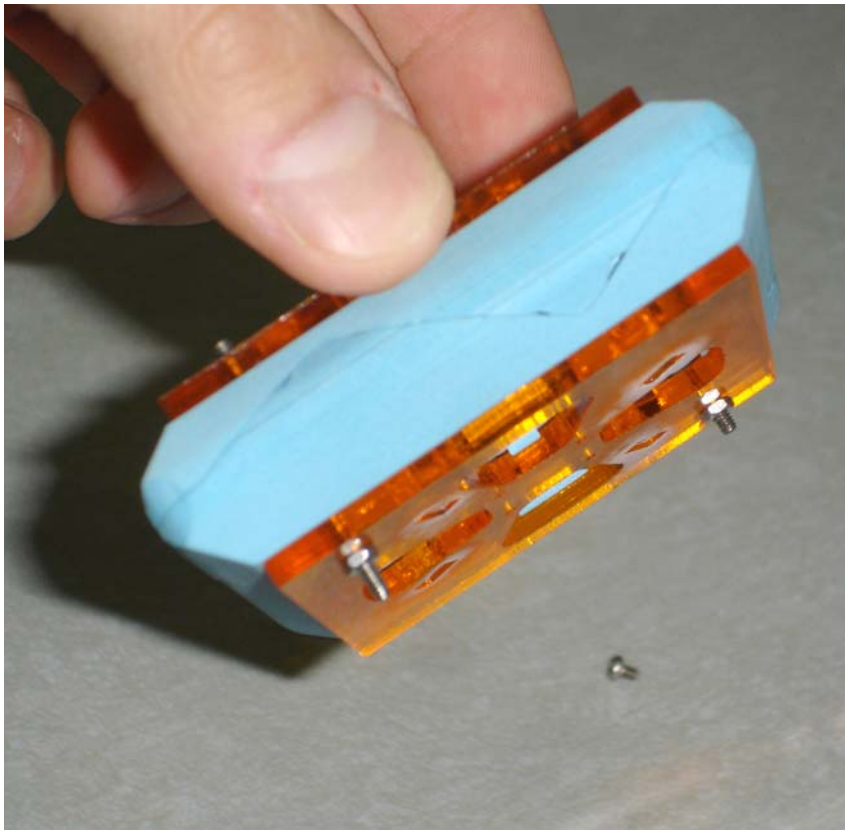


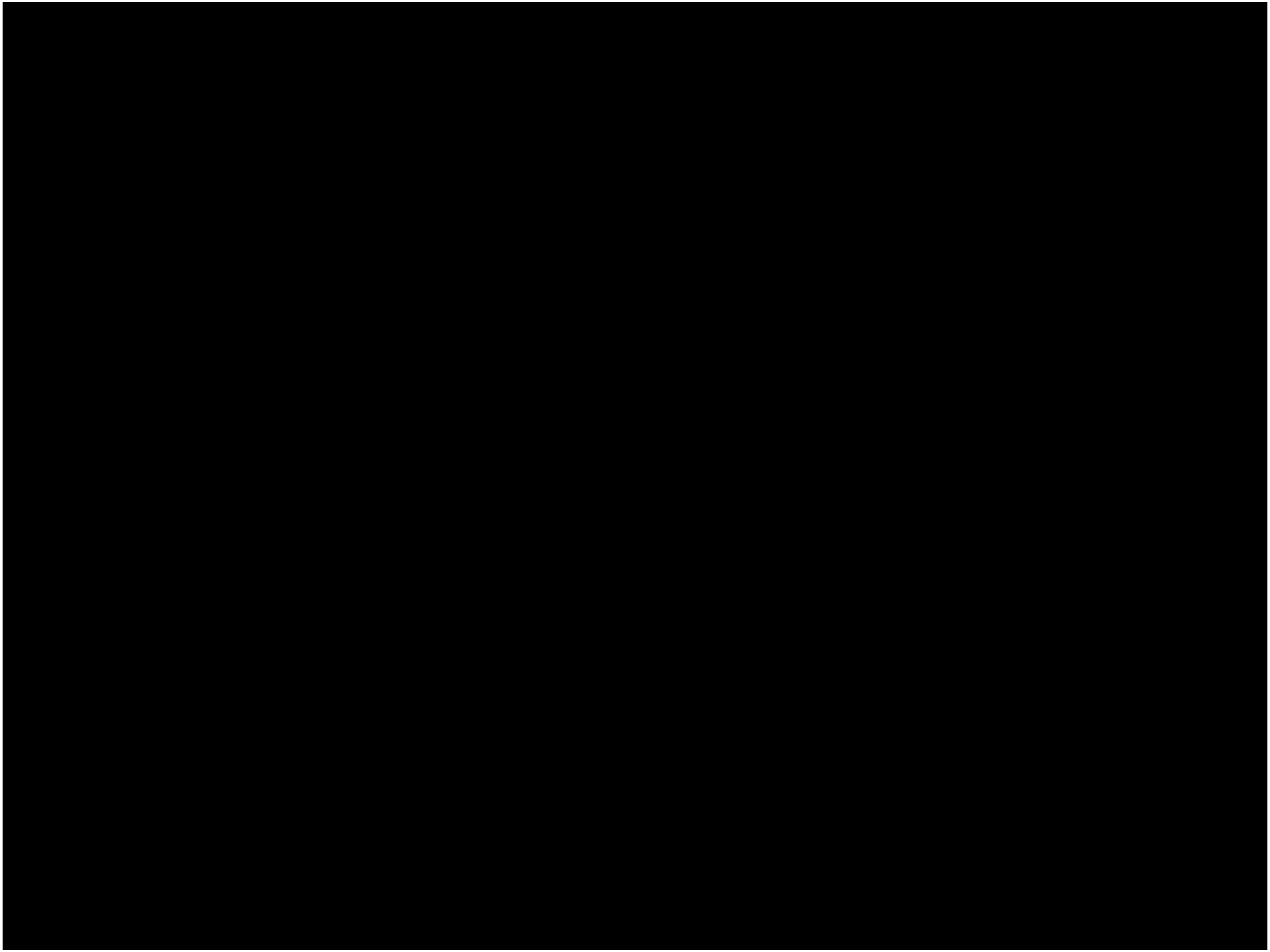


Passive Robot Latching and Unlatching

- Four elastic latches per interface
- Elastic latches are driven by SMA wires
- Acrylic is protected from melting by 4 coats of Nansulate High Heat

