NanoRobotics Lab
@ Carnegie Mellon

Biologically Inspired Miniature Robots

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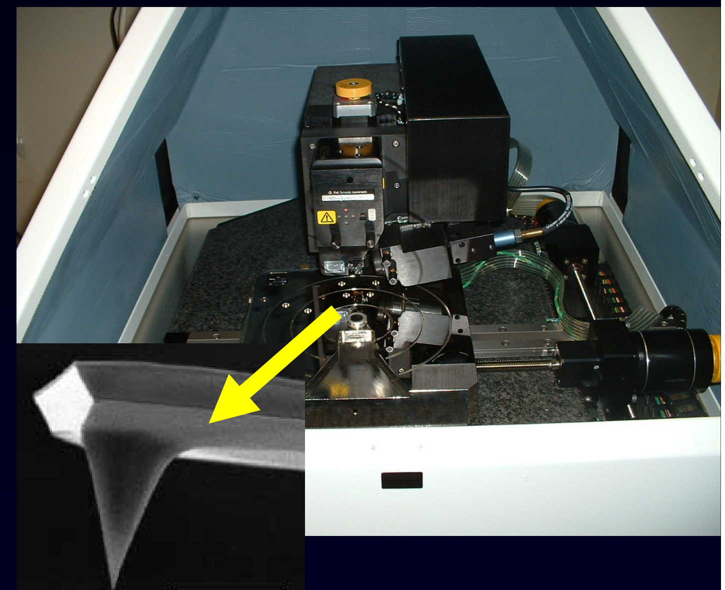
18-200 Lecture

Outline

- Introduction
- Bio-Inspired Adhesives
  - Climbing Robots
  - Endoscopic Capsule Robots
- Legged Locomotion on Water
  - Water-Walker
  - Water-Runner
- Conclusions

Micro/Nano-Robotics?

- **Programmable assembly and manipulation of micro- and nano-scale entities**
- **Design and fabrication of miniature robots down to sub-millimeter sizes**
  - **Locomotion and dynamics dominated by the principles of micro/nano-physics**
- **Programming and coordination of large number of these robots**



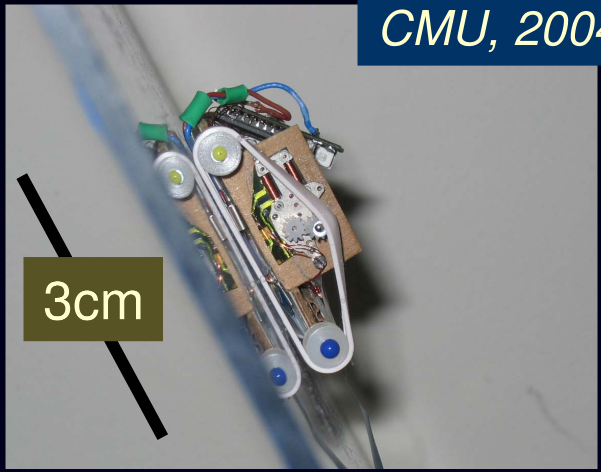
"*Micro/Nano-Robotics*" **course in Spring 2002/3/4/5/6**

Miniature Robots

- **Characteristics**
  - New physics and mechanisms
  - Most unique: ***Accessibility*** to smaller spaces
  - Smaller, faster, light weight, and cheaper
  - Massively parallel, in large numbers, and distributed

- **Challenges**
  - Necessity of novel micro/nanoscale actuators, sensors, mechanisms, materials, control, manufacturing, etc. techniques
  - Micro/Nanoscale physics
  - Complexity and uncertainties
  - Miniaturization limits on power sources

CMU, 2004



UC Berkeley, 2002

Robotics Field

- Involved basic disciplines:
  - Engineering: Electrical, computer, mechanical, and materials
  - Computer Science
- Depends on the size and applications, involves:
  - Basic Sciences (physics, biology, chemistry, and mathematics)
  - Medicine
  - Aeronautics (space)
  - …

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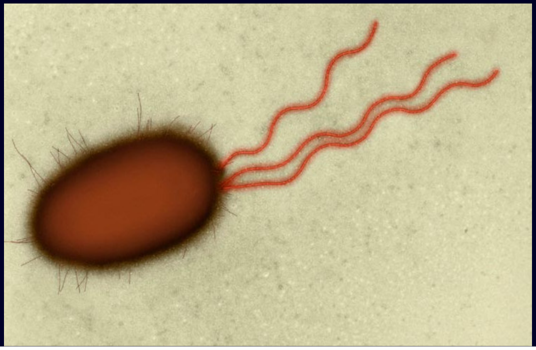
Biological Inspiration at Small Scales

- **Biological systems**
  - **Just *good-enough* solutions to survive (sub-optimal)**
  - **Robust and adaptive**
  - **Highly maneuverable (agile)**
  - **Multi-functional**

- **Bio-inspired design**
  - **More to learn from nature at the small scales**
  - **Robust locomotion in unstructured environments**
  - **Starting point**



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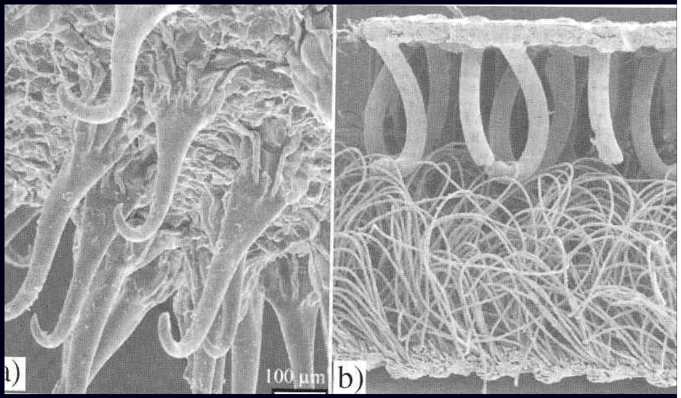
Bio-Inspired Robust Adhesives and Climbing Robots

Temporary Attachment Mechanisms in Nature



- **Mechanical interlocking** (plants/velcro, insects, humans, etc.)
- **Vacuum suction** (octopus, salamander)
- **Wet adhesion** (muscles, ants, cockroaches, frogs, crickets, etc.)
- **Dry adhesion** (geckos, spider, kissing bug)
- **HYBRID**

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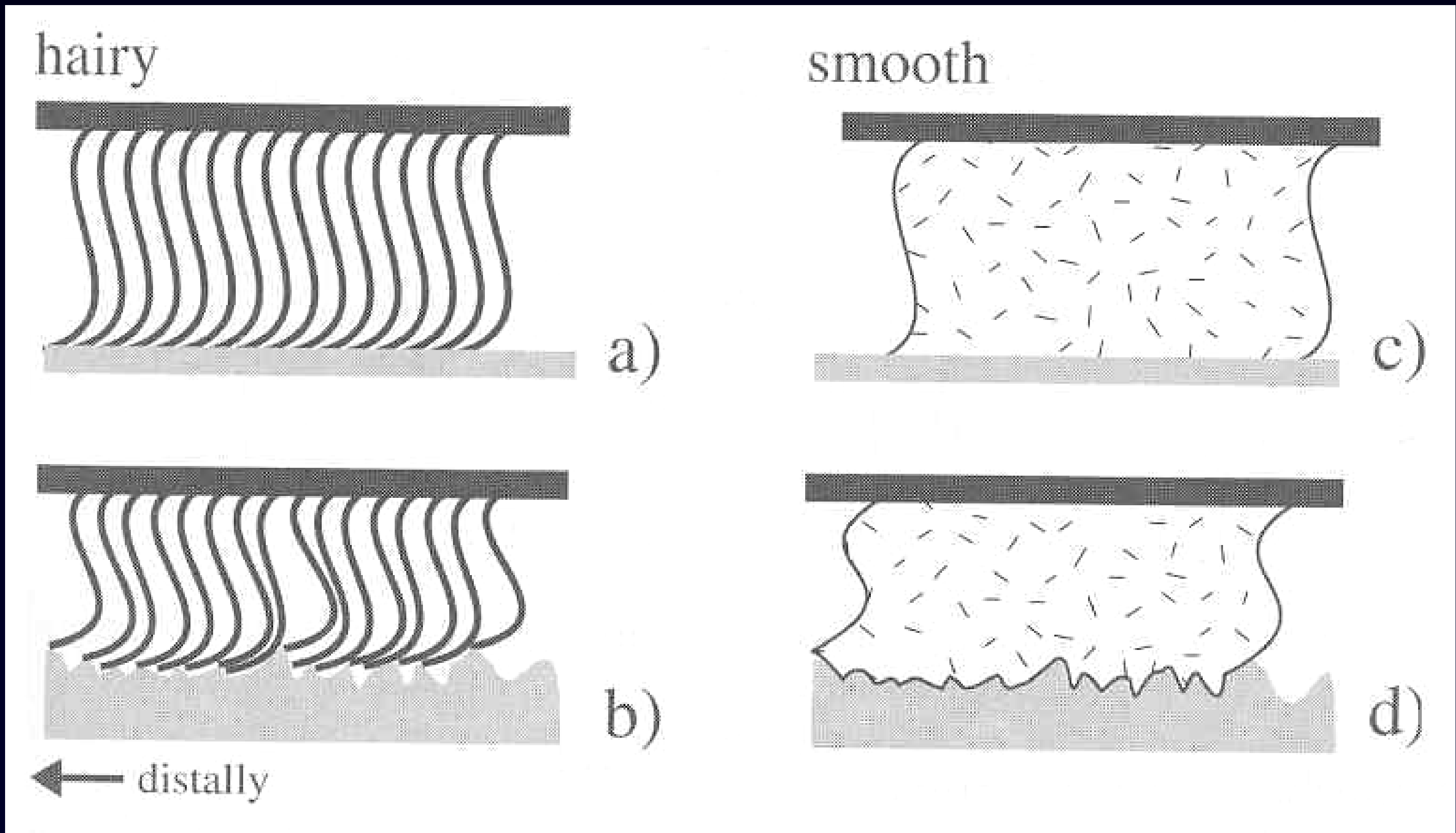
Attachment Mechanisms for Rough Surface Adaptation



