NanoRobotics Lab @ Carnegie Mellon

Mobile Micro-Robotics

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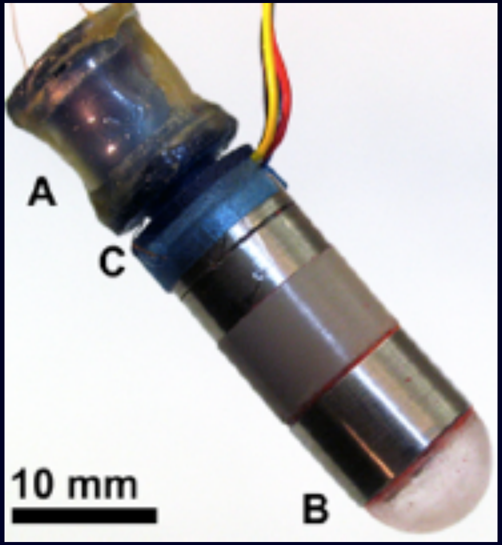
ICMC'11, 12 Sept. 2011

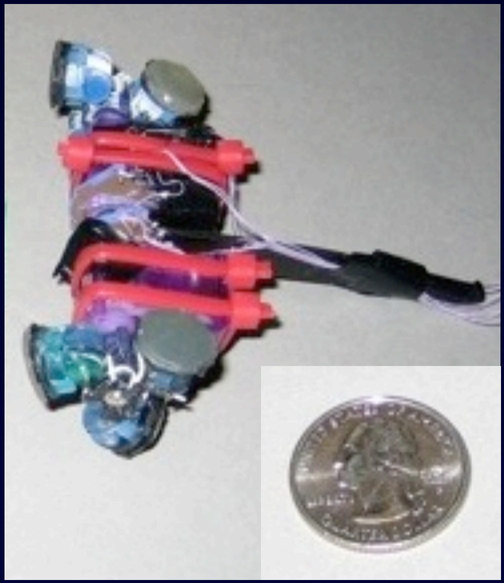
Outline

- Introduction
- Cell Actuated Micro-Robots
- Magnetic Micro-Robots
- Conclusions

Why Micron Scale Mobile Robots?

- Direct accessibility to smaller spaces/scales
- Smaller, faster, lightweight, and possibly cost-effective (portable, agile, & disposable)
- Potential of being massively parallel, in large numbers, and distributed
- Applications: Health-care, space, inspection and maintenance, environmental monitoring, entertainment, education, …





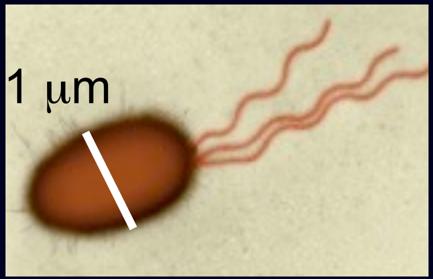
Characteristics of Micro-Robots*

- <u>Micron scale physics and dynamics</u>:
  - Increased surface area to volume (S/V) ratio:

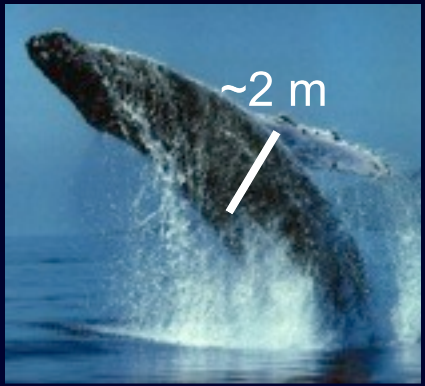
$$\frac{S}{V} \propto \frac{L^2}{L^3} \propto L^{-1}$$

    - Surface forces/drag/friction >> Inertial forces
      - Sticky & dissipative world!
    - Fast cooling, …
  - Inherently nonlinear, fast and stochastic dynamics
  - More sensitive to disturbances (and <u>morphology</u>)

- **<u>Limited everything</u> (actuation, power, computing, communication, and sensing)**



S/V = 10^3 /mm
Re = 10^{-4}
30-50 body length/sec



S/V = 10^{-4} /mm
Re = 10^8
0.4 body length/sec

*M. Sitti, *IEEE Rob. Autom. Mag.* **14**(1), 53 (2007)

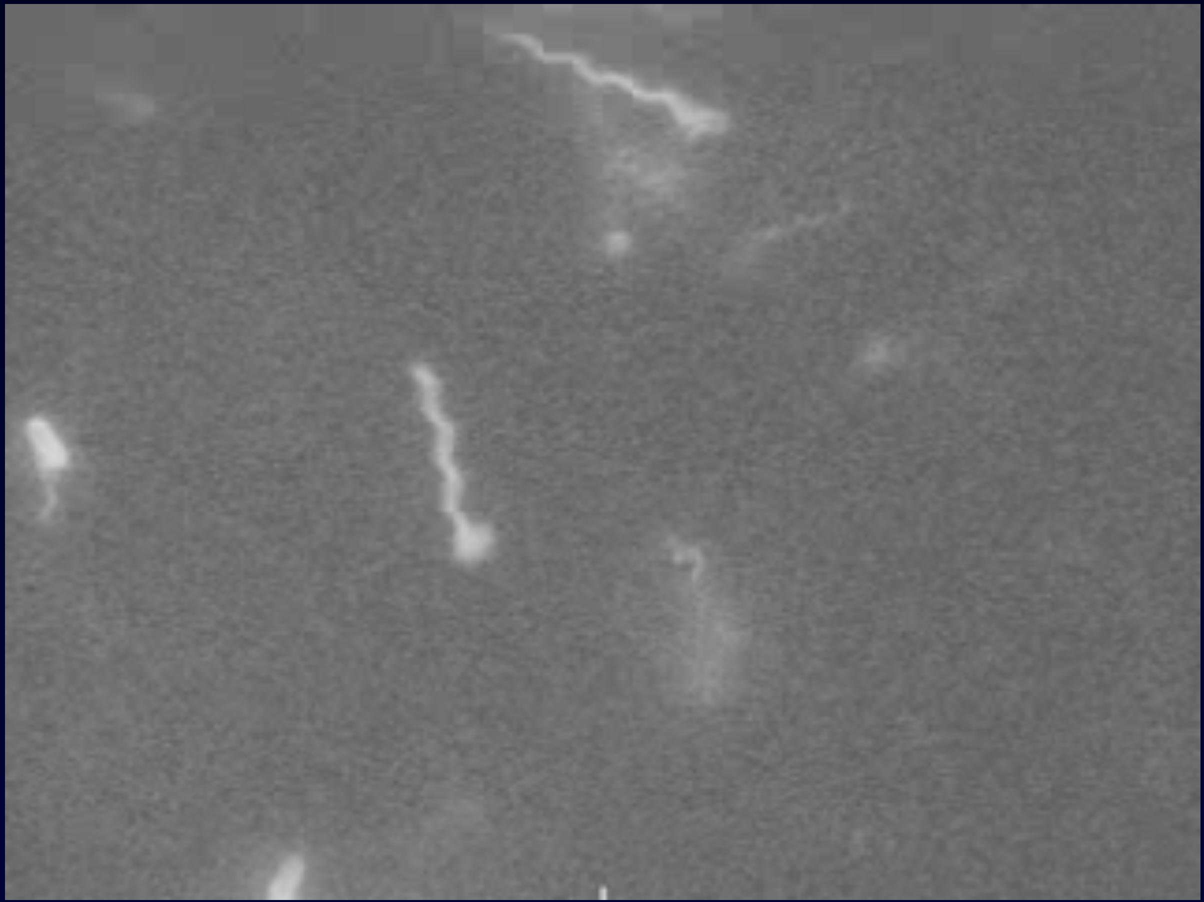
Bottleneck Challenge for Mobile Micro-Robots

Miniaturization limitation on on-board power source & actuation*

*M. Sitti, *Nature* **458**, 1121, April 2009

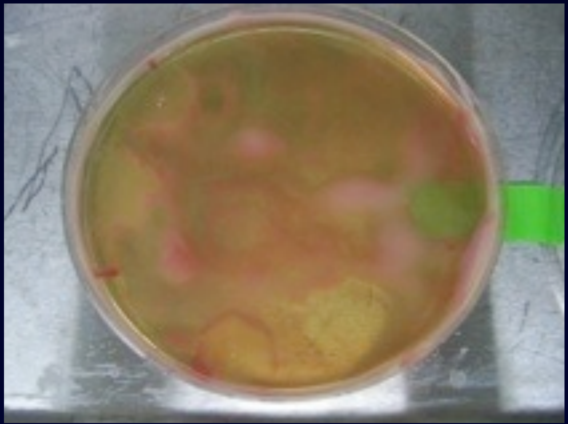
On-Board Actuation Approach: Cells as Actuators?

- Harvesting the motility of cells to actuate micro-systems
- Chemical energy inside the cell