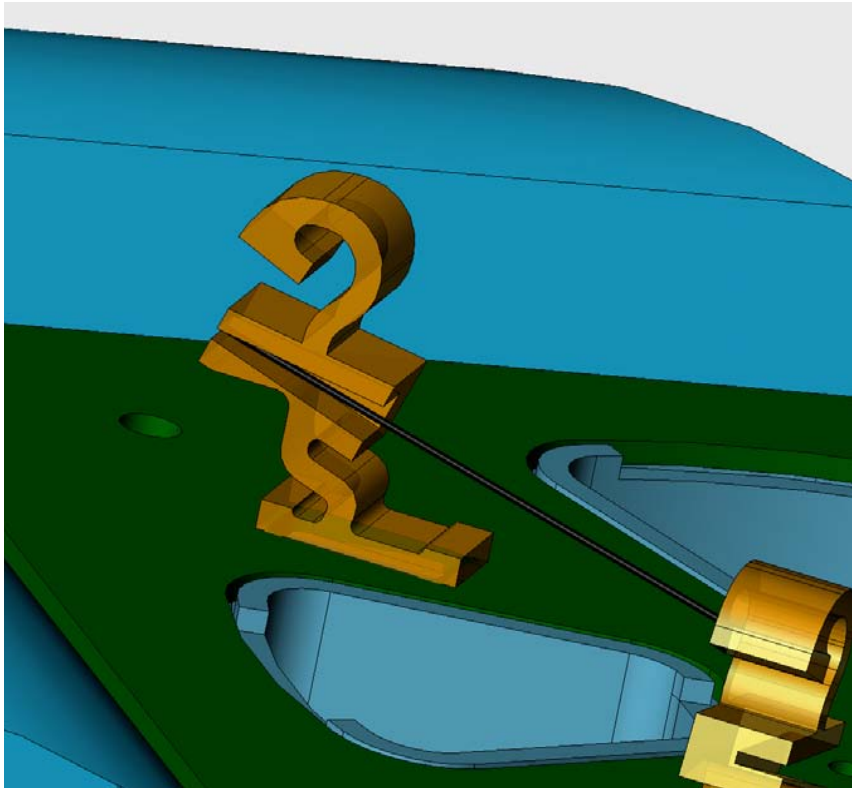


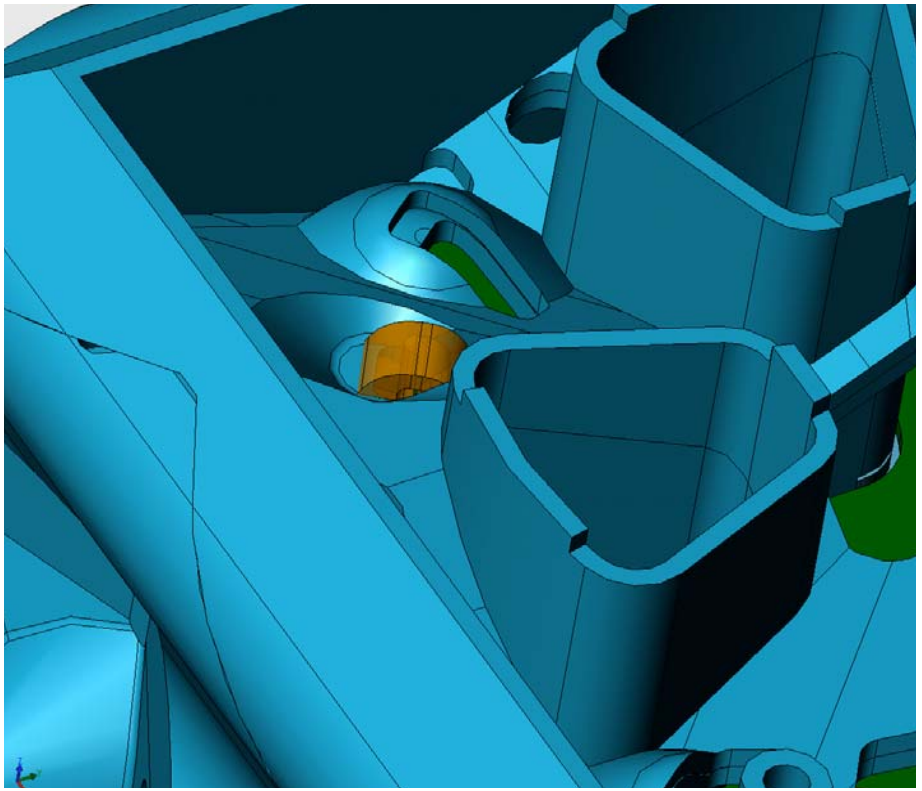




Active Robot Unlatching

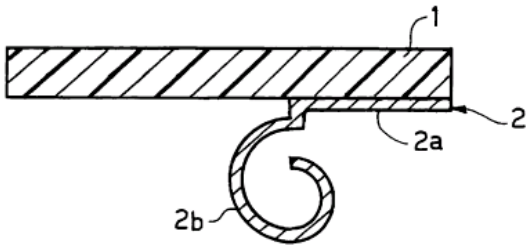
- Latch hook geometry allows passive interconnection
- Wire length 19.5 mm, required travel 0.5 mm (2.5 %)

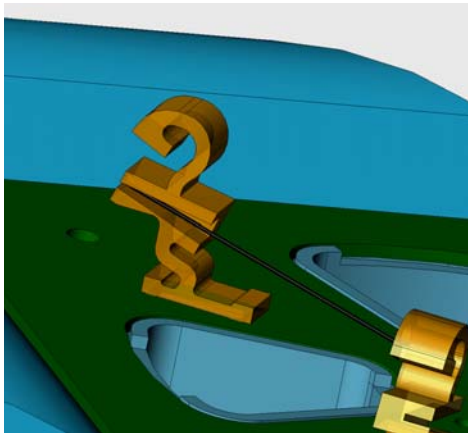




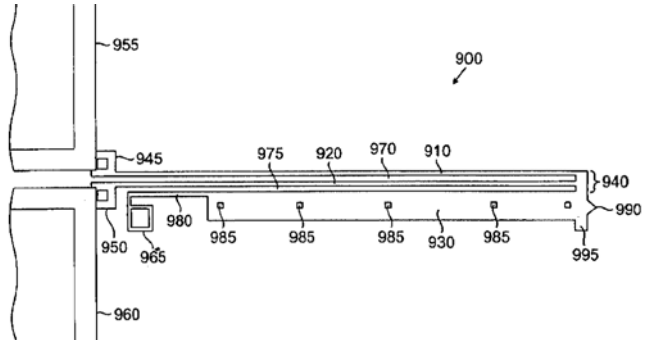
Active Robot Unlatching at Small Scales

- U.S. Patent 6,983,594 “Shape memory thin micro-actuator, and method for producing the same”

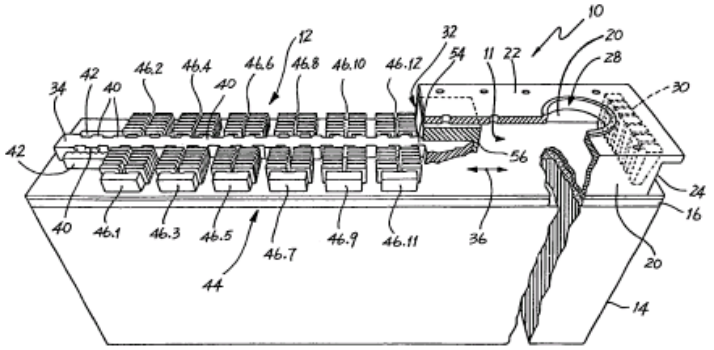




- U.S. Patent 6,691,513 “System and method for providing an improved electrothermal actuator for a micro-electro-mechanical device”