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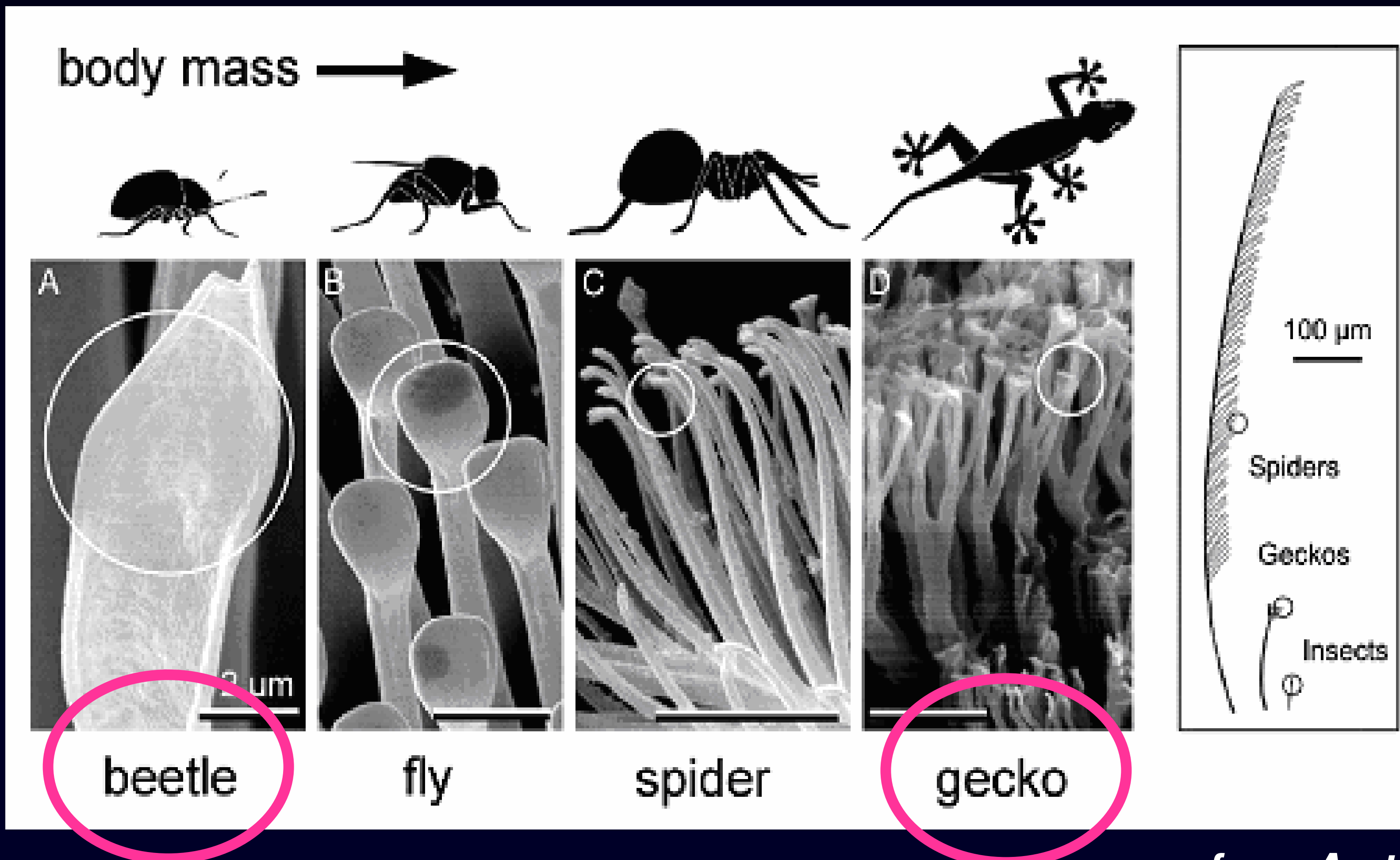
Biological Fibrillar Adhesives



from Arzt et al., PNAS, 2003

Higher hair density with smaller diameter

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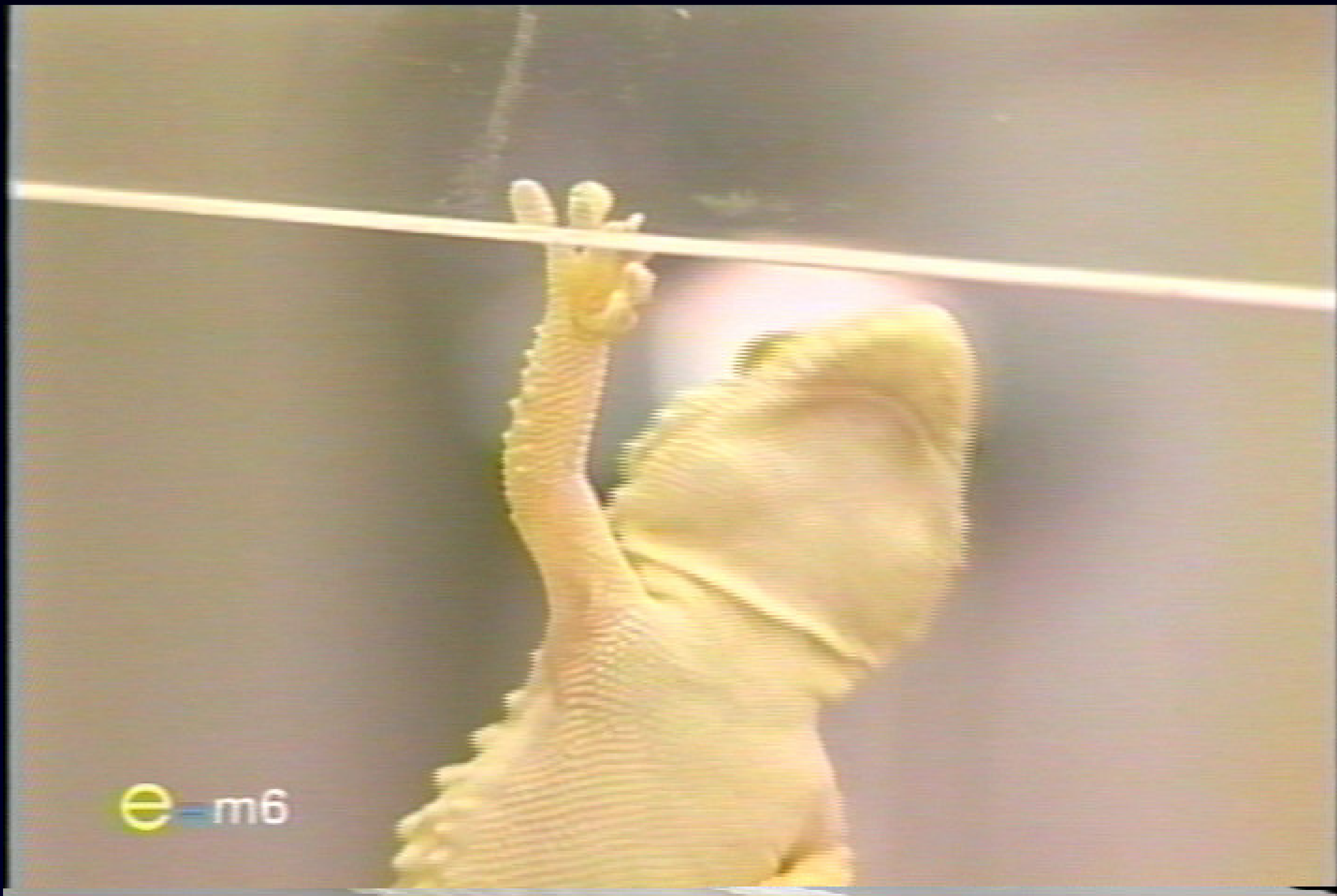
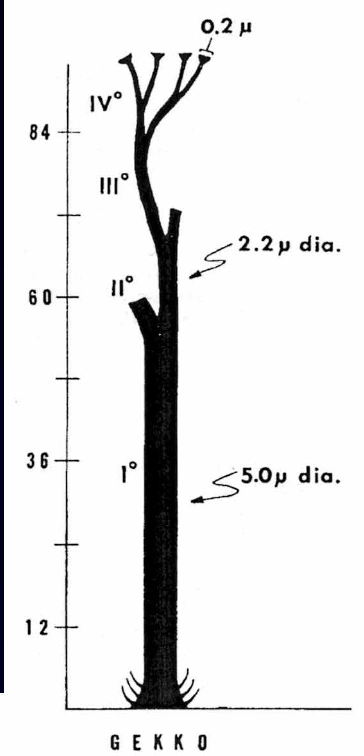
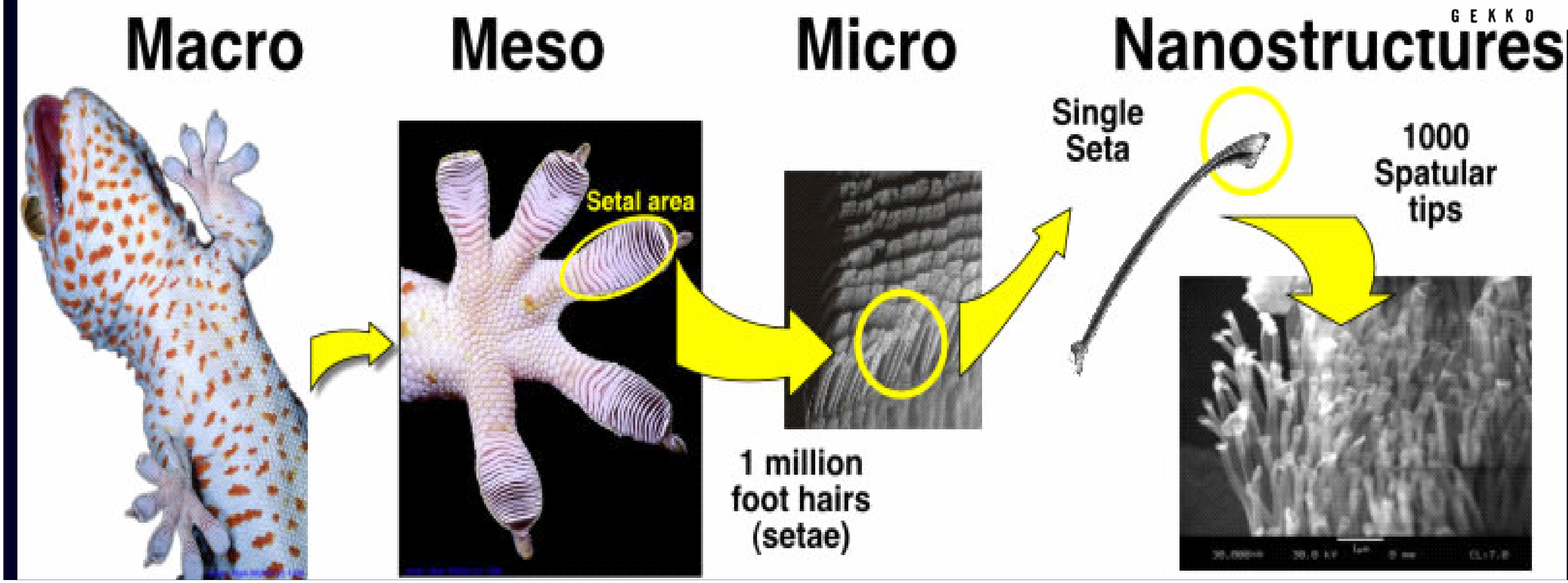