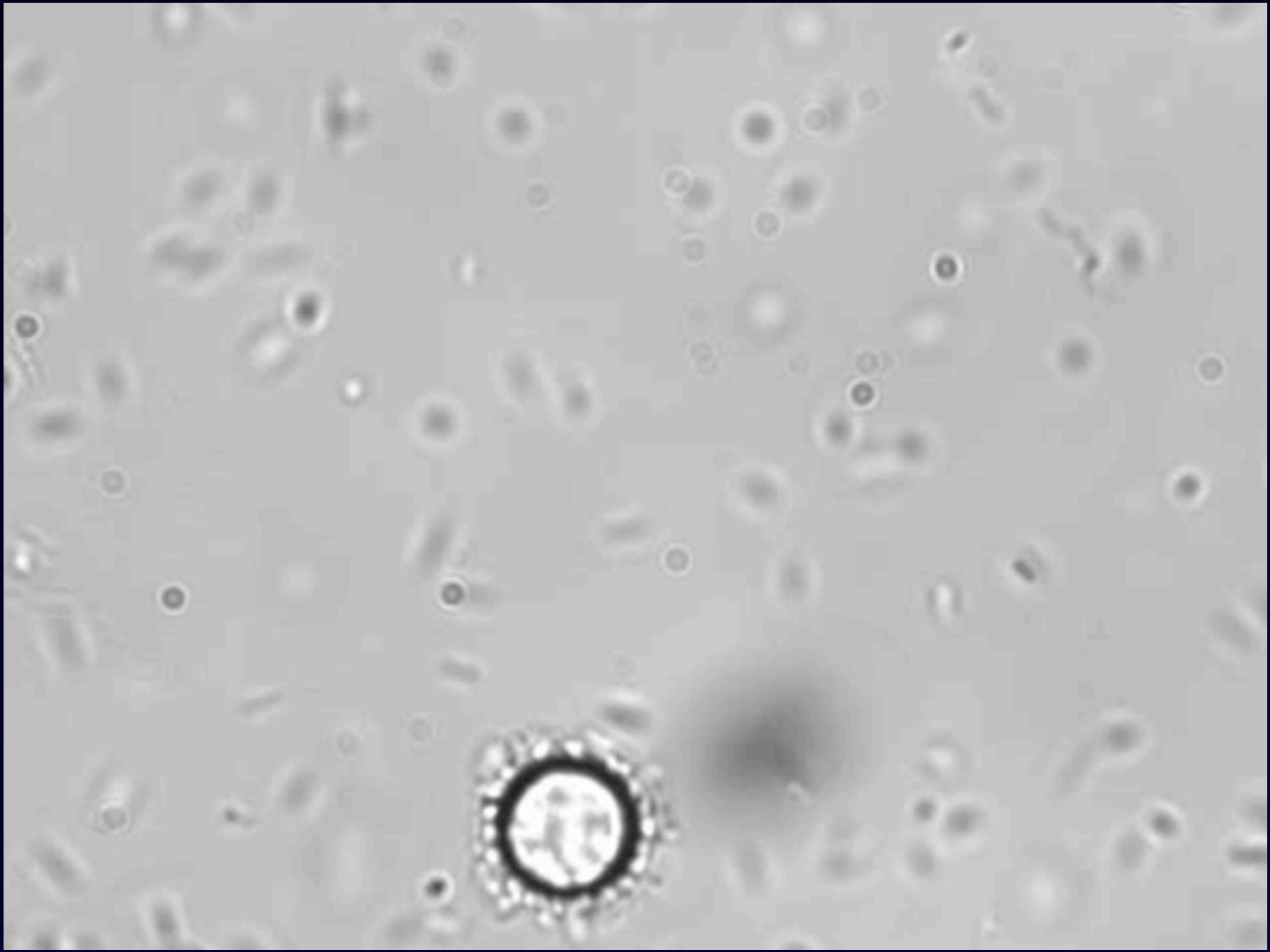


H. Berg, Harvard

Bacteria Propelled Micro-Beads



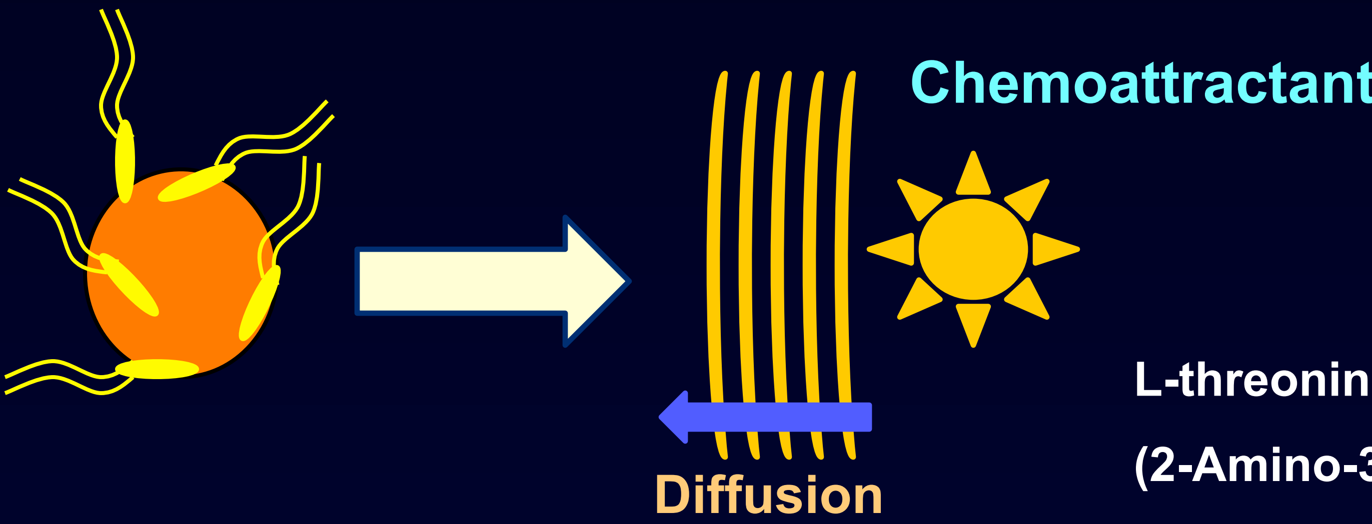
Blotting on the culture plate

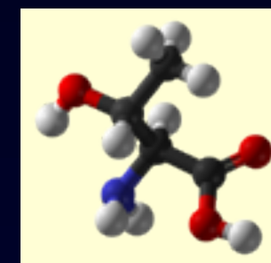


B. Behkam & M. Sitti, *Appl. Phys. Lett.* **90**, 23902 (2007)
B. Behkam & M. Sitti, *Appl. Phys. Lett.* **93**, 223901 (2008)
V. Arabagi, B. Behkam, E. Cheung, and M. Sitti, *J. Appl. Phys.* **109**, 114702 (2011)

Steering Control: Passive Steering Control using Chemotaxis

Bacteria moving towards chemical attractant gradients

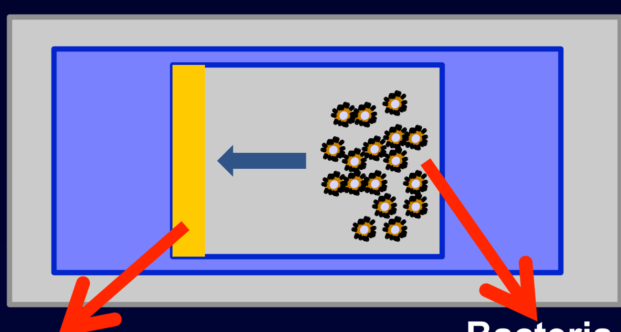




L-threonine (mixed with agar)

(2-Amino-3-hydroxybutanoic acid)

Properties	
Molecular formula	$C_4H_9NO_3$
Molar mass	119.12 g/mol
Diffusion coefficient	7.68 x $10^6 cm^2/s$

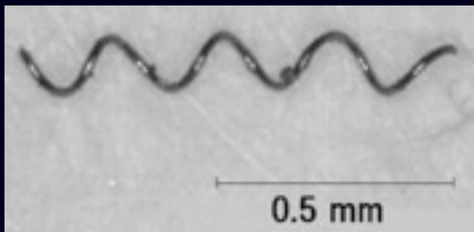


Chemoattractant

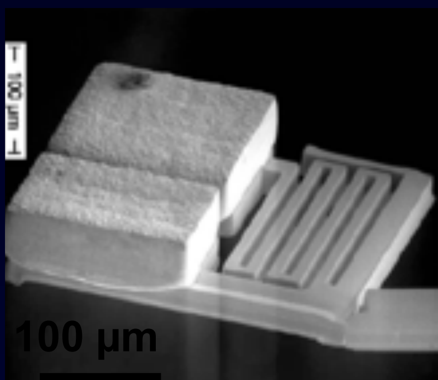
Bacteria-attached PS beads

Off-Board Approach: External Actuation

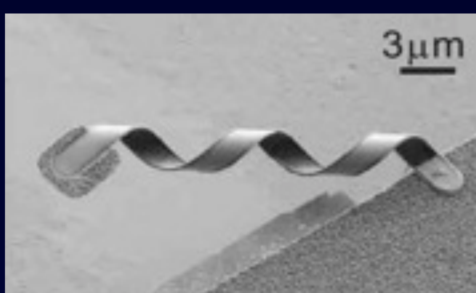
Magnetics



Yamakazi et al., Tohoku University, Japan (2001)
Rotational swimmer



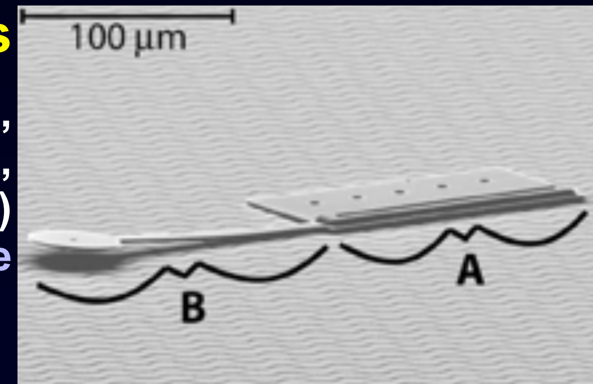
Nelson et al., ETH Zürich, Switzerland (2007)
Inertial resonant drive



Nelson et al. (2009) Fischer, et al. (2009)
Bacterial propulsion

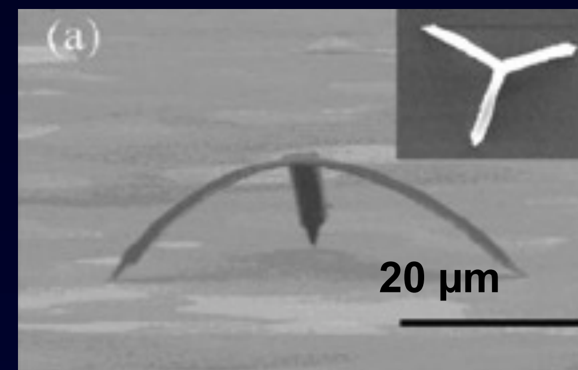
Electrostatics

Donald et al., Dartmouth College, USA (2005)
Scratch-drive



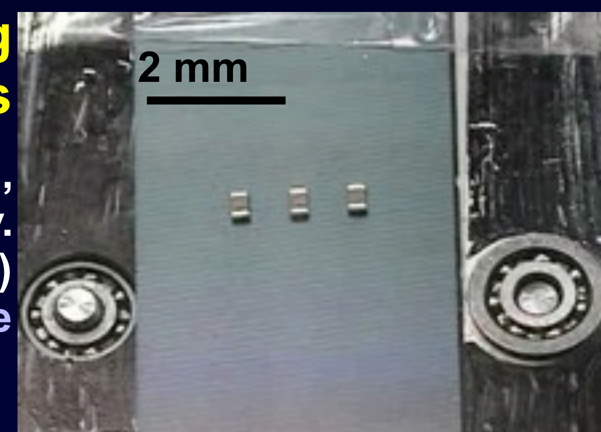
Thermal

Sul et al., U. North Carolina, USA (2006)
Laser excitation



Vibrating Surfaces

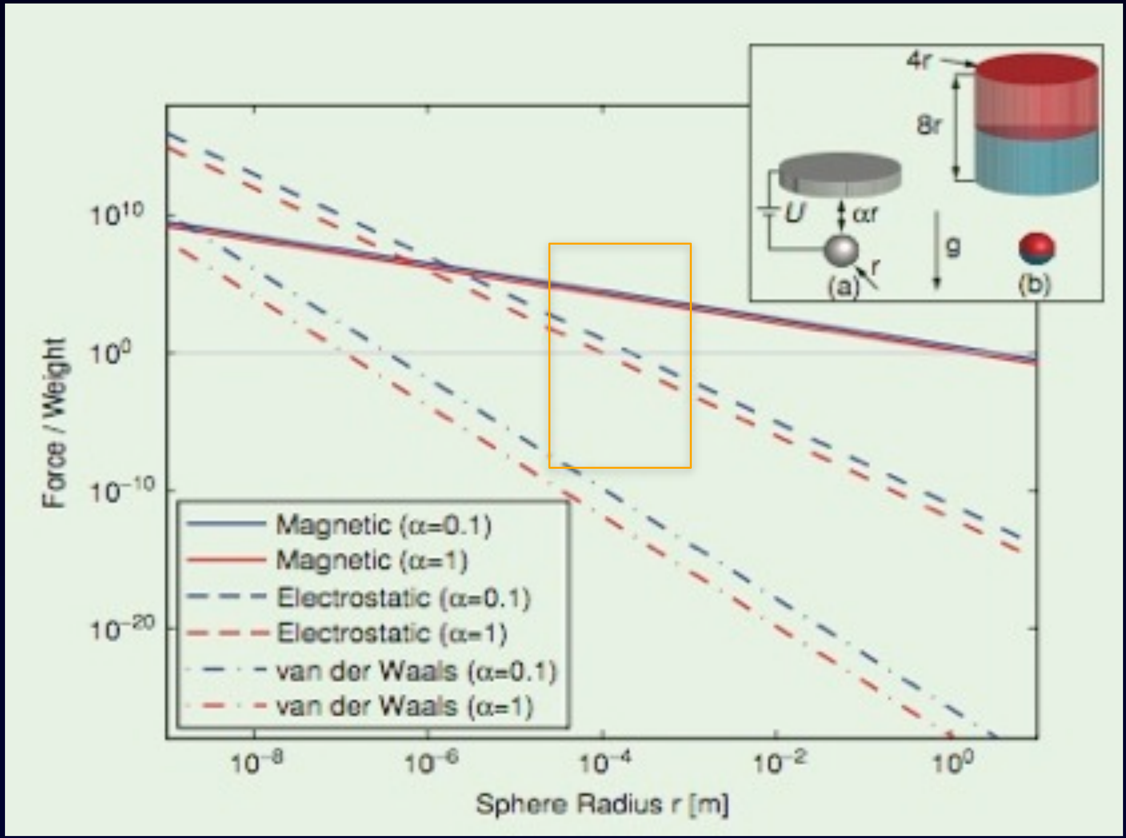
Mitani et al., Ritsumeikan Univ. Japan (2006)
Sawtooth surface



Why Magnetics?