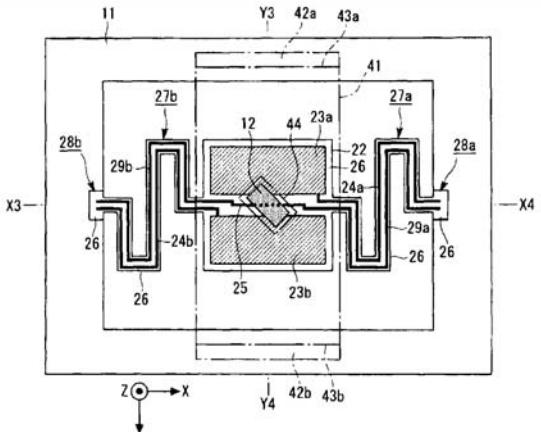


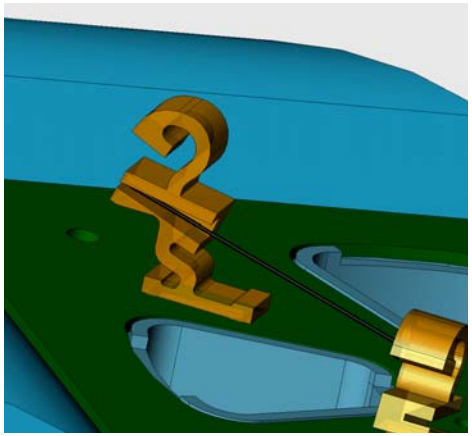
- U.S. Patent 6,454,396 “Micro electro-mechanical system which includes an electromagnetically operated actuator mechanism”



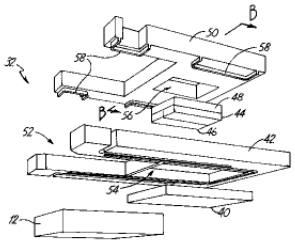
Active Robot Unlatching at Small Scales

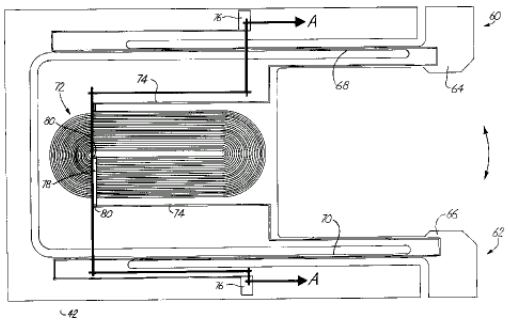
- U.S. Patent 6,936,950 “Micro-actuator utilizing electrostatic and Lorentz forces, and micro-actuator device, optical switch and optical switch array using the same”



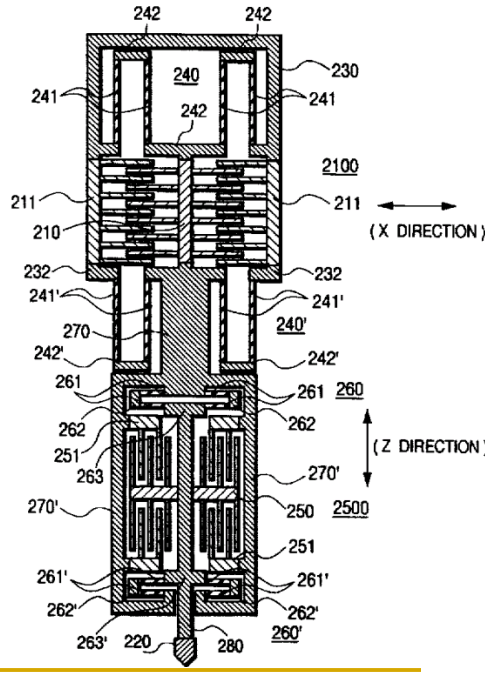


- U.S. Patent 6,661,617 “Structure and fabrication process for integrated moving-coil magnetic micro-actuator”



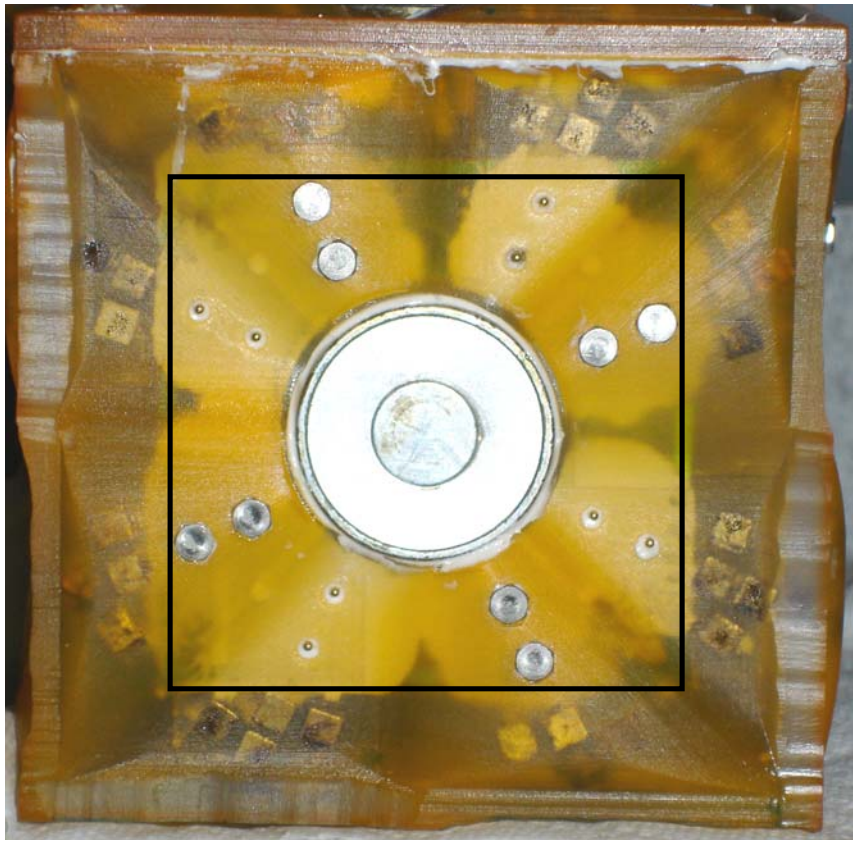


- U.S. Patent 5,801,472 “Micro-fabricated device with integrated electrostatic actuator”

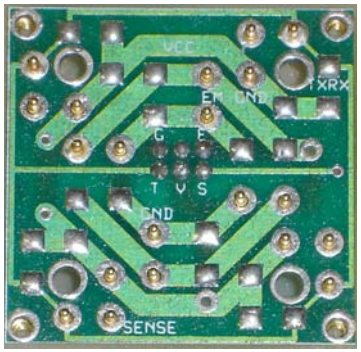


Electrical Interconnection

Oily Cubes I:
3 electric lines
17 terminals
60 mm x 60 mm (black square)