Features of Gecko Foot-Hair Adhesion

- **Hierarchical and multi length-scale structure and compliance (macro/micro/ nano)** [different for many species]
  - **Roughness adaptation**
  - **Enhanced adhesion and life-time**





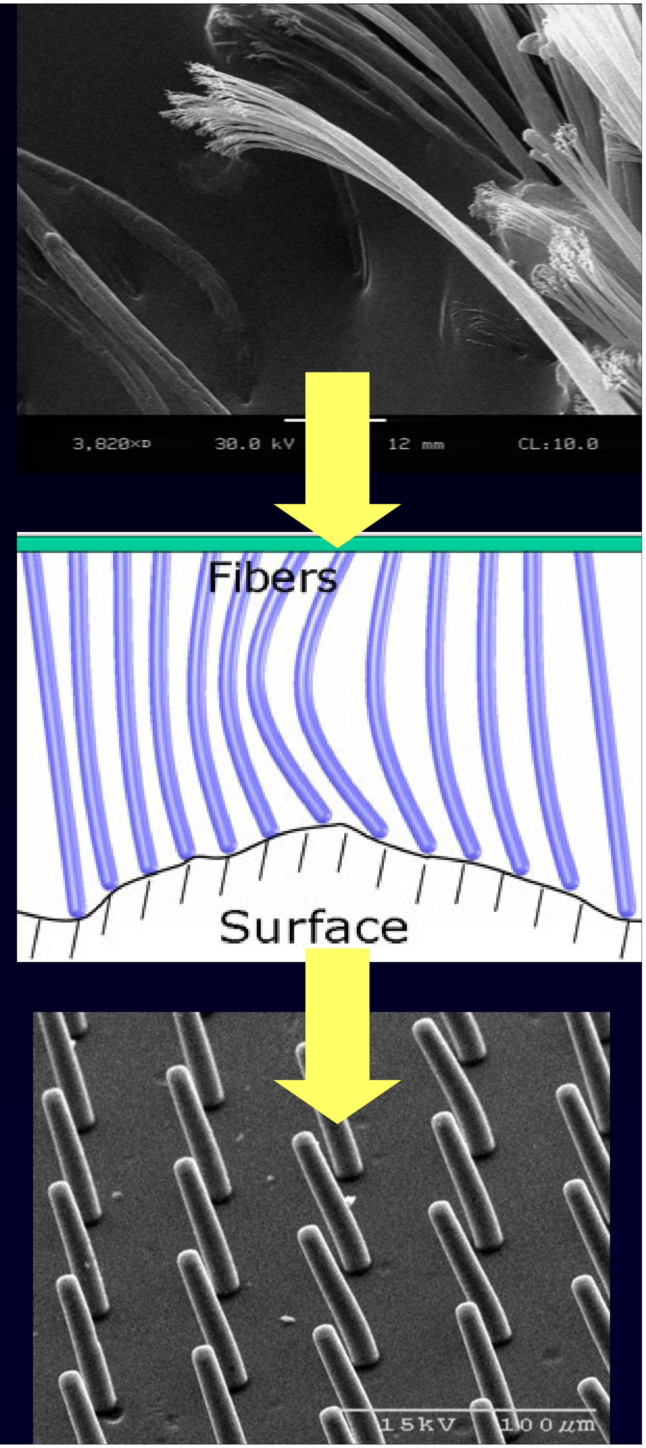
Other Features

- Generic principle: Dry adhesion using intermolecular forces such as van der Waals forces (10 N/cm^2 adhesion)
  - Sticking to almost any material in any environment (air/liquid/vacuum)
- Power efficient and fast attachment and detachment
  - Attaching in 10 ms (preloading) and detaching (peeling) in 16 ms (agility)
- Self-cleaning
  - Robustness against dirt and contamination
- Saucer type tip endings
  - Enhancing adhesion and pressure distribution

Synthetic Fibrillar Adhesive Design

- **Functional Requirements**
  - Strong adhesion and efficient detachment
  - Rough surface adaptability
  - Self cleaning
  - Durability

- **Design Parameters**
  - Fiber geometry (diameter and aspect ratio)
  - Hierarchy
  - Density
  - Tip shape
  - Young's modulus and tensile strength
  - Fiber orientation



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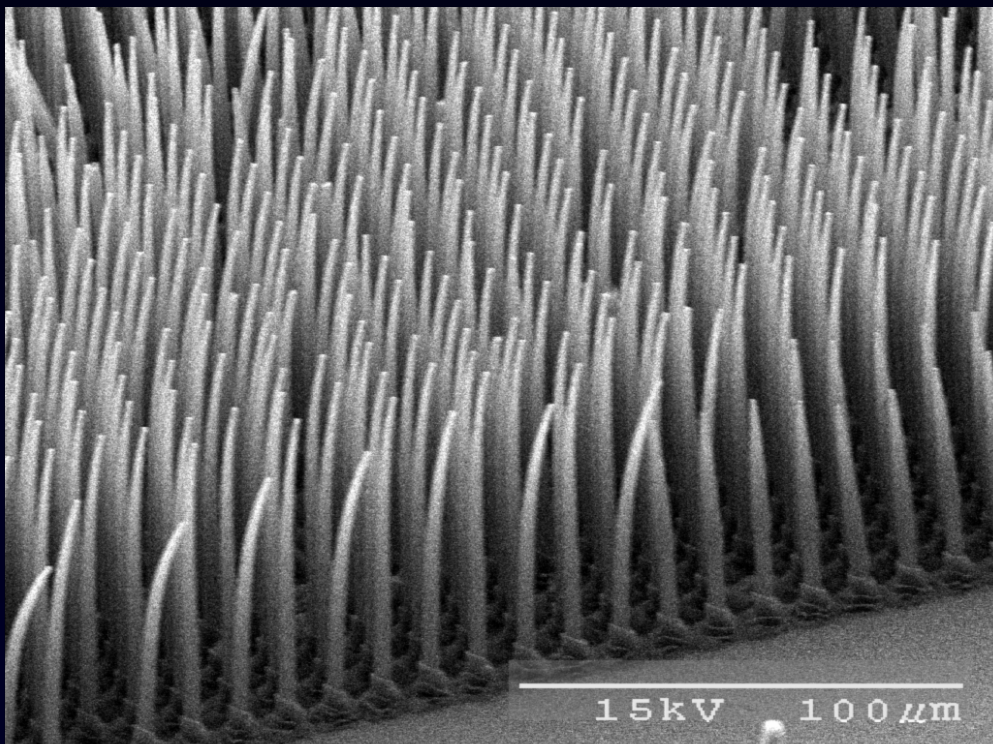
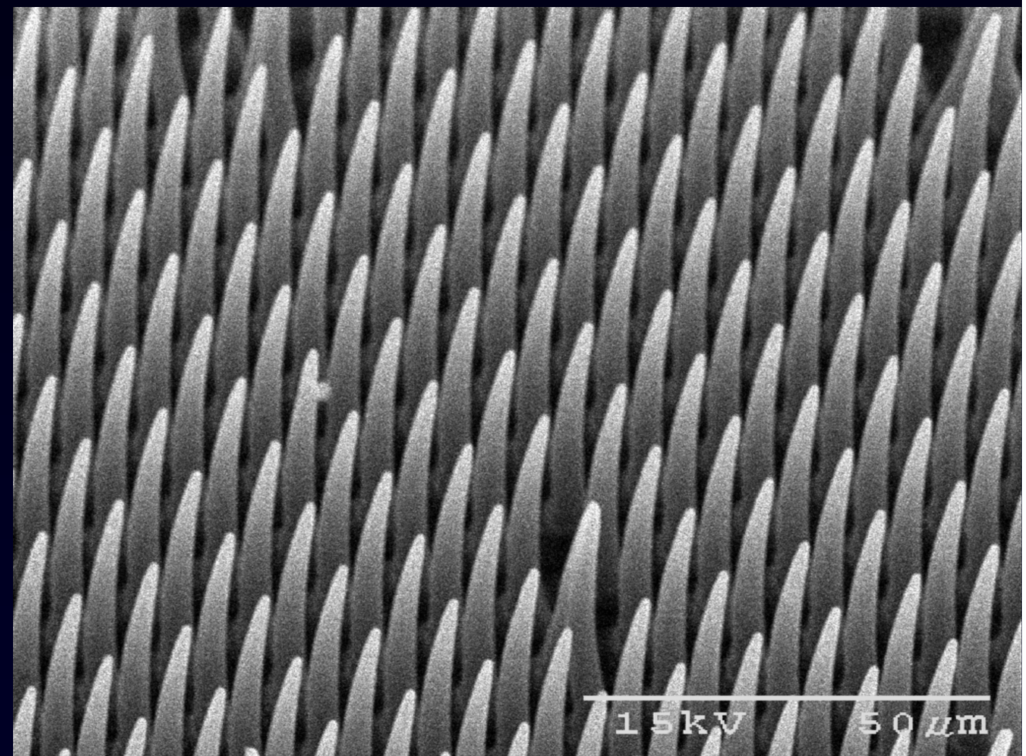
Polyurethane Micro-Fibers by Molding a Silicon Micro-Channel Template