- Versatile and Robust
  - No specialized surfaces (vs. electrostatics, vibrations)
  - Long range
  - No specialized environments (vs. dirt & humidity)
  - No line of sight (vs. optical)

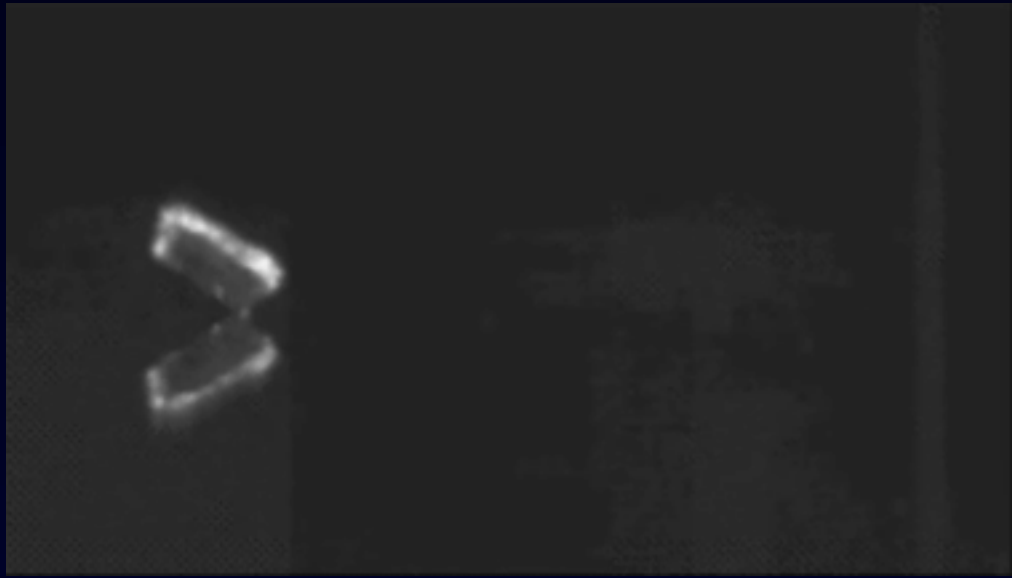
- Favorable to micro-scale
  - High forces & torques (vs. surface forces, friction, electrostatics, inertial)



Abbott et al, IEEE RAM, 14(1), 2007

Proposed Micro-Robot: Mag-μBot

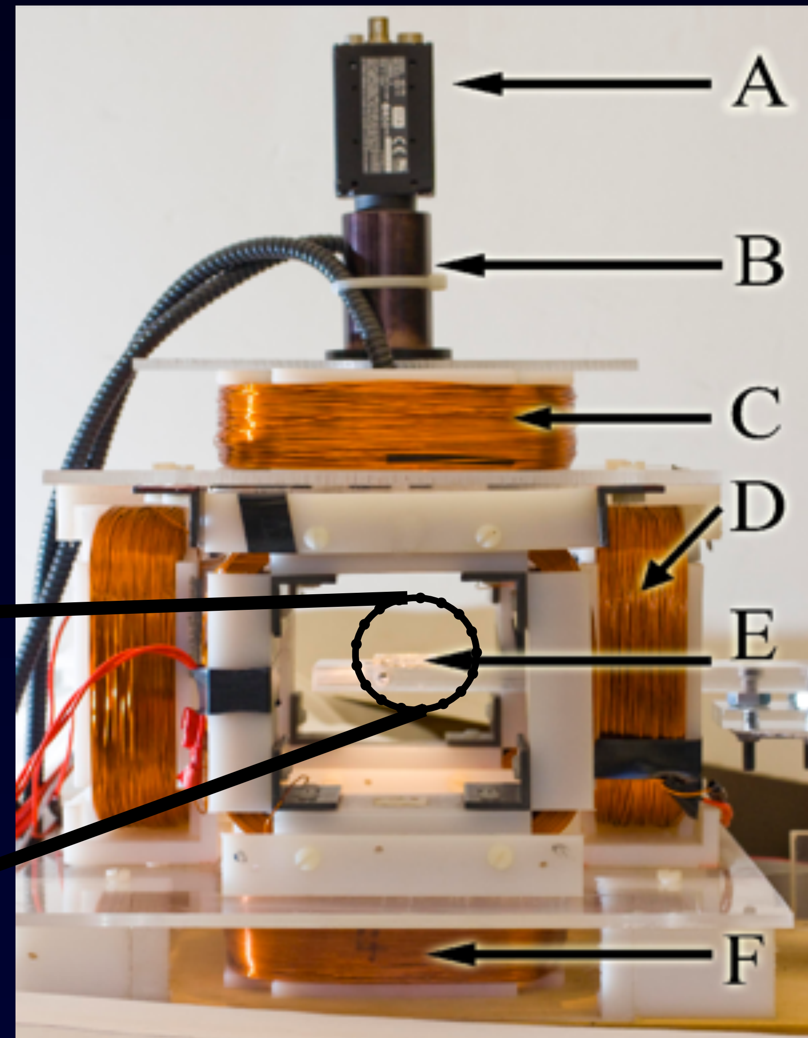
- **Permanent magnet based (NdFeB)**
  - **Arbitrary planar geometry**
  - **Operates on many surfaces**
- **Pulsed magnetic fields used**
  - **< 1 mT sufficient**
  - **Induced stick-slip motion**
  - **Primarily torque-based motion**
- **Operates in gases, vacuum, liquids**
  - **60 mm/s in air**
    (> 150 body lengths/sec)
  - **40 mm/s in water**
  - **In liquids up to ~50 cSt**



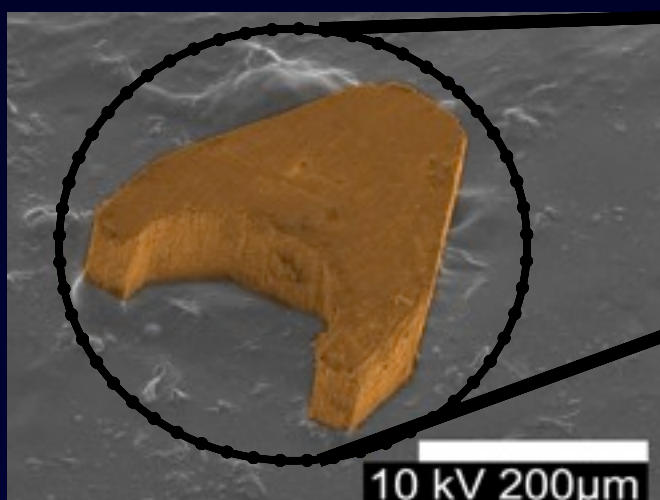
C. Pawashe, S. Floyd, and M. Sitti,
IJRR **28**(8), 1077 (2009)

Experimental Setup

- A: Camera
- B: Microscope
- C: Top Coil
- D: Horizontal Coil
- D: Surface and Robot
- F: Clamp Coil