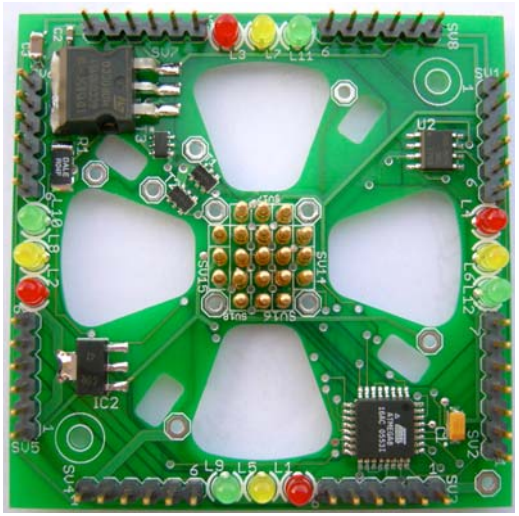


Oily Cubes II:
5 electric lines
20 terminals
40 mm x 40 mm



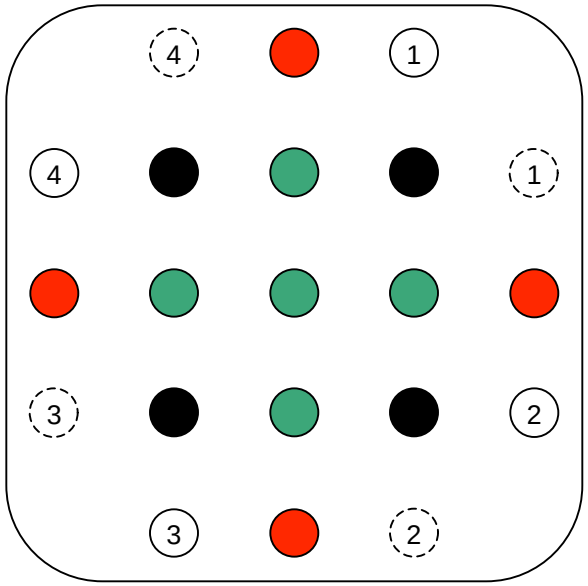
Oily Cubes III:
11 electric lines
21 terminals
12 mm x 12 mm