Polyurethane (2 GPa)
2 micron fibers
1:20 aspect ratio



PDMS (0.6 MPa)
2 micron fibers with tapered ends

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PDMS 4 micron Fibers Lifting 300 gr

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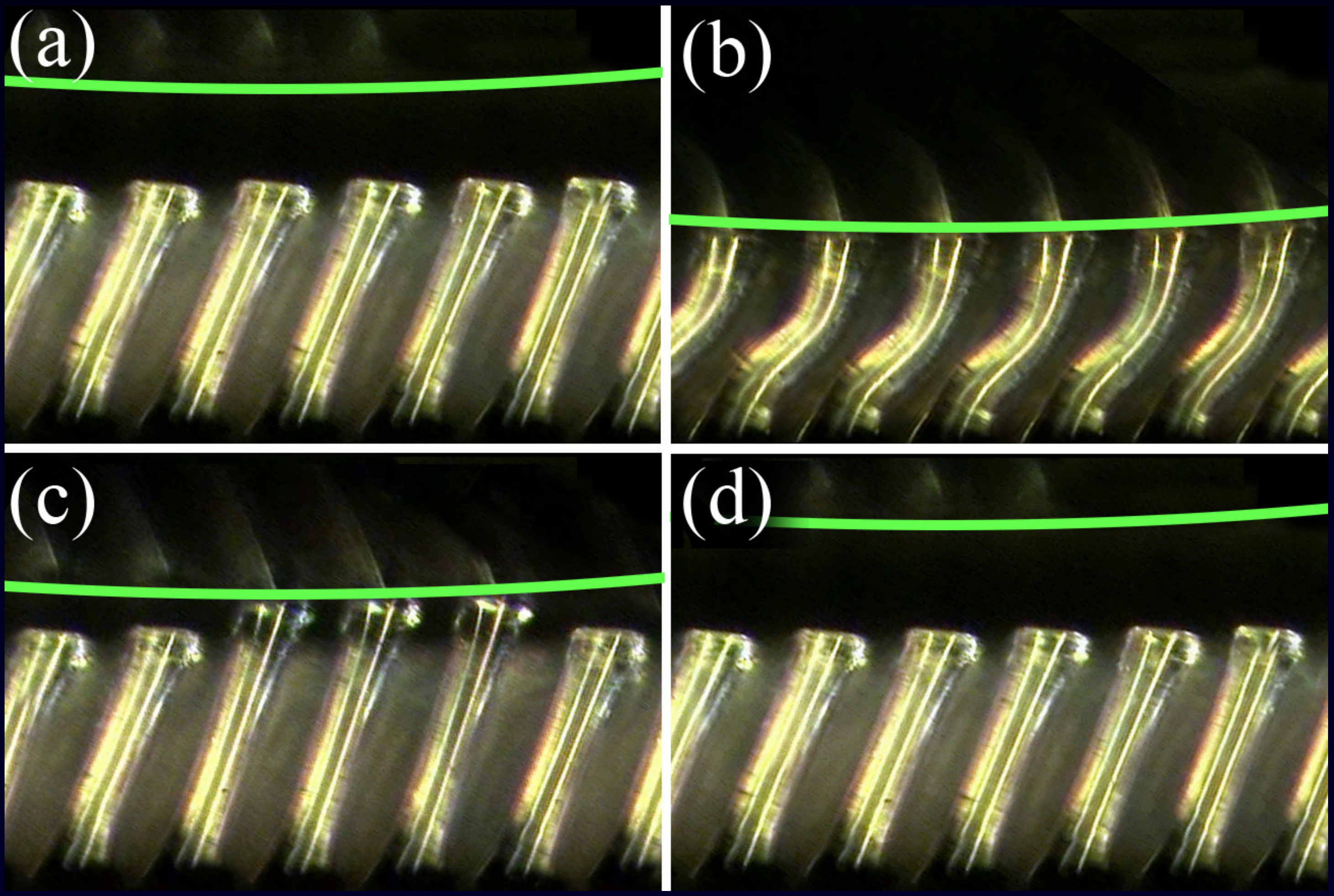
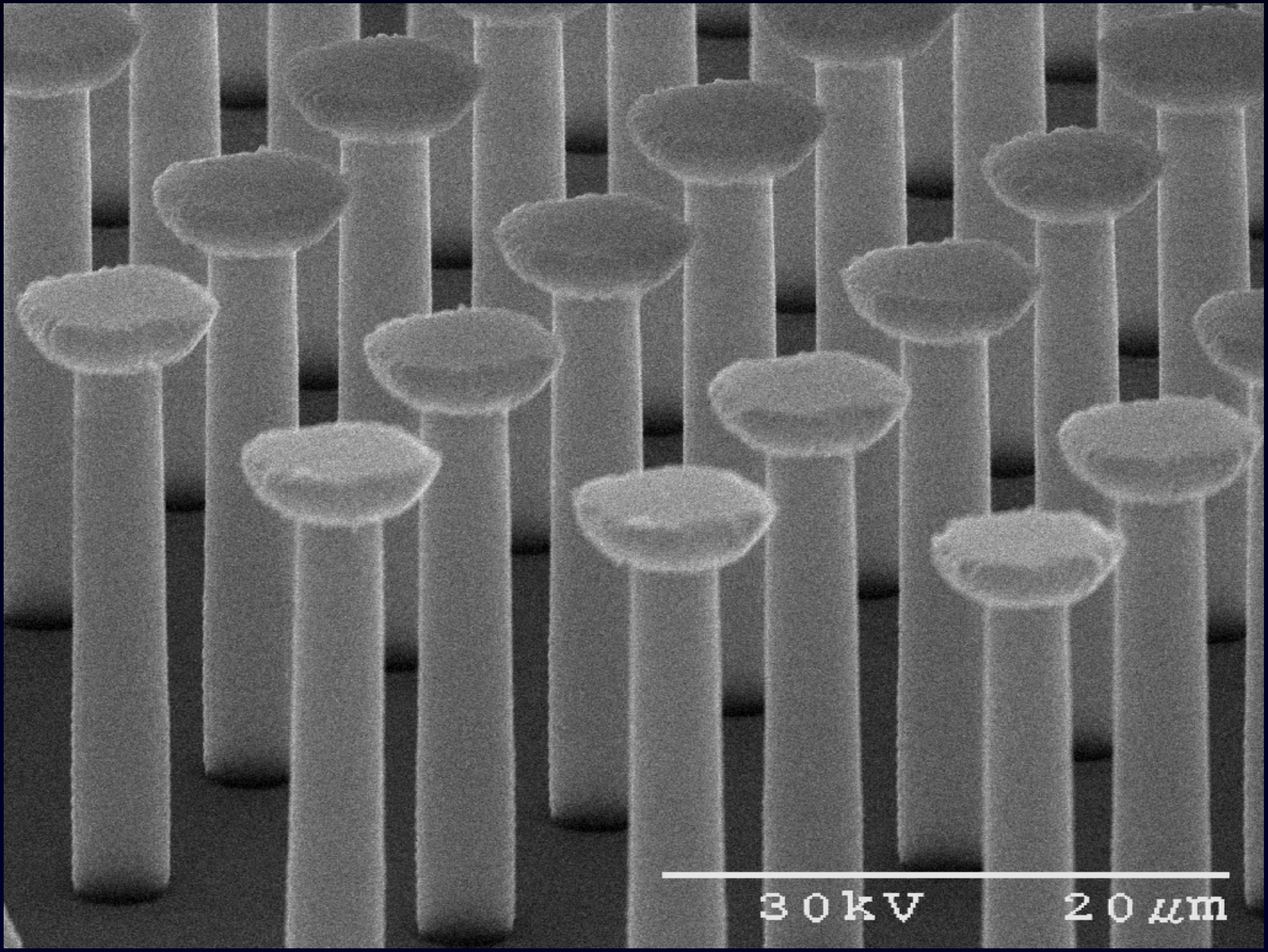
Angled Polyurethane Microfibers by Two-Step Molding