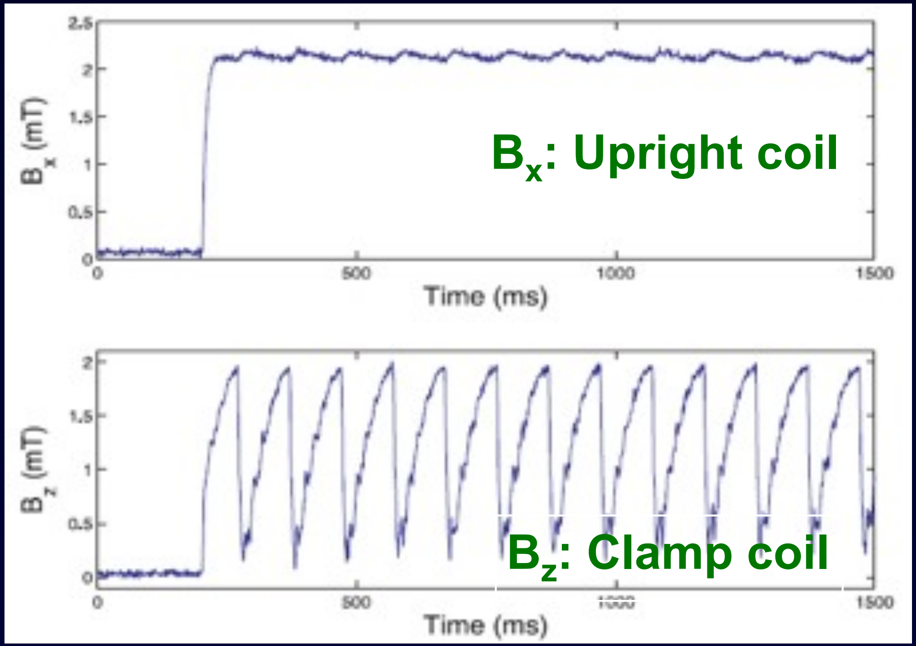


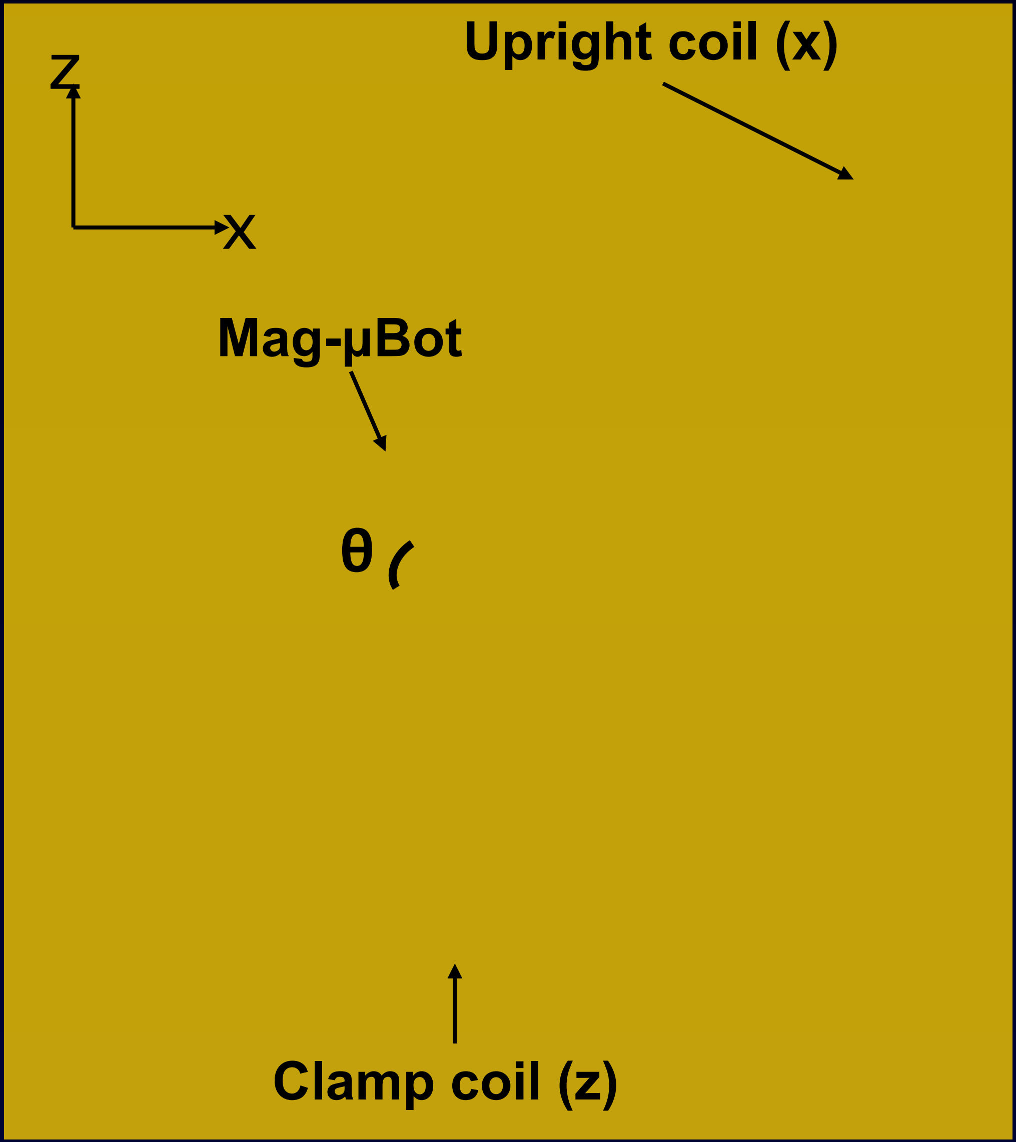
Laser micro-machined
permanent magnet micro-robot



Mag-µBot Actuation: Oscillating Magnetic Fields

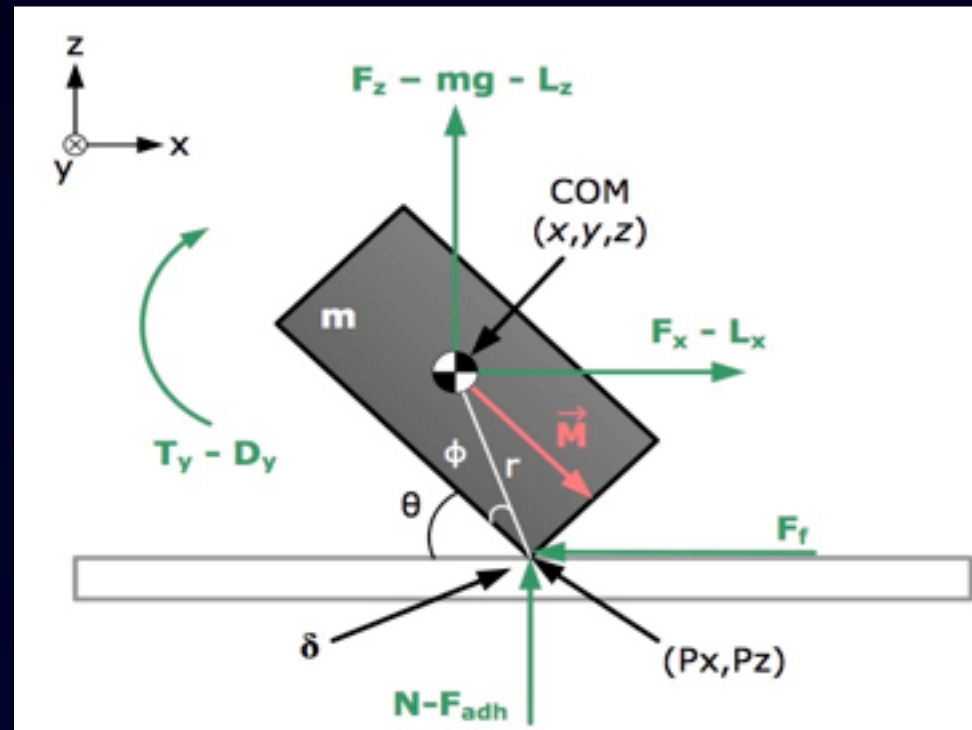
- **Out of Plane Pulsing**
  - Top coil pulsed
  - Upright coil biased
  - Asymmetric waveform
  - Speed control (frequency, amplitude)





Modeling Mag-μBot Behavior in 2-D

- Forces
  - T_y: Magnetic torques (1s of μN)
  - D_y: Damping torque (1s of μN)
  - F_f: Friction Force (100s of nN)
  - N: Normal Force (100s of nN)
  - F_{adh}: Adhesion (100s of nN)
  - mg: Weight (100s of nN)
  - F_x, F_z: Magnetic forces (10s of nN)
  - L_x, L_z: Damping force (1s of nN)



Side-View Free Body Diagram

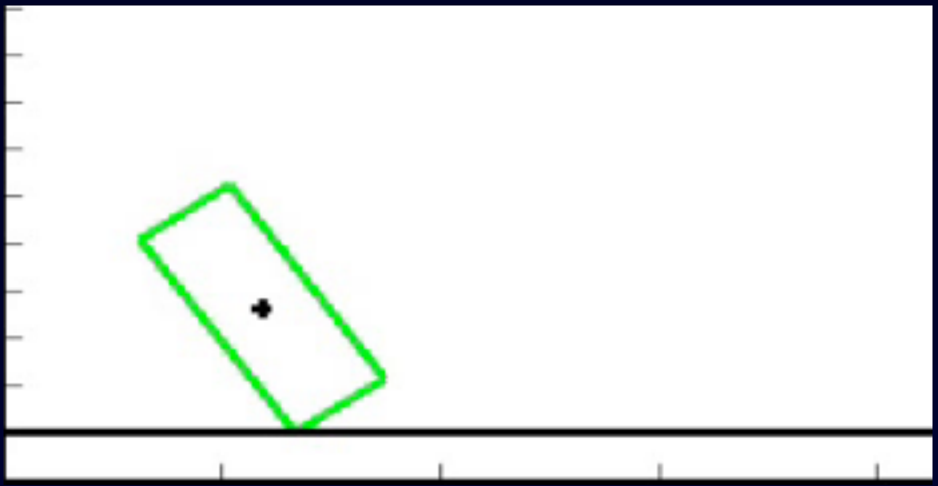
- Objective
  - Create a dynamic simulation
  - Predict robot behavior
  - Predict robot velocity

$$
\begin{aligned}
m\ddot{x} &= F_x - F_f - L_x \\
m\ddot{z} &= F_z - mg + N - F_{adh} - L_z \\
J\ddot{\theta} &= T_y + F_f \cdot r \cdot sin(\theta + \phi) - (N - F_{adh})r \cdot cos(\theta + \phi) - D_y
\end{aligned}
$$

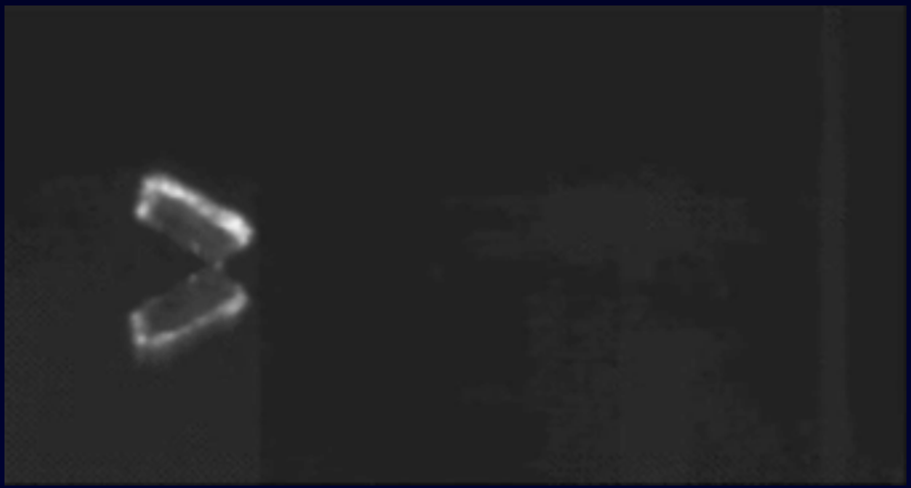
Painlevé Paradox (1895)

Simulation Results: Behavior

- Stick-slip behavior is achieved in simulation
  - Sawtooth pulsing waveform



Simulated motion



Experimental 1/200x video of motion

Micro-Object Manipulation

Contact Manipulation

- **Objects from 20 µm to 900 µm manipulated in fluids**
  - **Reduced adhesion and friction in liquids**
  - **Smaller objects possible, constrained by visual feedback**

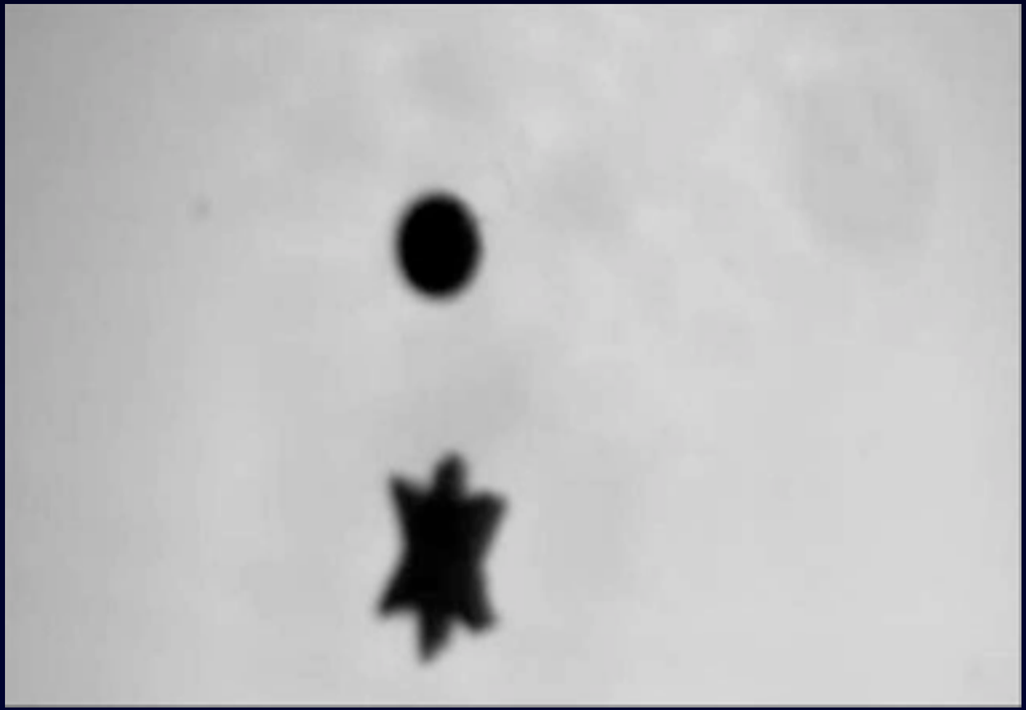
20 µm polystyrene spheres underwater
Laser-cut Mag-µBot, 1x realtime