Whole PCB
60 mm x 60 mm

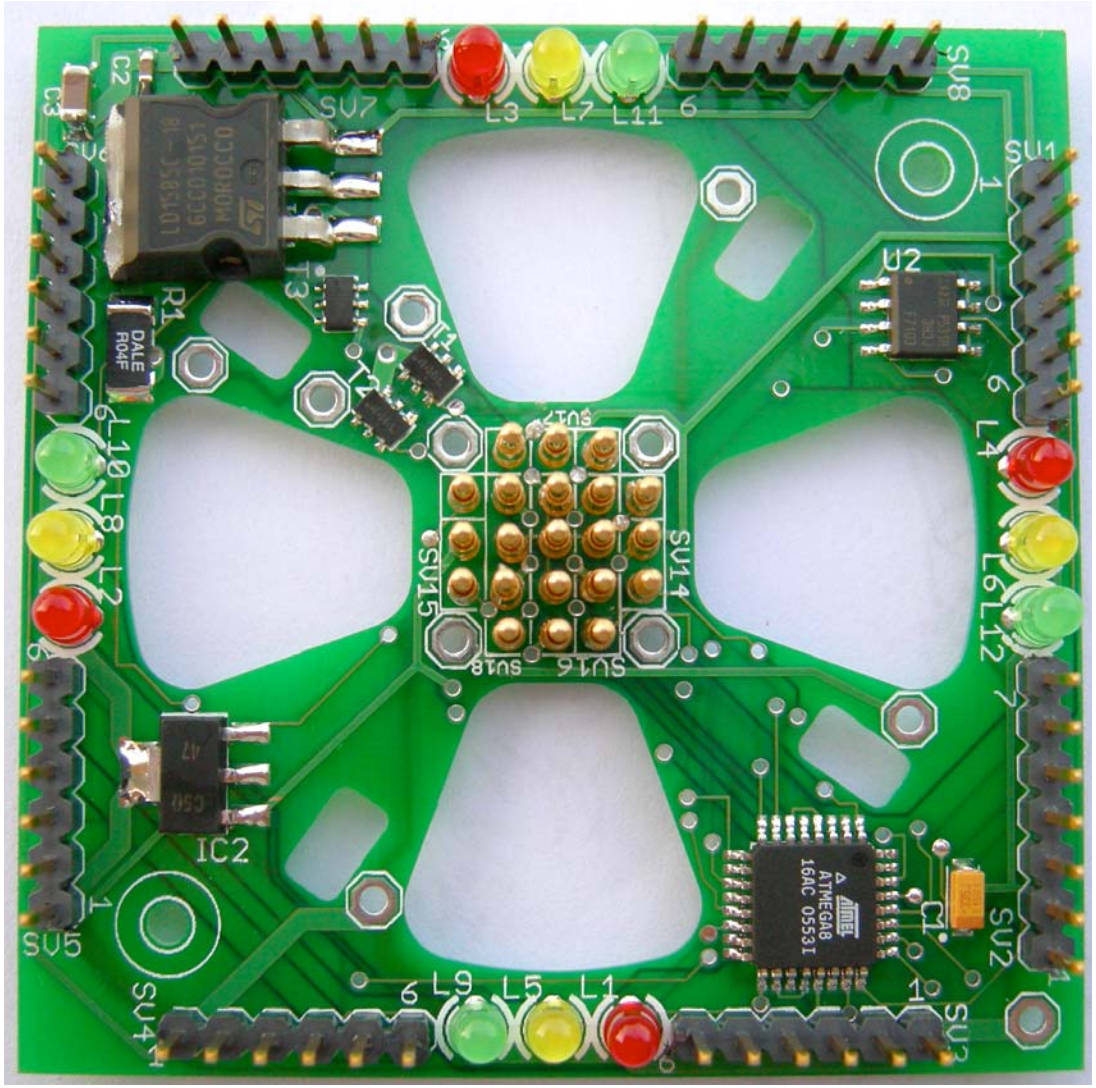


Electrical Interconnection

- Hermaphroditic pin-to-pin connectors
- Symmetric contact pattern

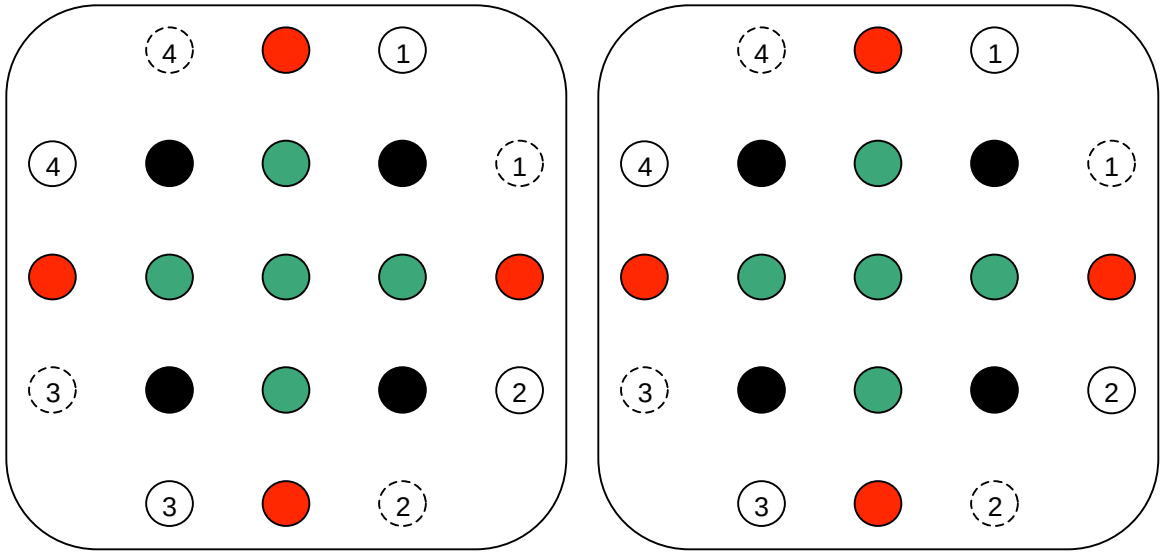


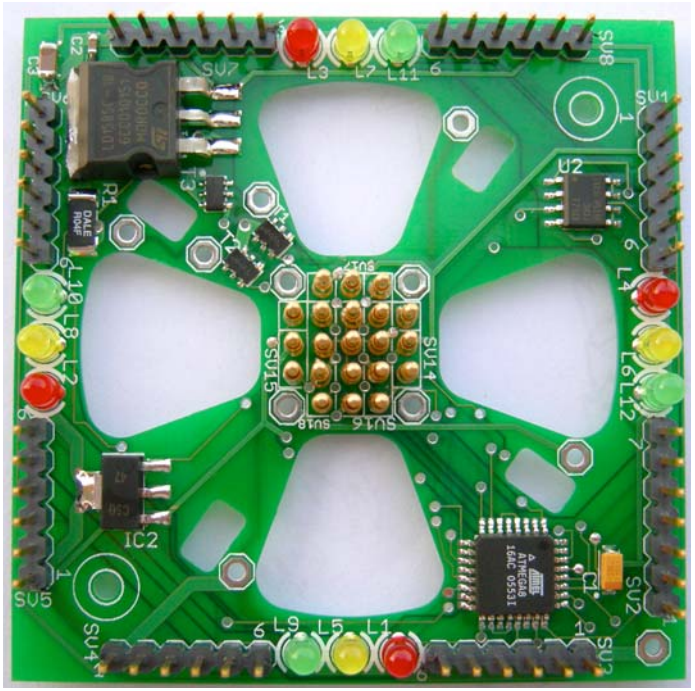
- communication
- ground
- power
- 1 - orientation sensor inputs
- 1 - orientation sensor outputs



Orientation Sensing and Communication

- Face-to-face interconnection matches sensor inputs with outputs





- communication
- ground
- power

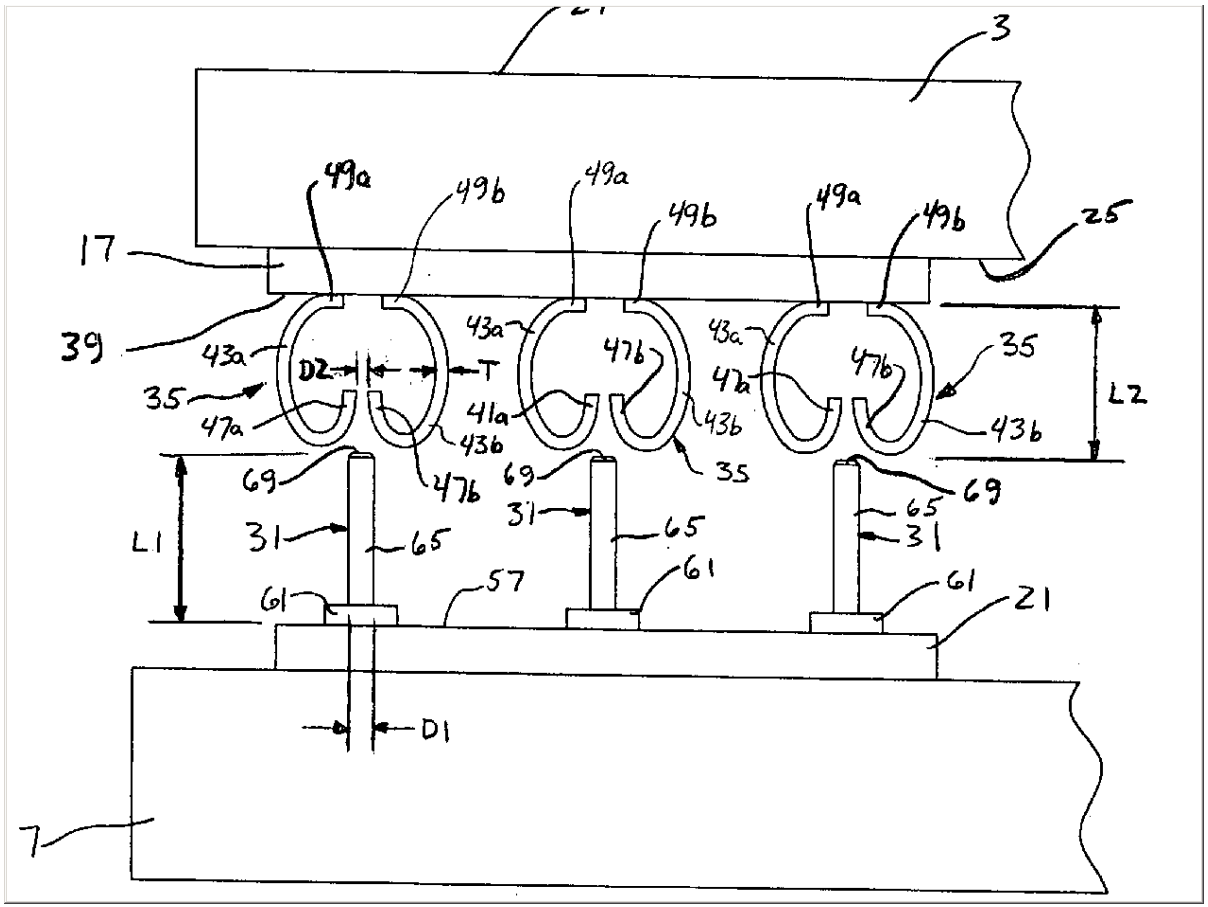
1 - orientation sensor inputs

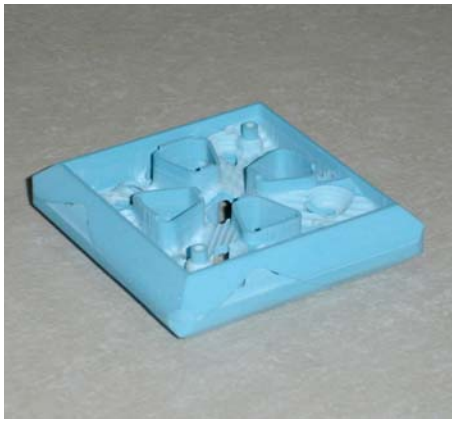
1 - orientation sensor outputs

- One wire Dallas common bus communication protocol
- One PCB per side simplifies manufacture