Contacting to a 12 mm diameter sphere

Optical Lithography based Micro-Fibers with Spatular Tips



S. Kim and M. Sitti, Applied Physics Letters, 2006 (in press).

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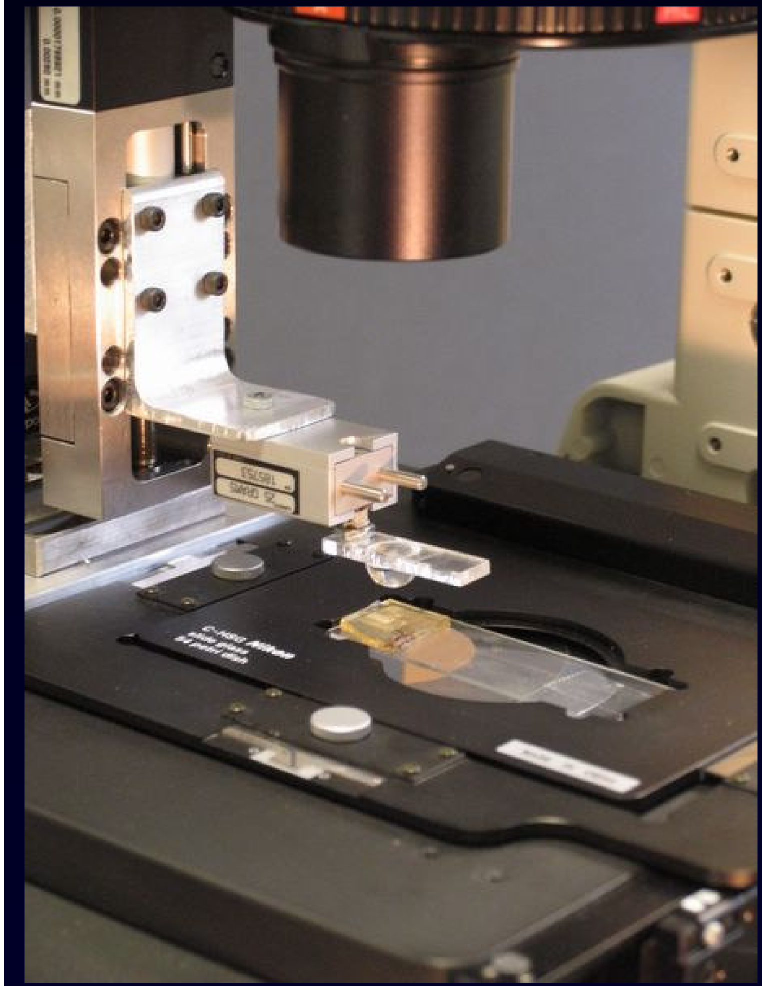
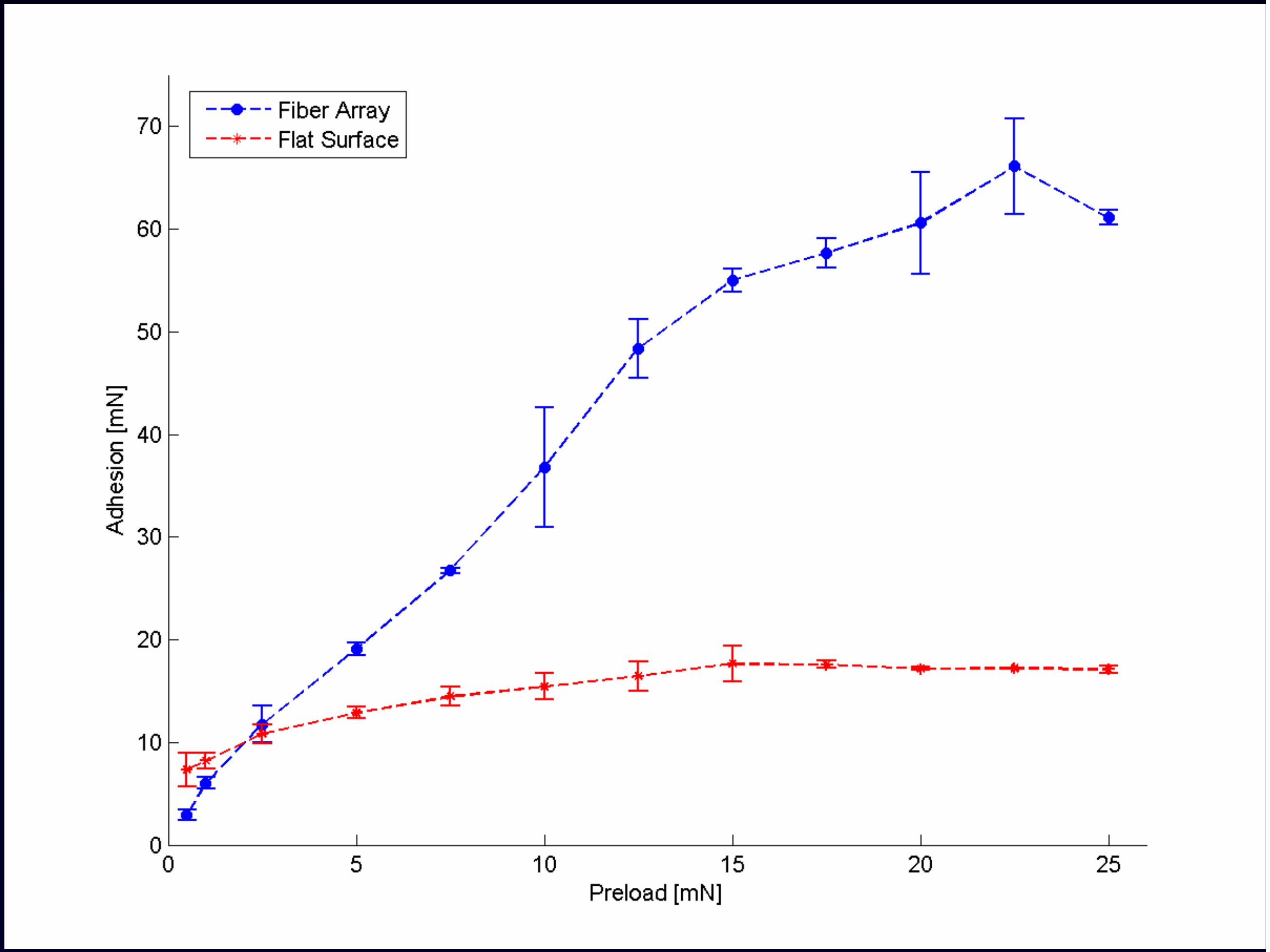
Macroscale Microfiber Adhesion on a 12 mm Diameter Sphere





Adhesion enhancement due to microfibers with flat tips

Applications of Gecko Adhesives

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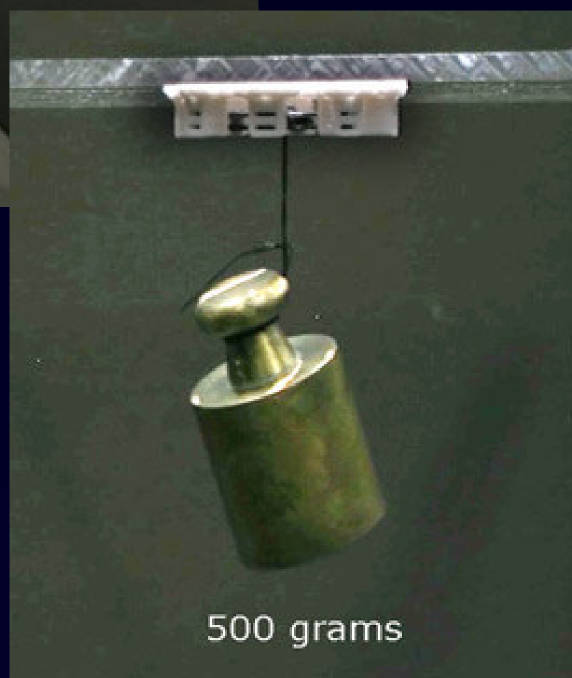
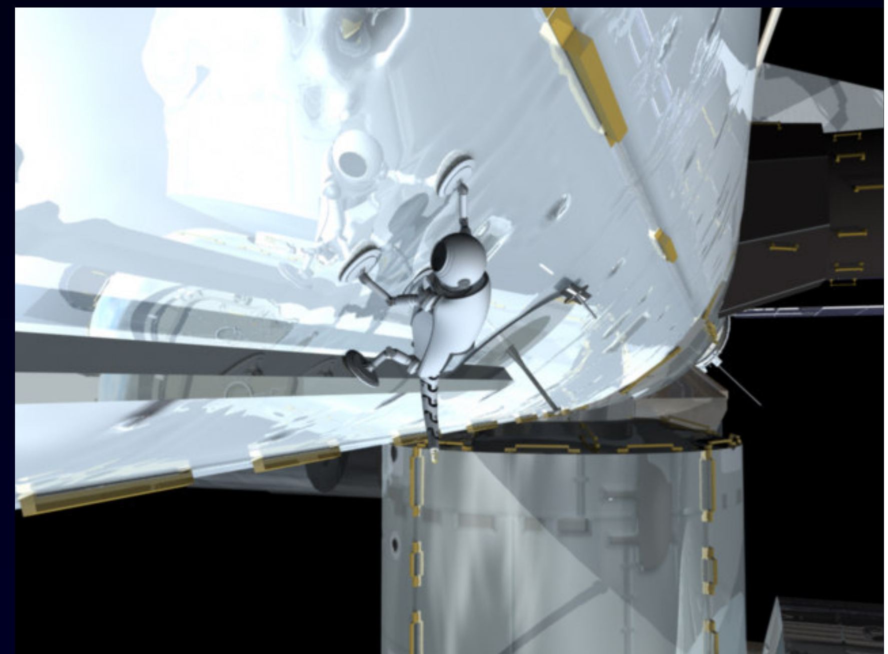
Gripper Design for Space Shuttle Inspection Robots (NASA/Northop Gruman)