350 µm Al/polyurethane peg underwater
Polymer star-shaped Mag-µBot, 1x realtime

Non-Contact Manipulation

- Fluid boundary layers generated by moving Mag-μBot
  - Drag force applied to micro-objects from fluid (Reynolds number < 1)

50 μm polystyrene sphere, silicone oil

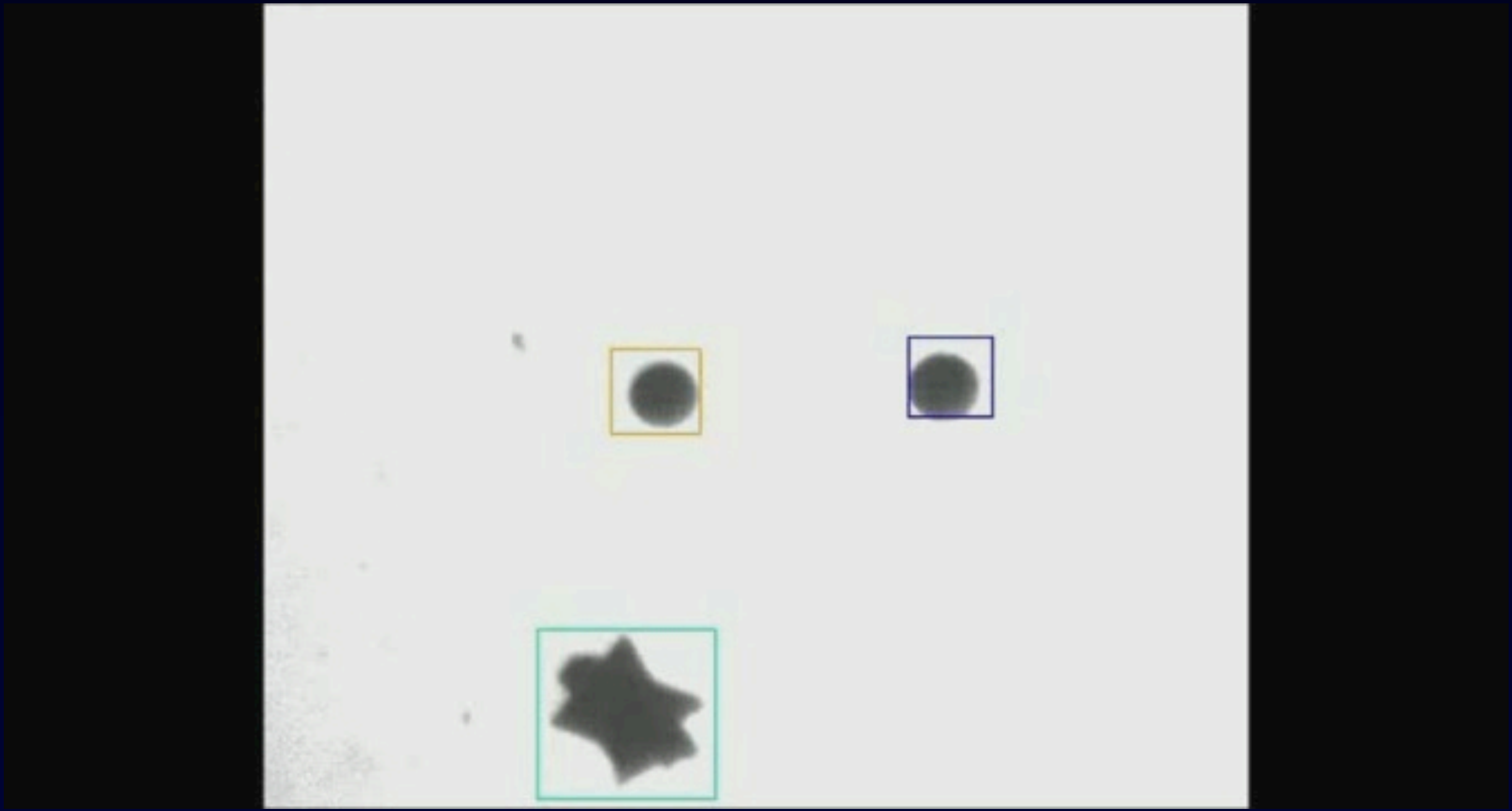


230 μm polystyrene sphere, silicone oil

C. Pawashe, S. Floyd, & M. Sitti, *IEEE Trans. Robotics* **25**(6), 1332 (2009)

Autonomous Two-Particle Assembly

- Utilize side pushing to assist precise positioning for micro-assembly



C. Pawashe, E. Diller, S. Floyd, & M. Sitti, under review

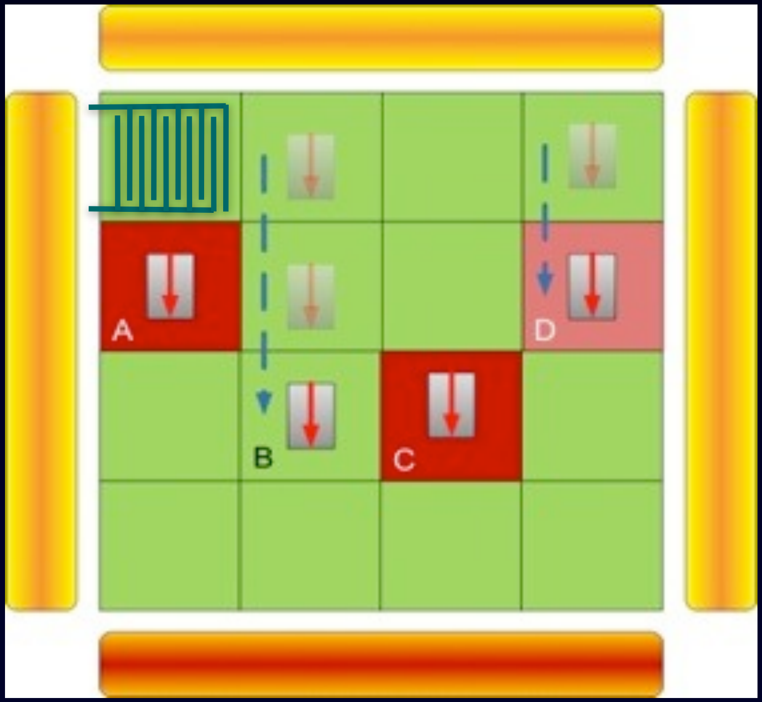
Autonomous Particle Transportation by Spinning

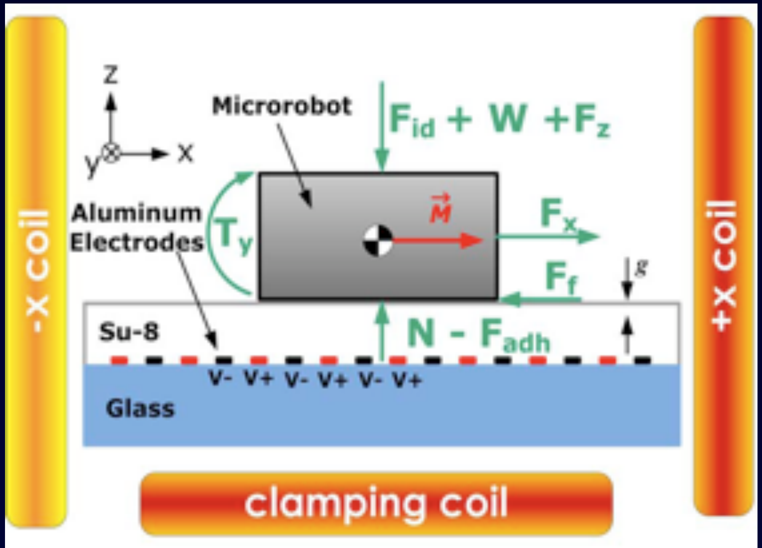
Demonstration of
single micro-manipulator
manipulating single micro-object

Multiple Micro-**Robot Control**

- Fundamental problem: addressability
  - **Global magnetic fields**
  - **Solution?**

Multi-Robot Control using Patterned Surfaces

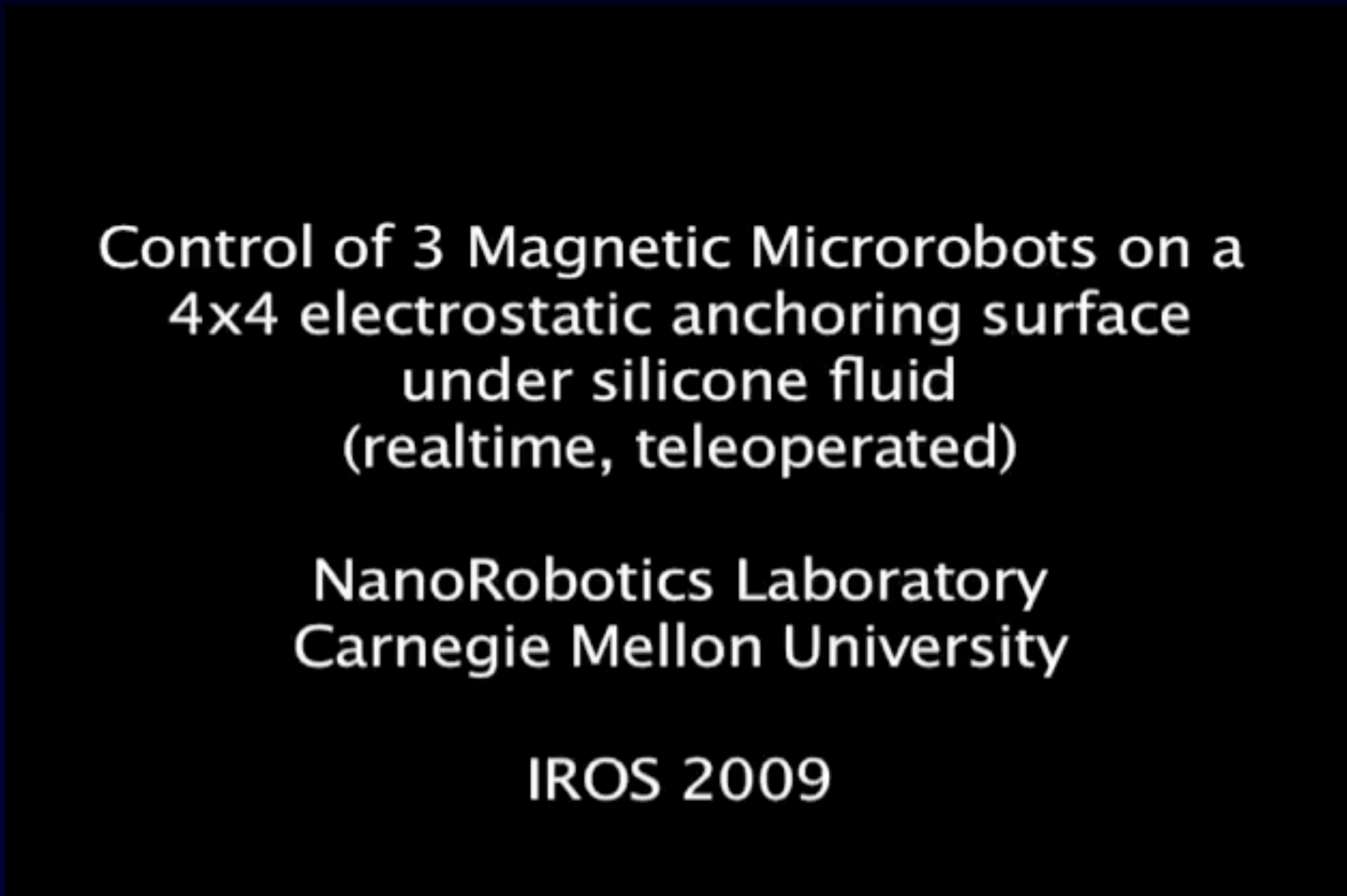




- Special surface covered with interdigitated electrodes
- Capacitive coupling selectively anchors robots to surface in non-ionic liquids
- Unanchored robots continue translating
- Favorable scaling up