Electrical Interconnection at Small Scales

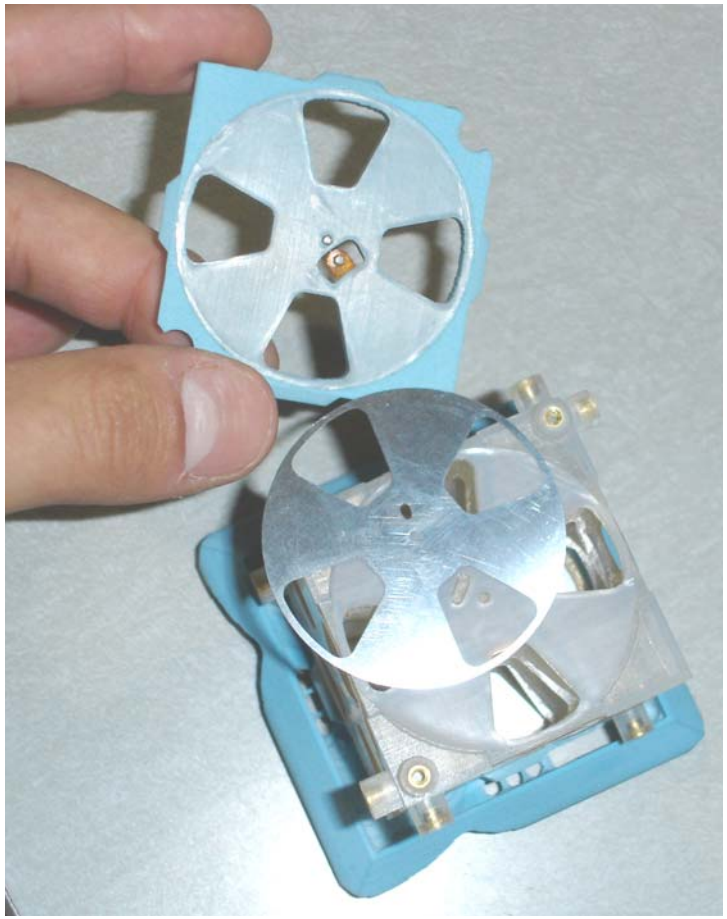
- U.S. Patent 6,881,074 “Electrical circuit assembly with micro-socket”

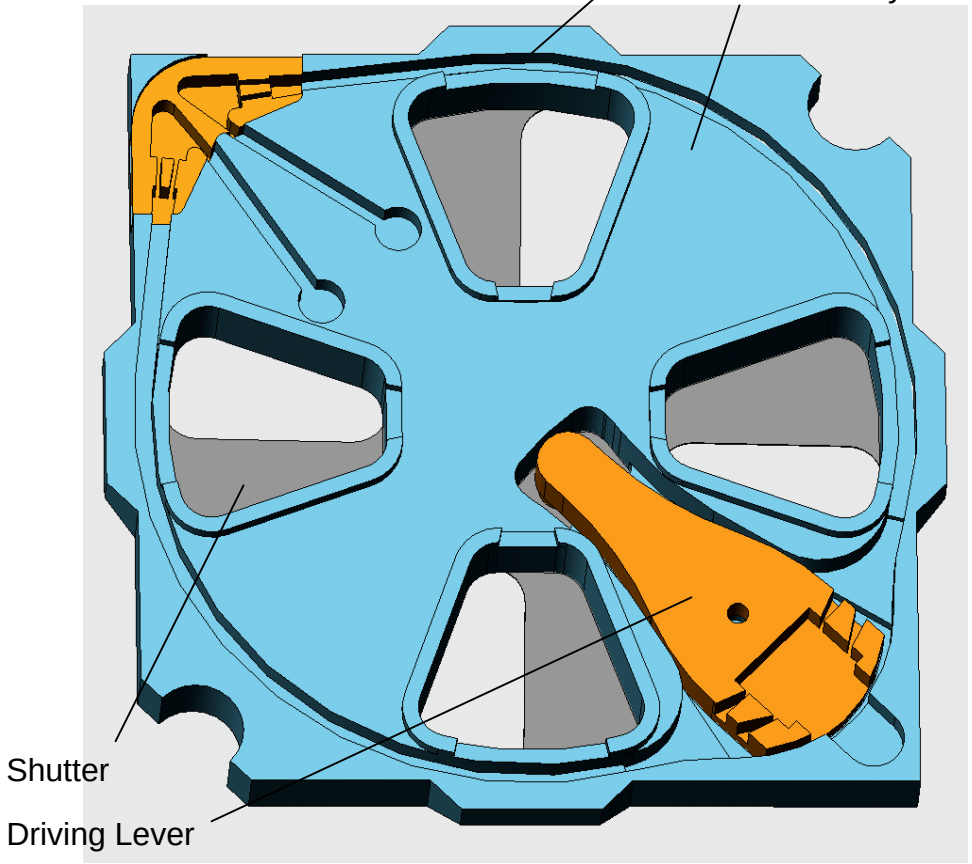




Valve Actuation

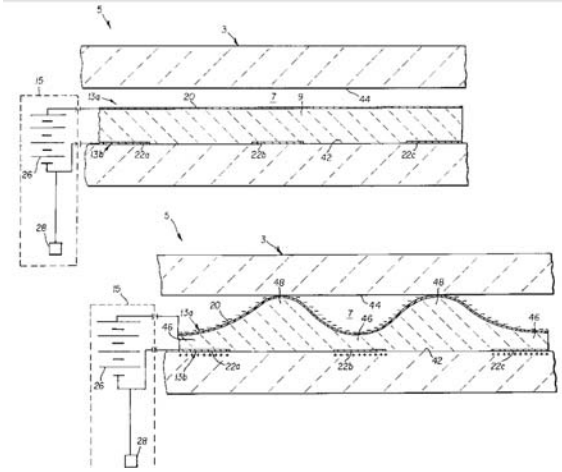
- 0.006” stainless steel valve driven reversibly by two sets of SMA wires
- Teflon pads reduce the friction of valve and SMA wires

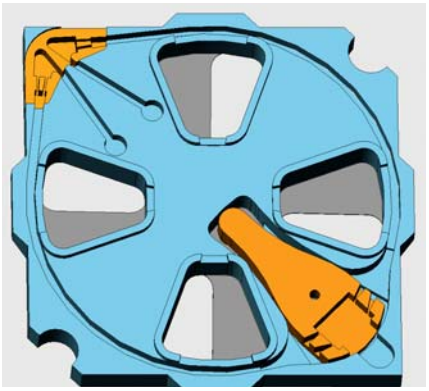




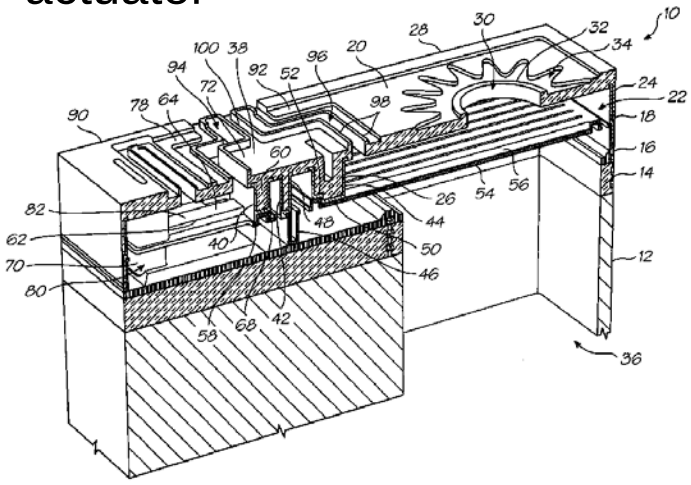
Valve Actuation at Small Scales

- U.S. Patent 6,626,416 “Electrostrictive valve for modulating a fluid flow”