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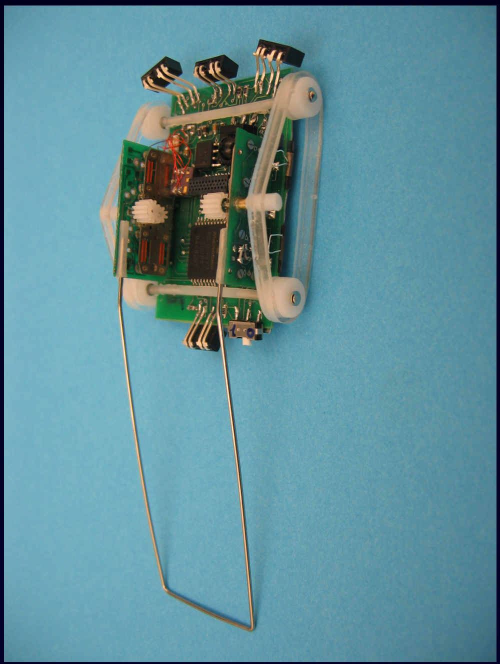
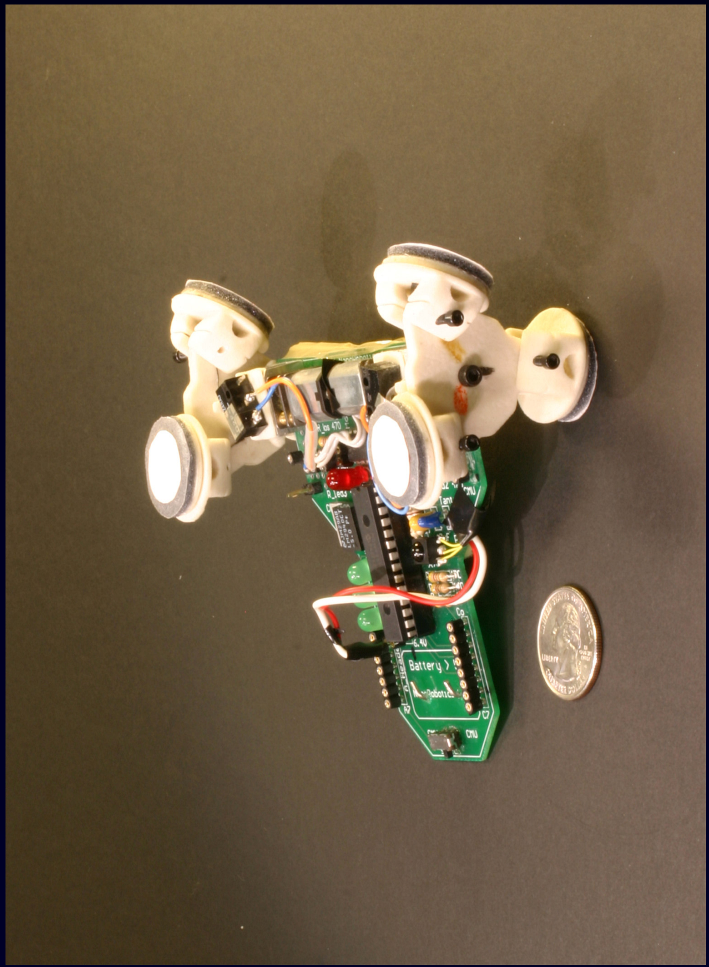
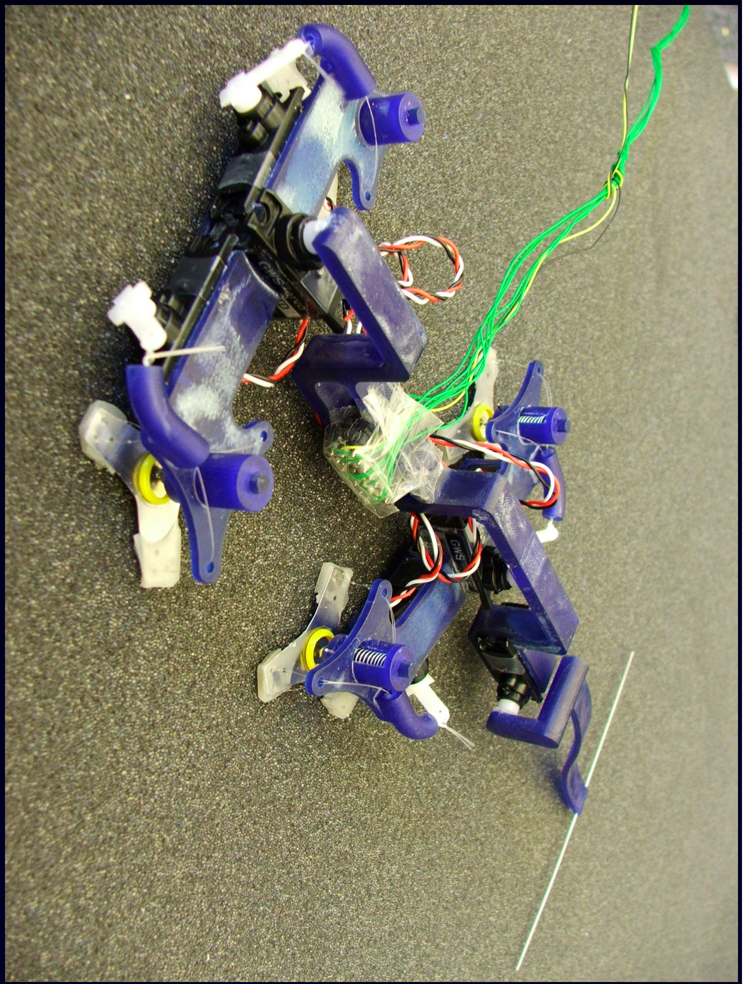
Miniature Climbing Robots



Tankbot



Tri-Legged design: Waalbot



Gecko inspired design: Geckobot

Tank Climbing Robot

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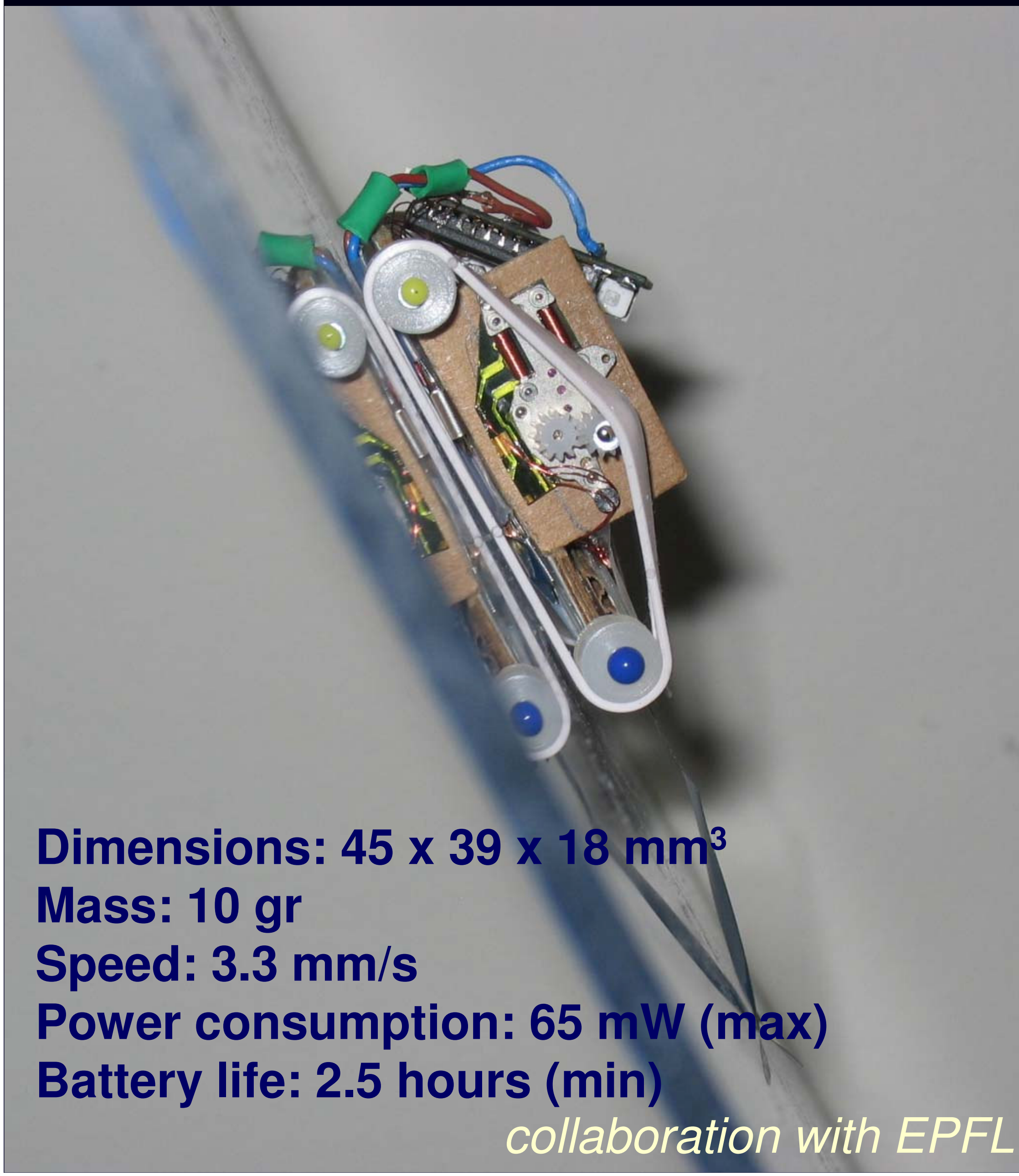

Dimensions: 45 x 39 x 18 mm^3
Mass: 10 gr
Speed: 3.3 mm/s
Power consumption: 65 mW (max)
Battery life: 2.5 hours (min)