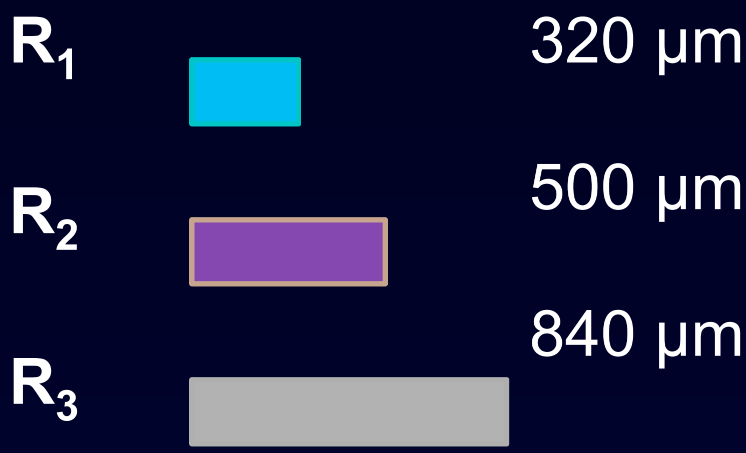
C. Pawashe, S. Floyd, and M. Sitti, *Appl. Phys. Lett.* **94**, 161408 (2009)

Three Mag-μBots In Operation (changing

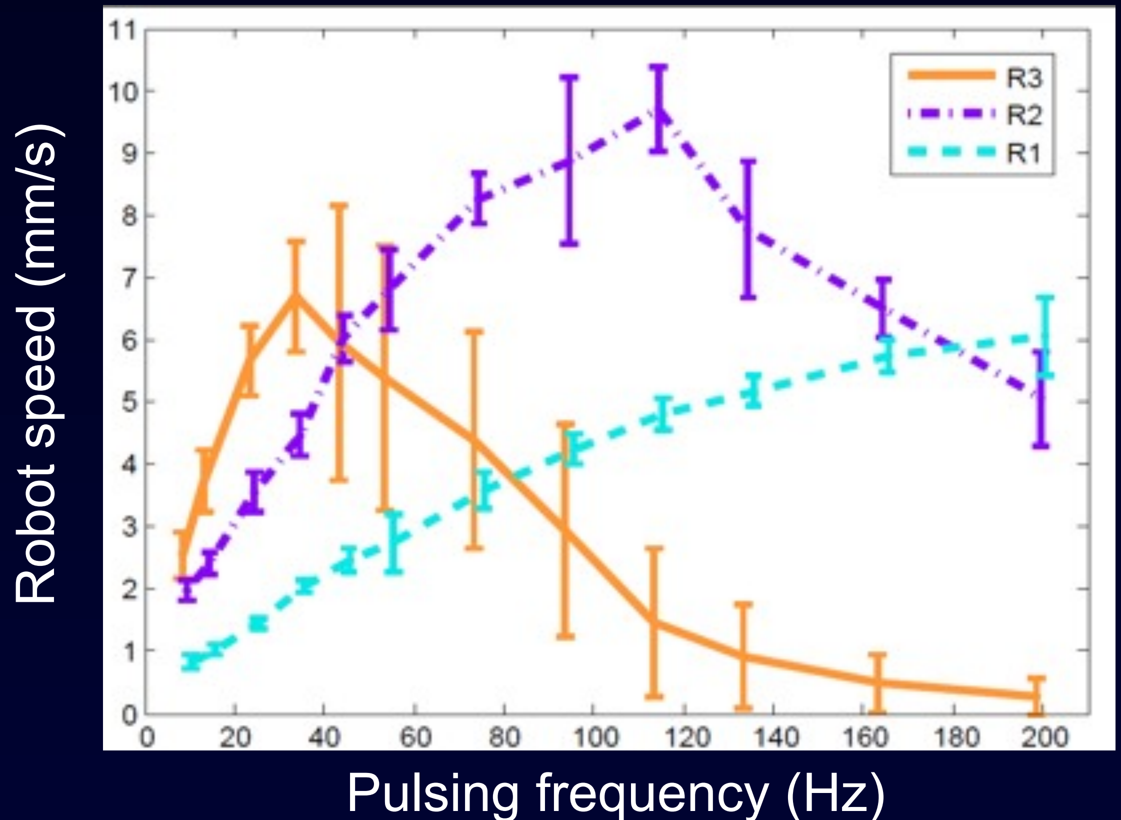


Best Paper Award in IEEE/RSJ Intelligent Robots and Systems Conference (2009)