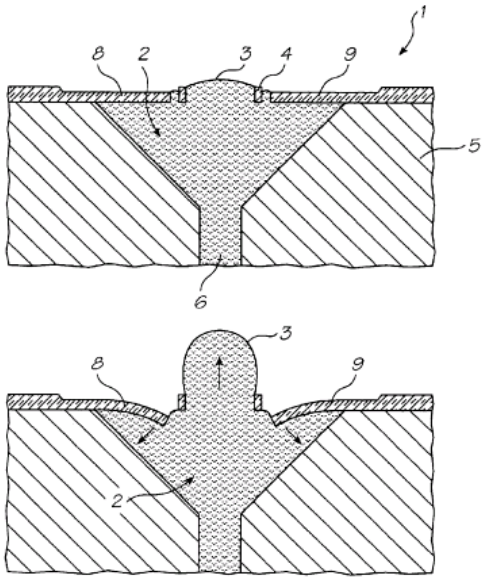




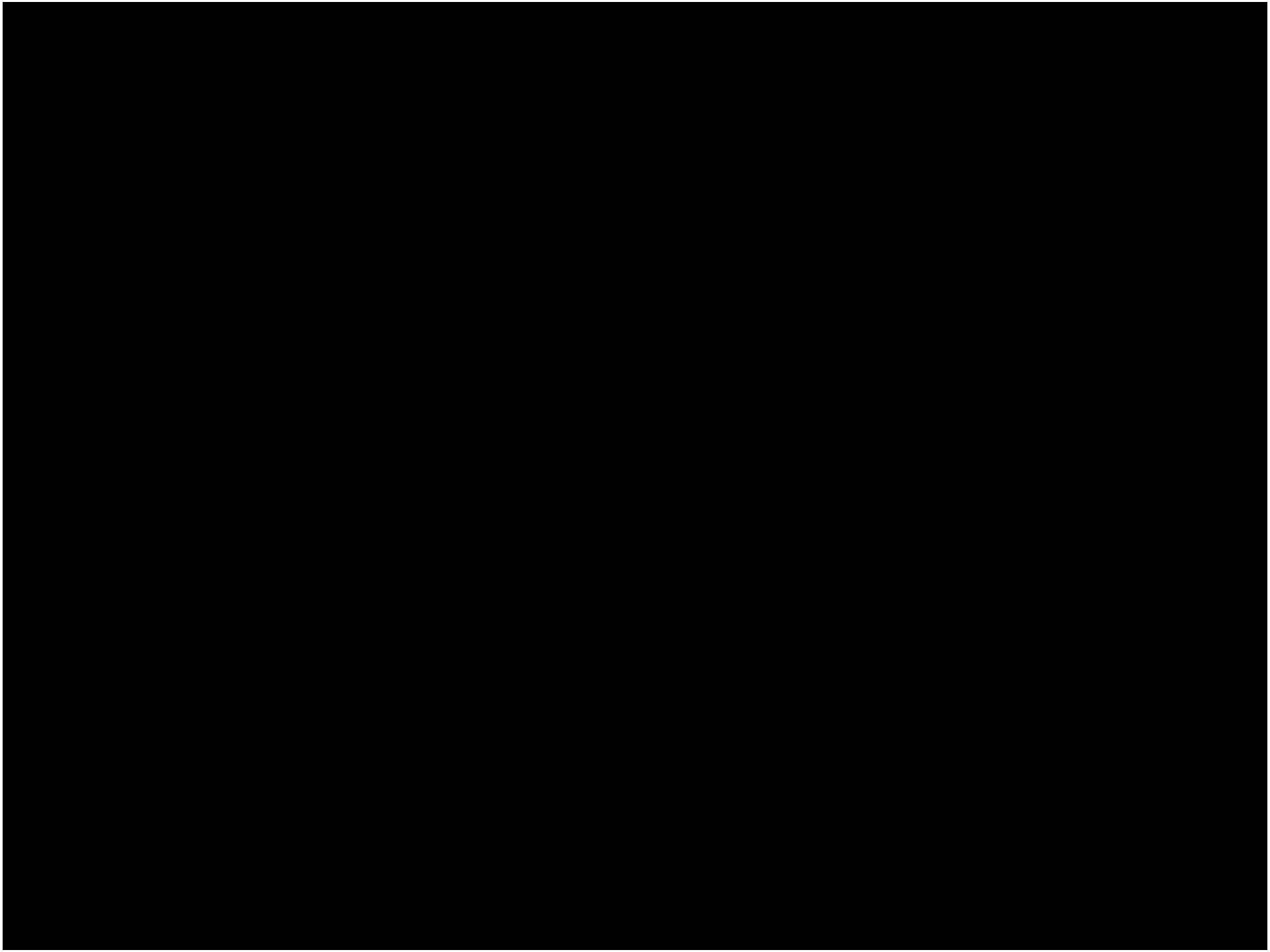
- U.S. Patent 6,948,799” Micro-electromechanical fluid ejecting device that incorporates a covering formation for a micro-electromechanical actuator



- U.S. Patent 6,969,153 “Micro-electromechanical fluid ejection device having actuator mechanisms located about ejection ports