collaboration with EPFL

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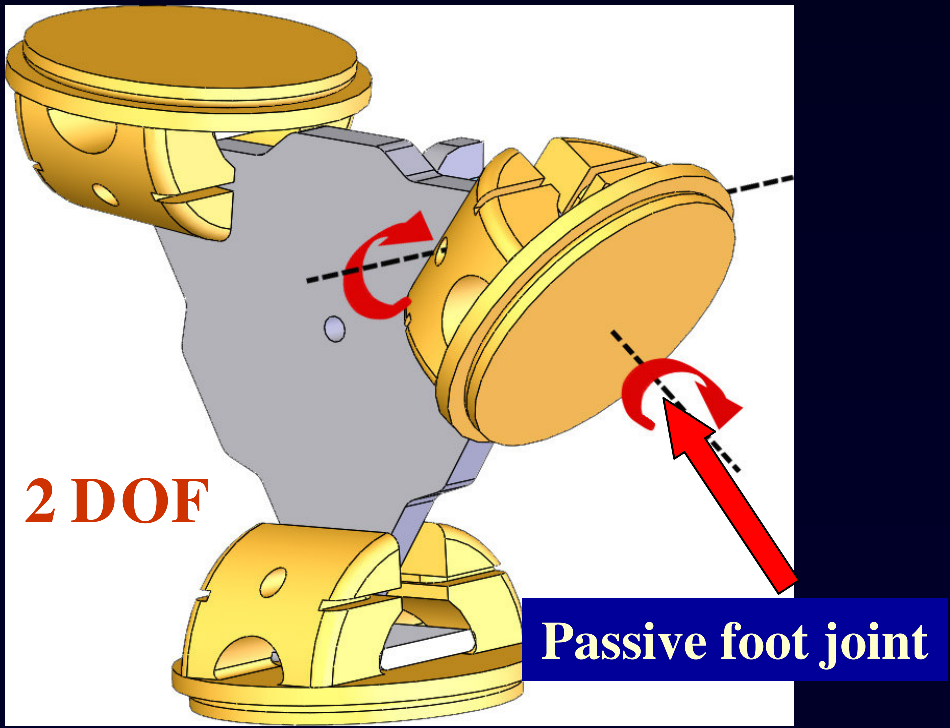
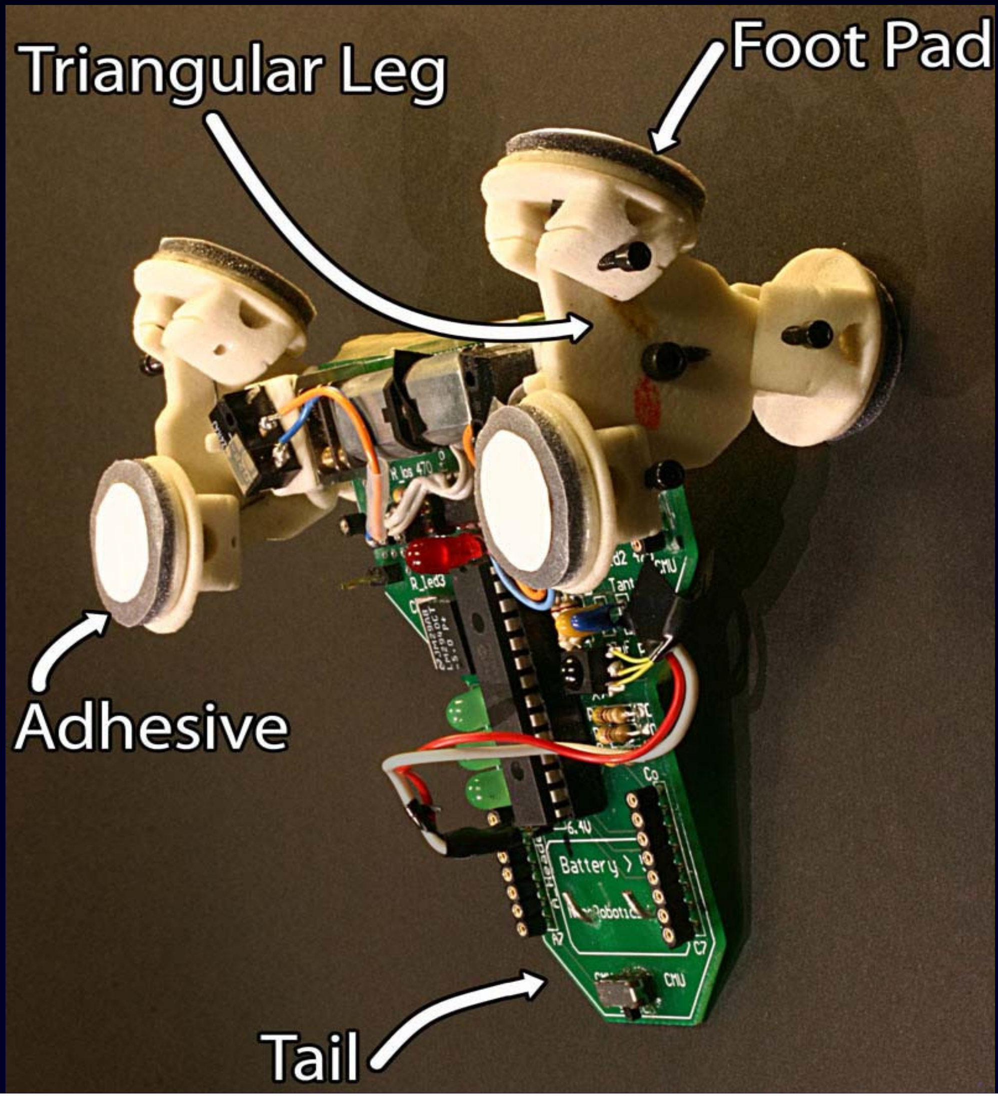
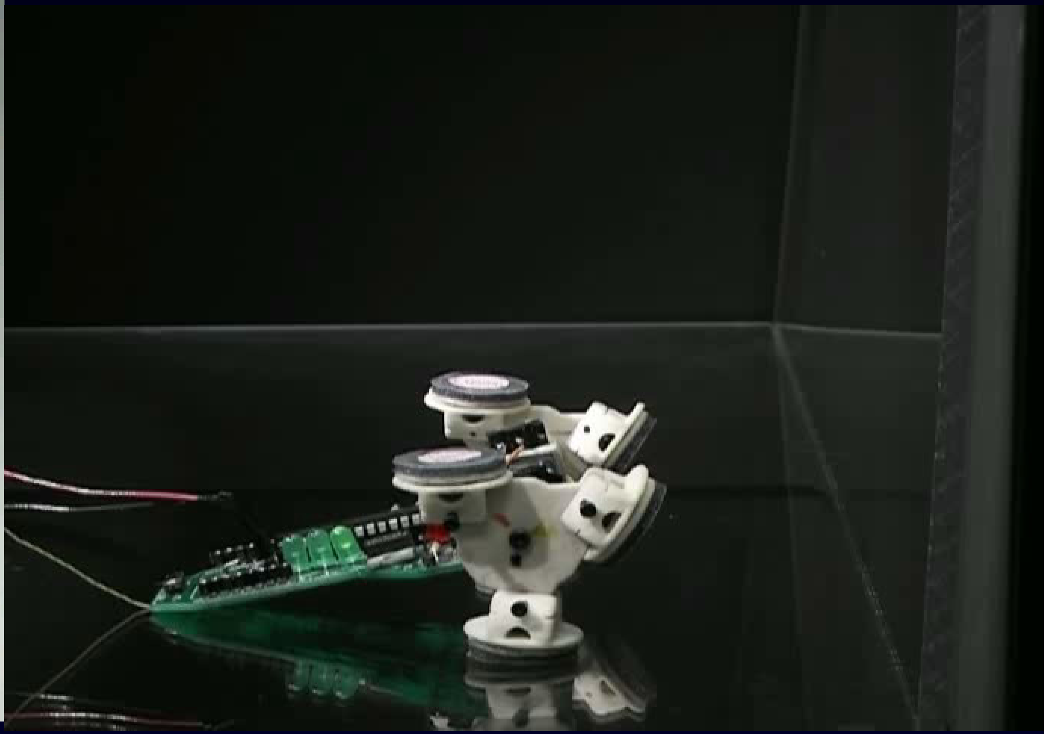
Tri-Legged Design

- Semi-autonomous
- Non-tethered
- Pre-programmed or teleoperated
- 100 grams; 13 cm long





Movies

M. Murphy and M. Sitti, *IEEE/ASME Trans. on Mechatronics*, 2006 (in press).

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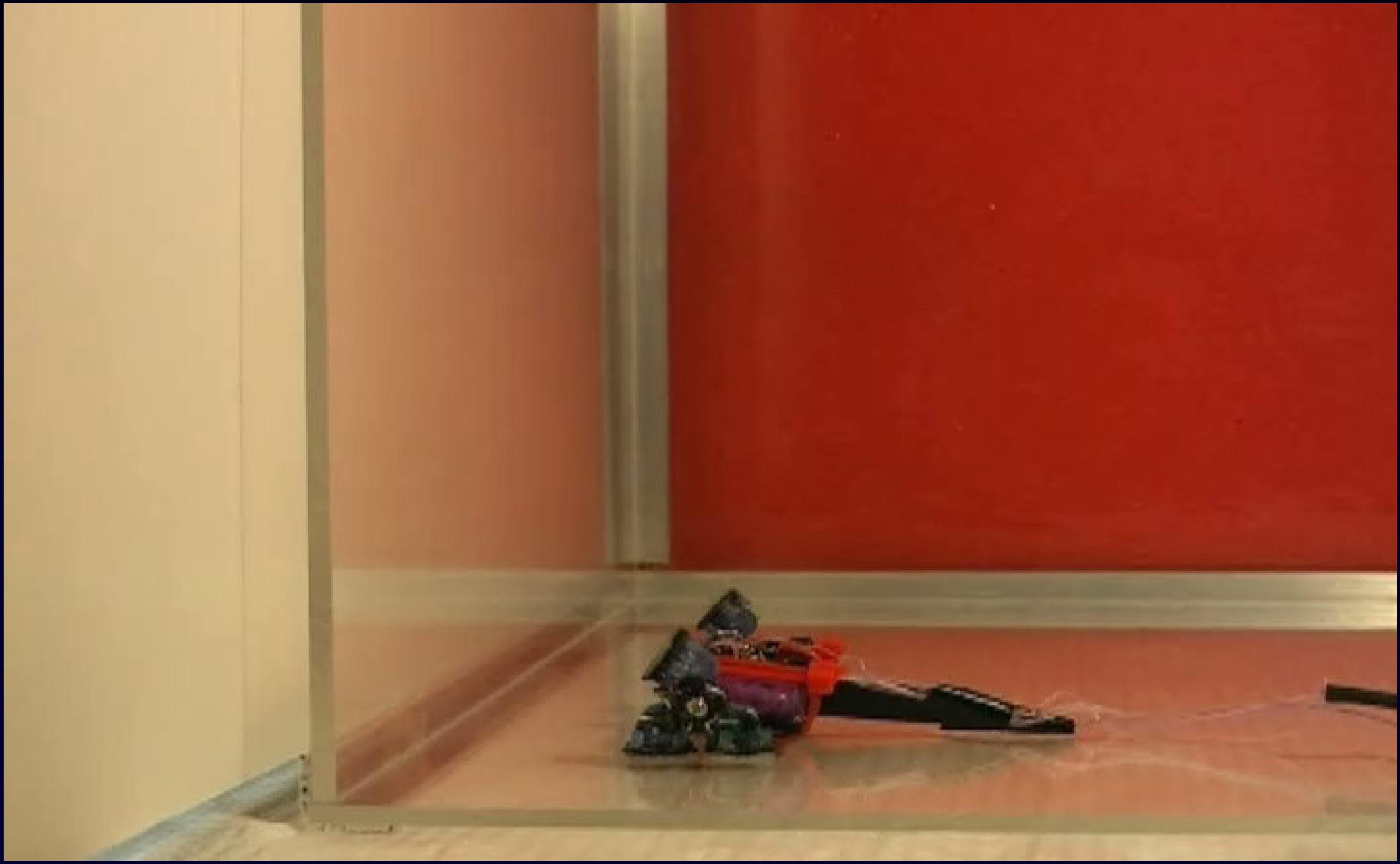
Current Waalbot II…