Control of Heterogeneous Teams of Magnetic Micro-Robots

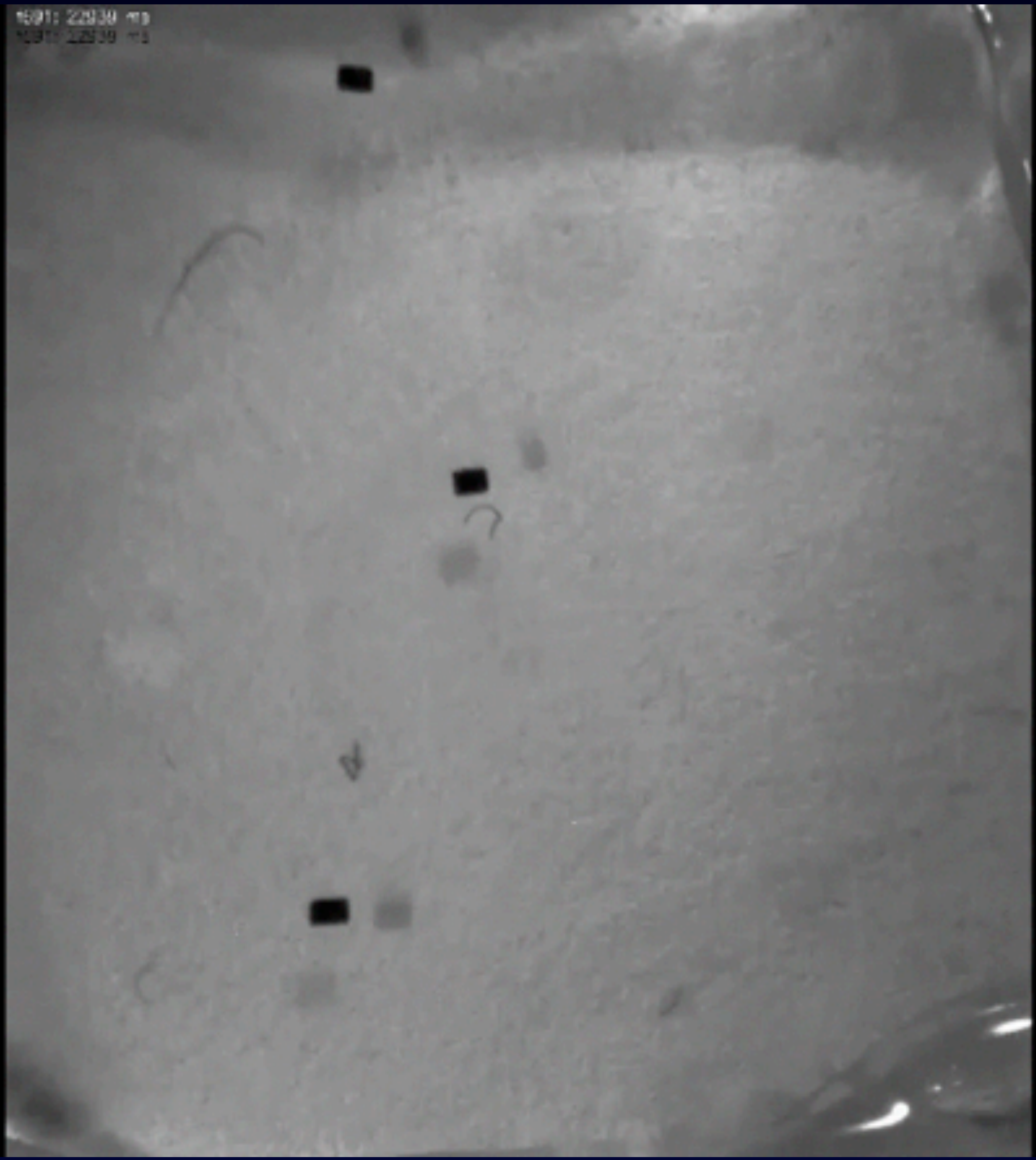


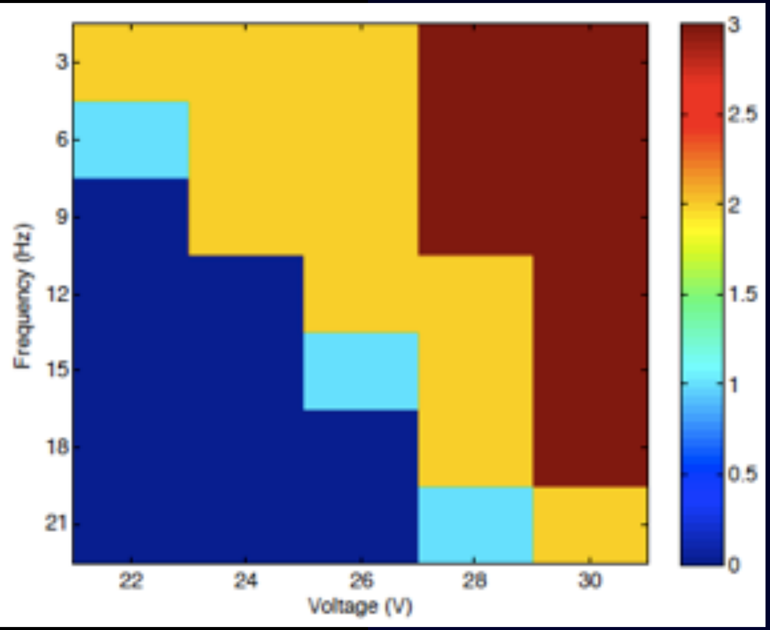
Frequency Response



S. Floyd, E. Diller, C. Pawashe, and M. Sitti, *Int. J. Robotics Research* (2011)

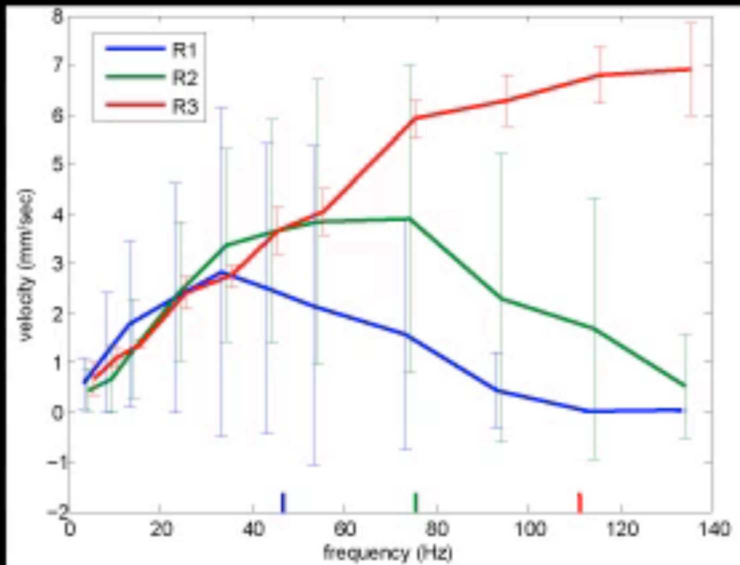
Three Micro-Robot Control





Real-time

Heterogeneous Control of Multiple Magnetic Micro-Robots on Arbitrary Surfaces



Eric Diller
Steven Floyd
Chytra Pawashe
Metin Sitti

Carnegie Mellon
ENGINEERING

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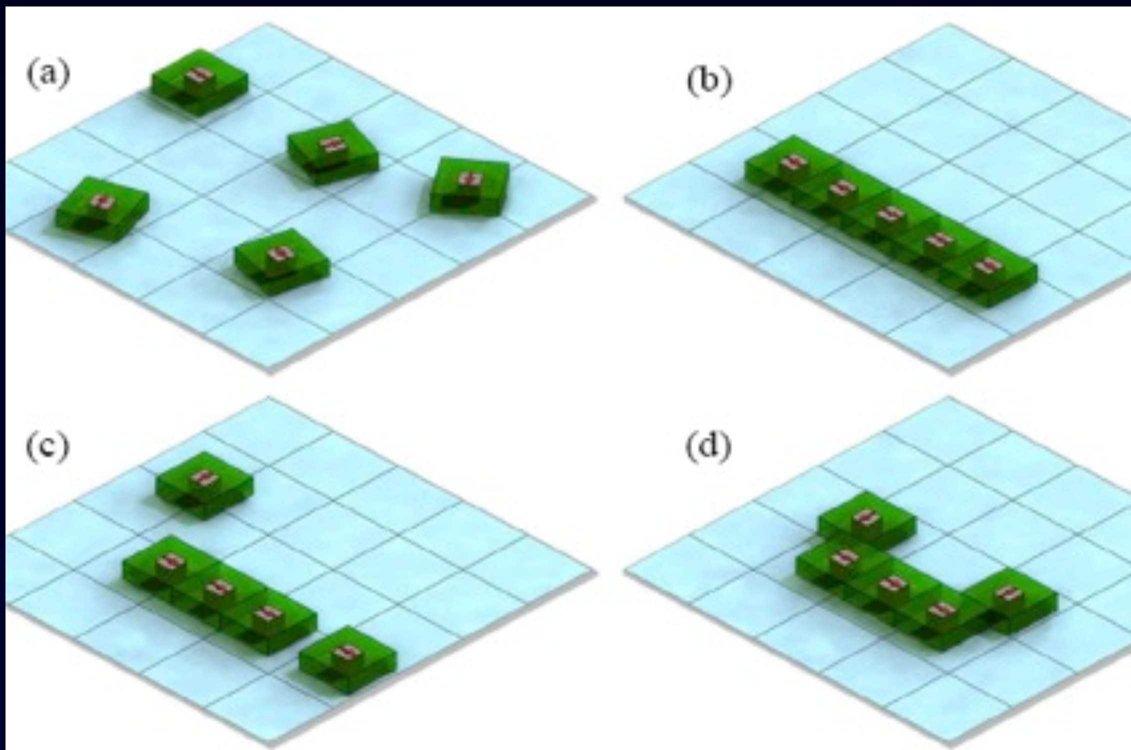
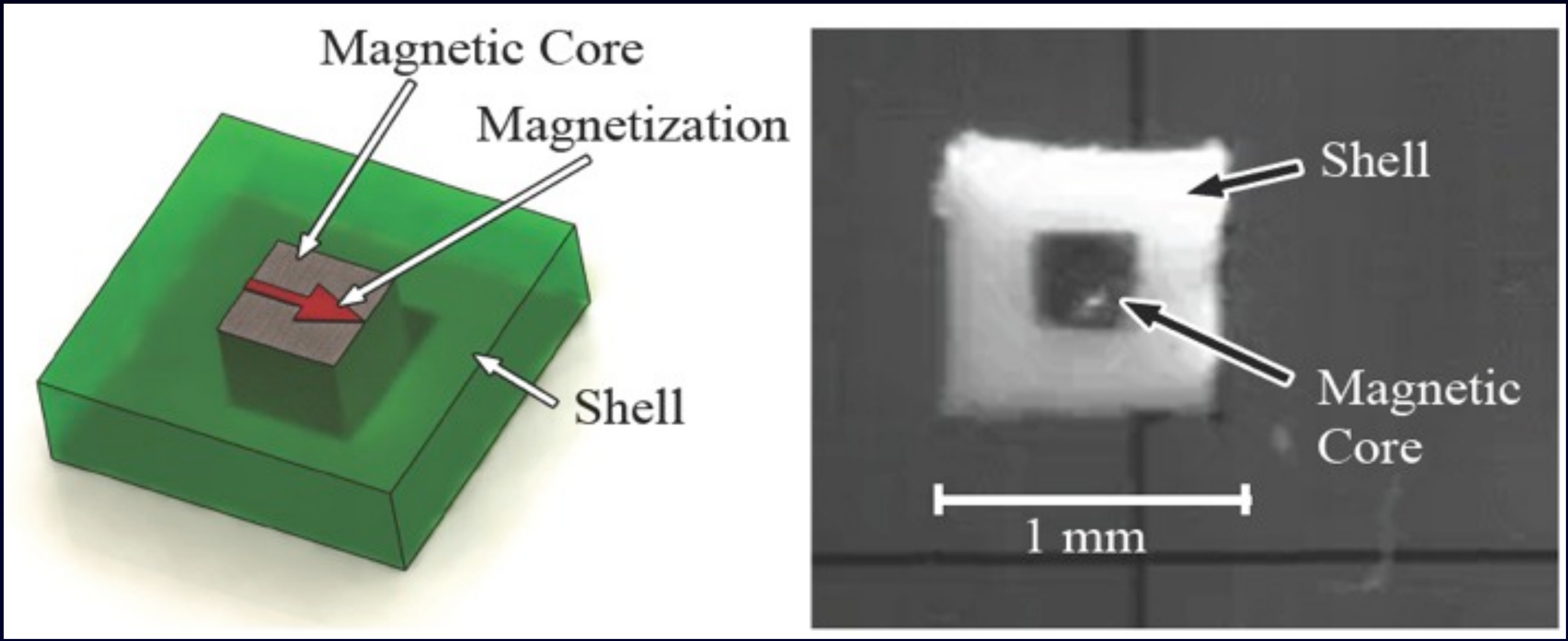
Reconfigurable Micro-Systems (Programmable Matter)?



- Multiple robots form temporary structures
- Structures stick together magnetically
- Disassemble using the patterned surface

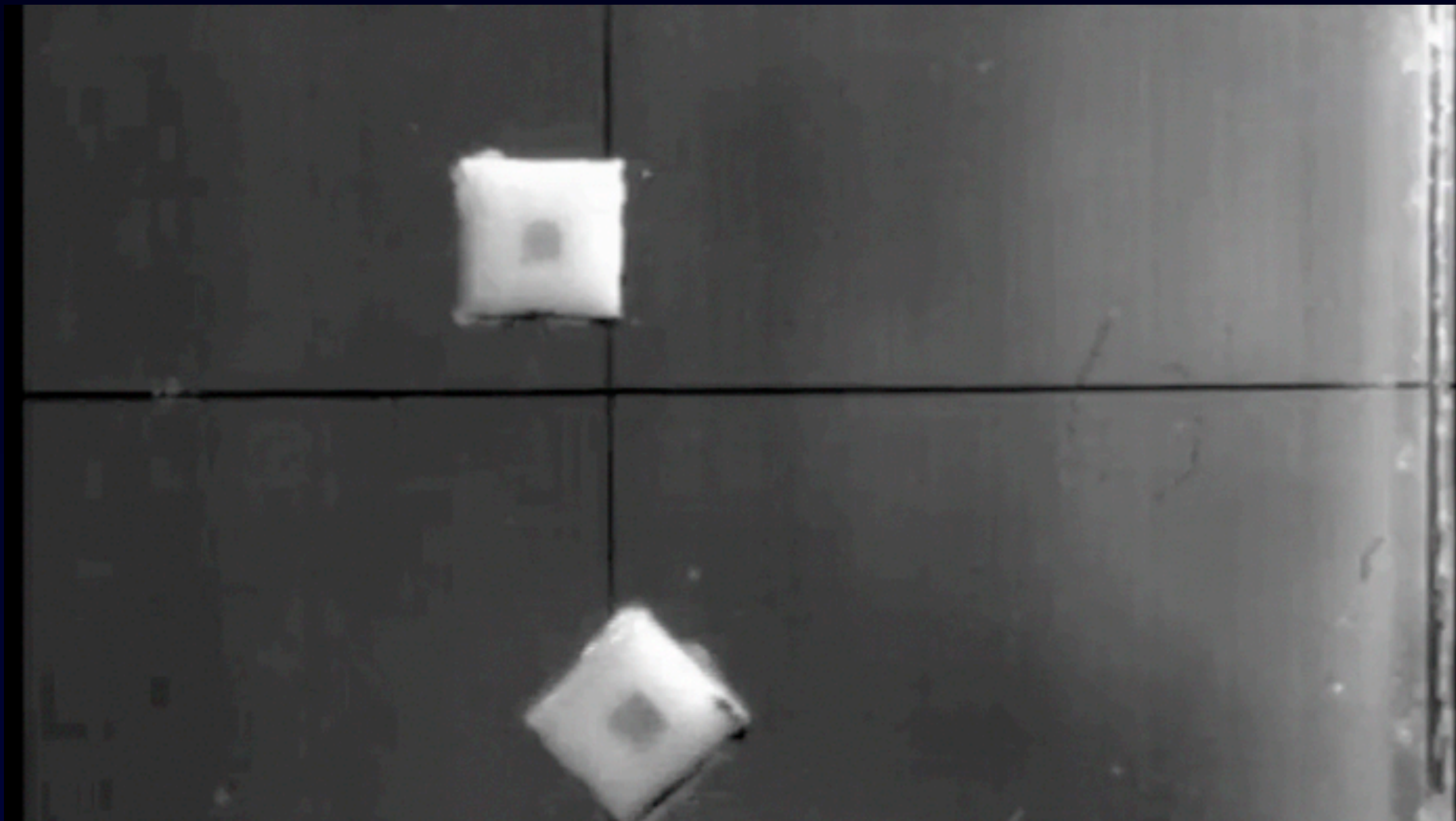
Claytronics,
S. Goldstein *et al*.
CMU & Intel

Magnetic Micro-Modules (Mag-μMods)