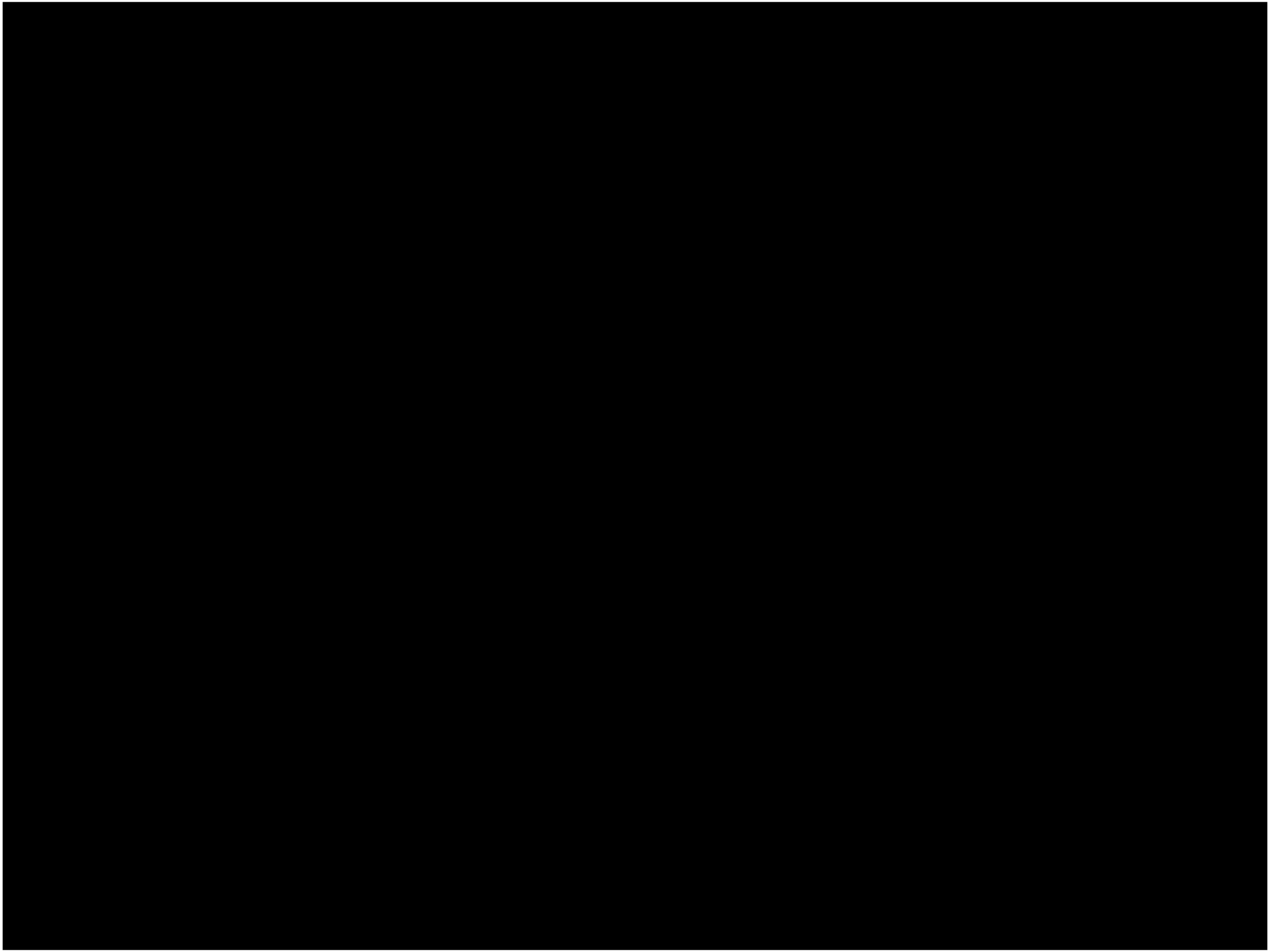


Experimental Module Manipulation: Attraction and Release



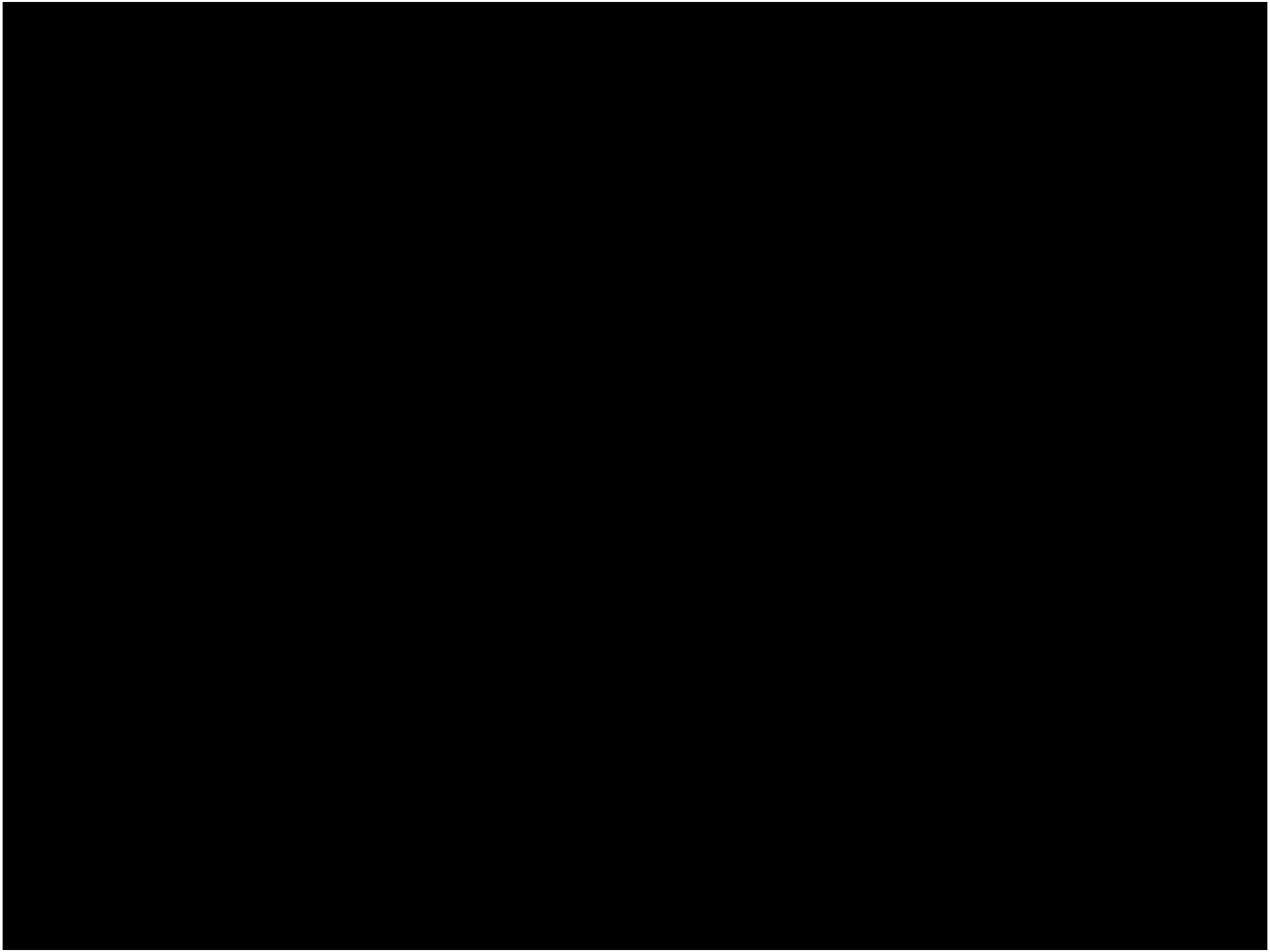
Experimental Module Manipulation: Attraction and Release

- *Problem:*
  - Module misalignment and clogging
- *Solution:*
  - Periodic valve closing and re-opening while expecting module attachment

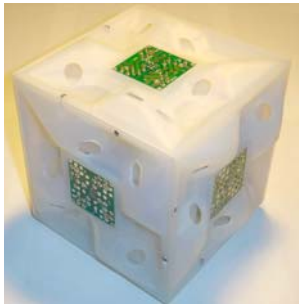


Remote Module Manipulation

- *Task:*
  - (Desirably) influence the motion of passively floating modules
- *Solution:*
  - Change fluid flow patterns by appropriate flow redirection through various sets of active valves



Prototype comparison chart

Criteria			
3D grid size	100 mm	130 mm	80 mm
Module volume	1 liter	2.197 l	0.512 l
Module weight	0.81 kg	1.78 kg	0.415 kg
Fluid volume	47.9 l	47.9 l	63.5 l
Relative density	0.021	0.048	0.008
Connection time	14.9 min x 5	32.1 min x 5	*38.6 min x 3*
Rel. conn. time	1.810 min	7.496 min	*0.933 min*

Current Tasks

- Assemble all 20 modular robots from the outsourced parts
- Conduct multi-module experiments in self-assembly, reconfiguration, batch assembly
- Compare physical system performance with available simulations, improve simulator based on observations
- Test algorithms for assembly and reconfiguration obtained in the simulation