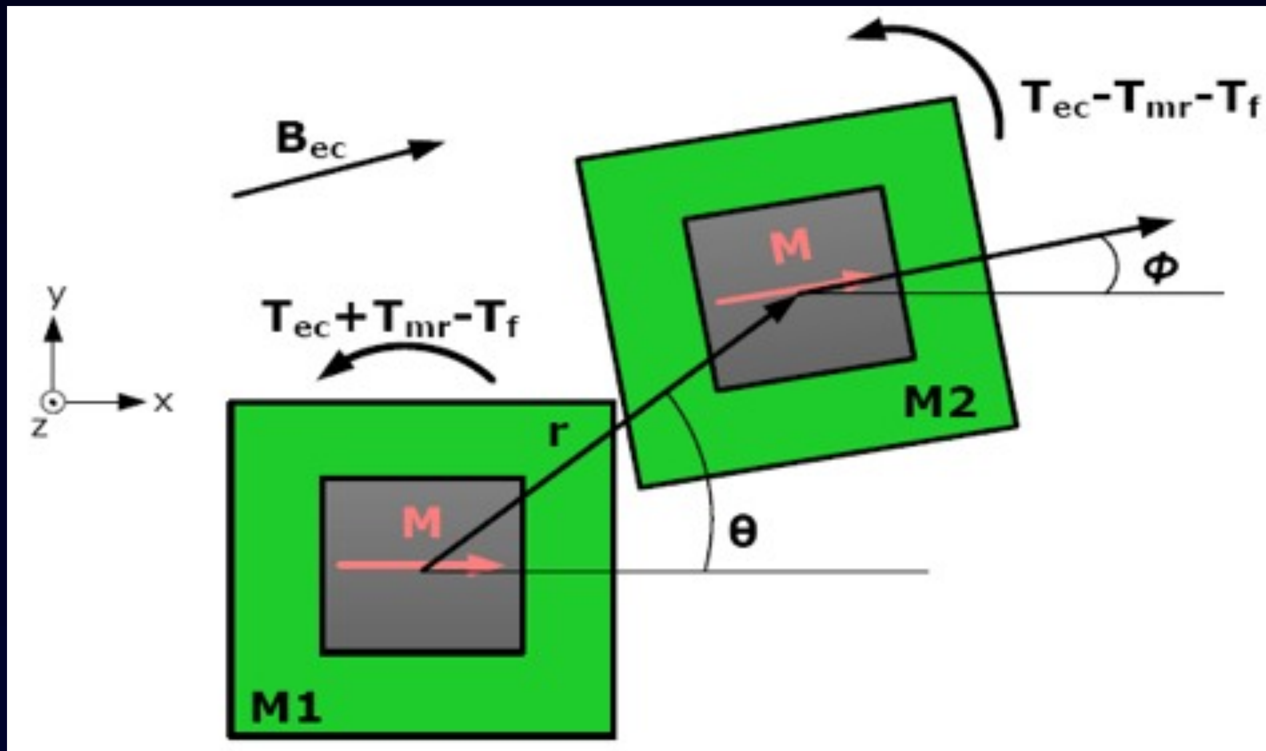


- Shells are added to Mag-μBot
  - Increases inter-robot distance, decreasing magnetic attraction
- Makes non-contact separation feasible

Assembly Routine



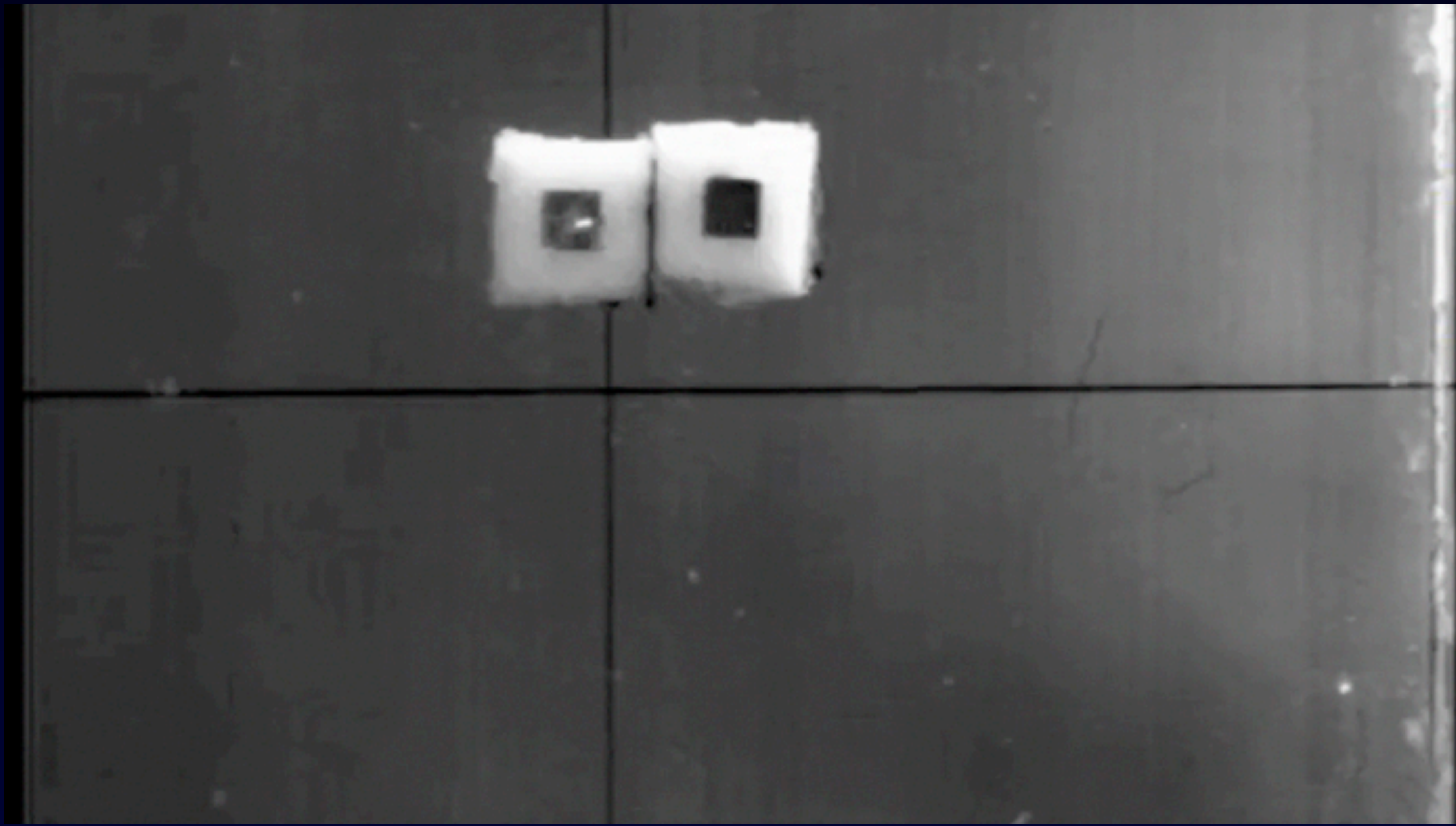
In-Plane Rotation based Disassembly



1) Anchor M1
2) Twist M2 in-plane into magnetically neutral orientation
3) Walk M2 away

$$B = 0.3mT$$

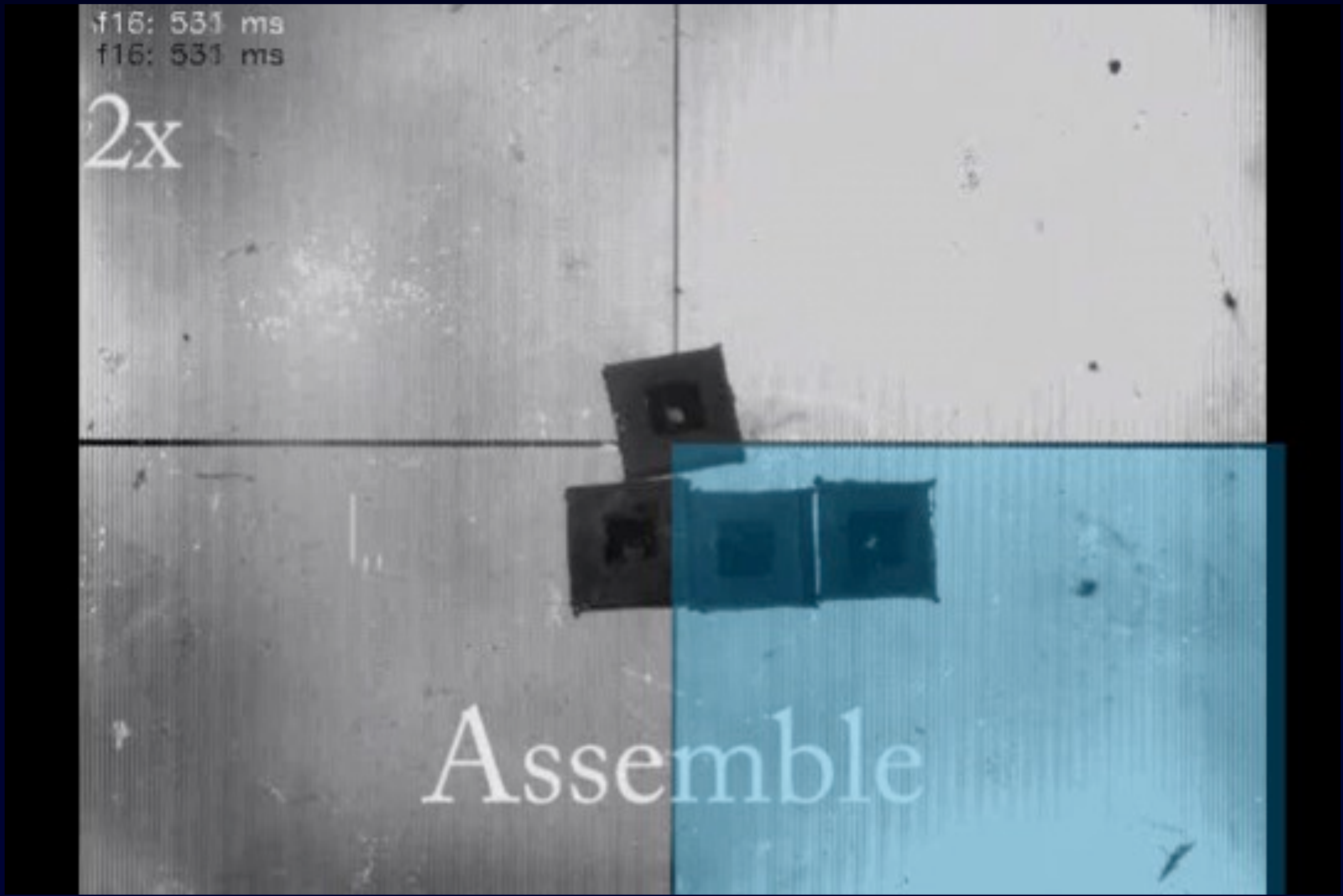
In-Plane Rotation Disassembly Experiment



Electromagnetic coils used (only low fields necessary)

Reconfiguration Demonstration

- Assemble, reconfigure, disassemble



500 µm

2x speed

E. Diller, C. Pawashe, S. Floyd, & M. Sitti, *Int. J. Robotics Research*, published on-line

Conclusions

- Teams of magnetic untethered micro-robots using external actuation in limited workspaces
  - Morphology matters for micro-robots!

- Smart materials, softness and passive dynamics could enable power efficient and minimalist miniature robots!

Post-Docs:

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Slava Arabagi (Post-doc, Harvard)
Bahareh Behkam (Assist. Prof., Virginia Tech)
Eugene Cheung (Apple Inc.)
Steven Floyd (Arete Associates)
Paul Glass (nanoGriptech LLC)
Seok Kim (Assist. Prof., UIUC)
Mike Murphy (BostonDynamics)
Amrinder Nain (Assist. Prof., Virginia Tech)
Cagdas Onal (Post-doc, MIT)
Chytra Pawashe (Intel)
Bilsay Sumer (Assist. Prof., Turkey)
Afshin Tafozzoli (Spain)
Ozgur Unver (Assist. Prof., Turkey)

NanoRobotics Lab

THANKS!