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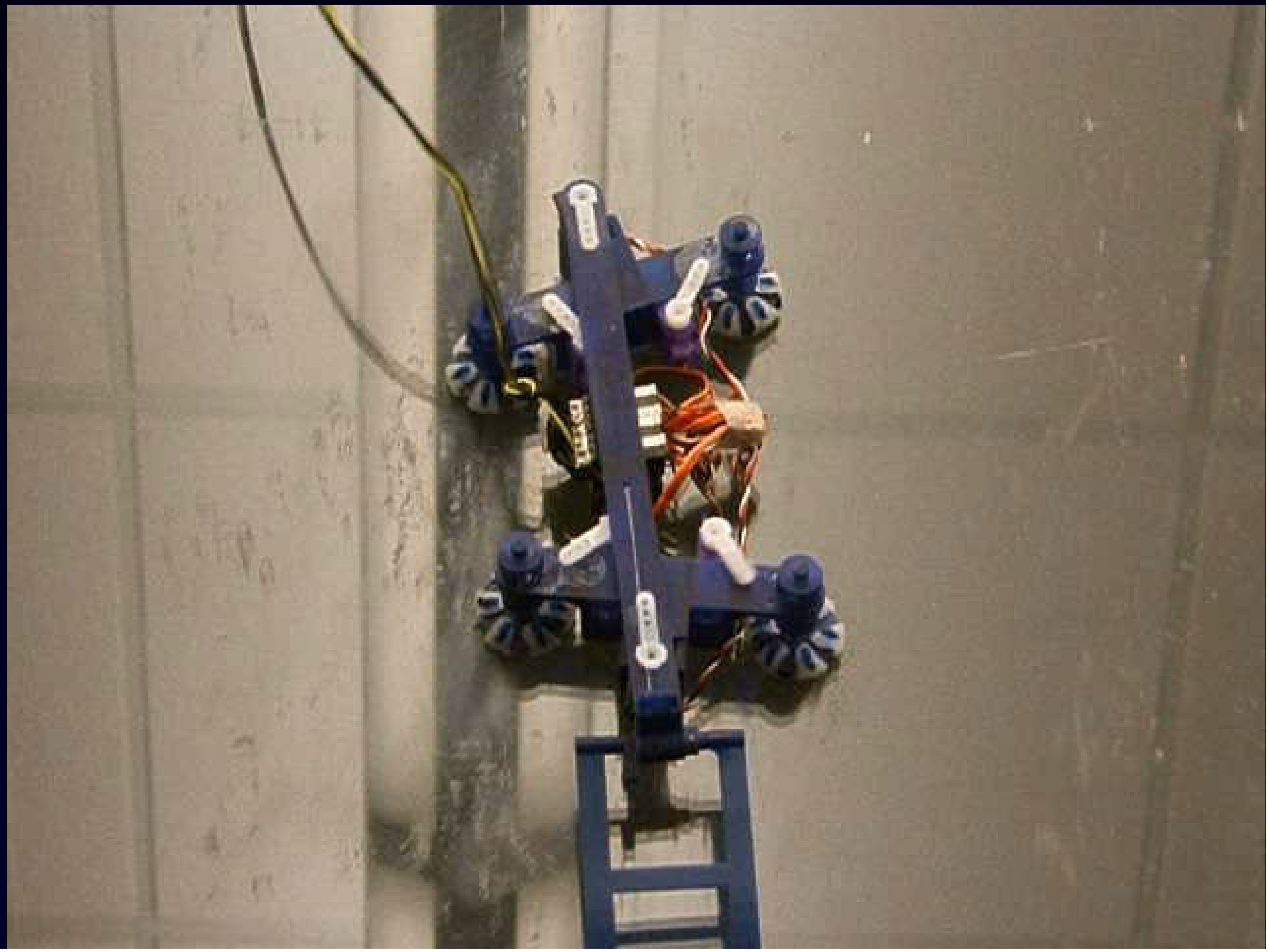
Geckobot



80 degrees slope
Acrylic surface
~10 cm

O. Unver and M. Sitti, *IEEE Trans. on Robotics*, 2006 (under review).

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Endoscopic Capsule Robots in the Digestive Tract

Pill Camera

Given Imaging, Olympus, ...

Robotic Pill Camera

- Increased controllability and performance
- Novel applications: biopsy, drug delivery, etc.

Funded by 21st Century Frontier Program, Korea

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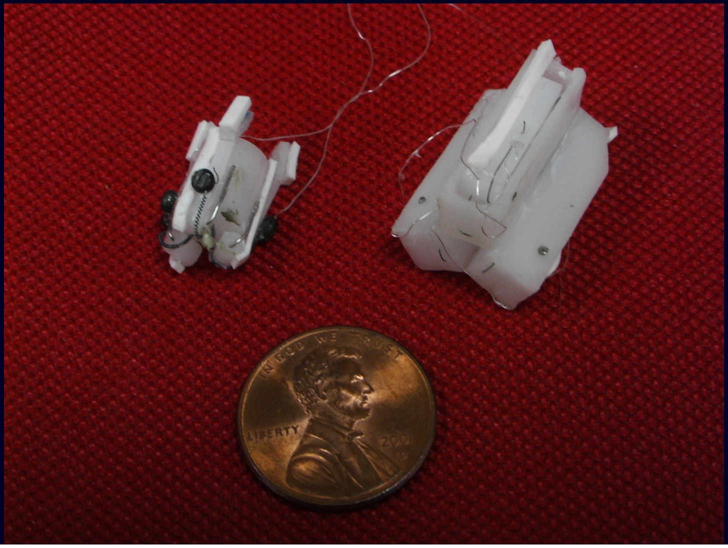
Camera Integrated Clamping Capsule Robot



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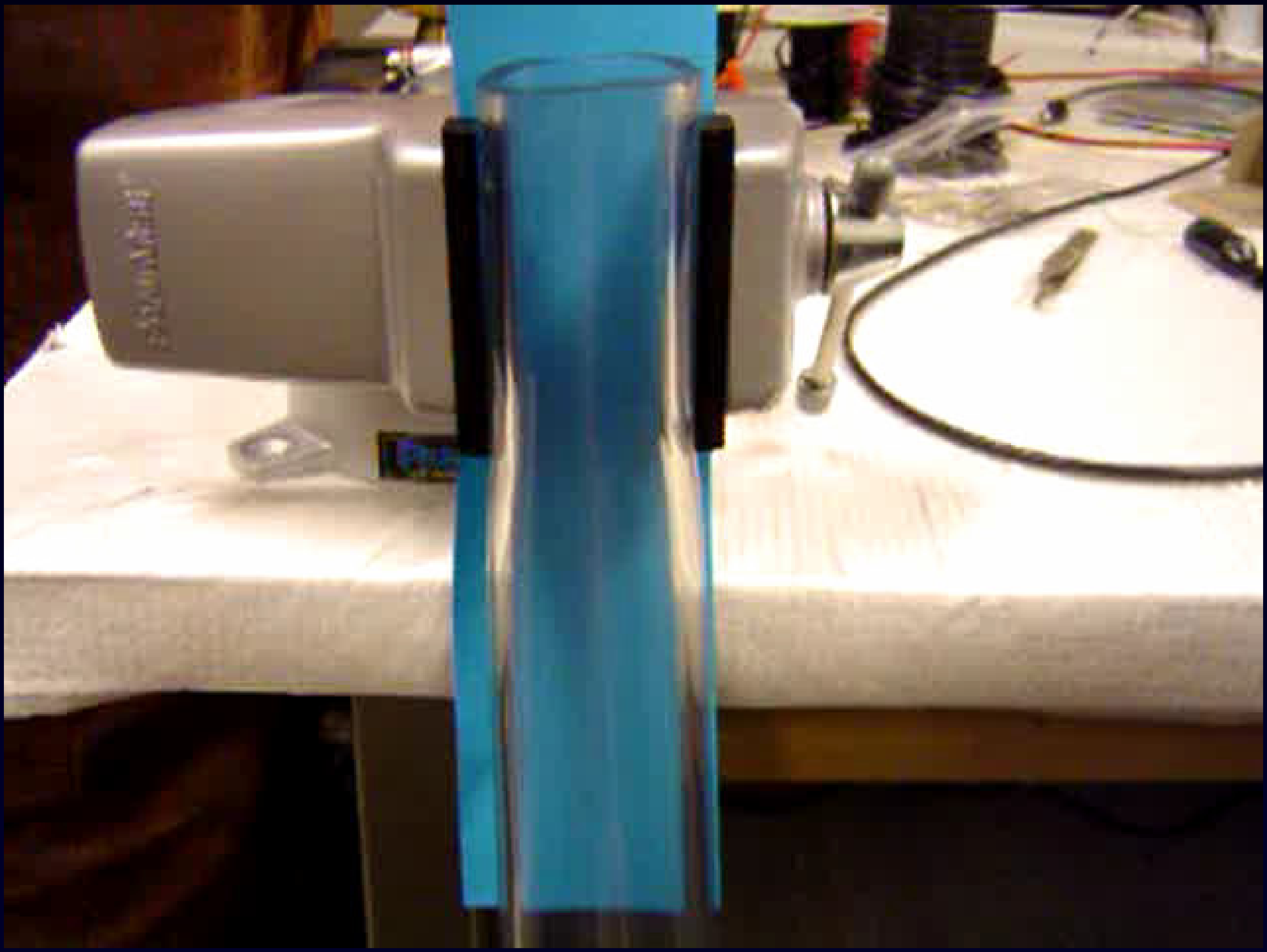
Tests in a Plastic Tubing



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Legged Locomotion on Water #1: Walking on Water

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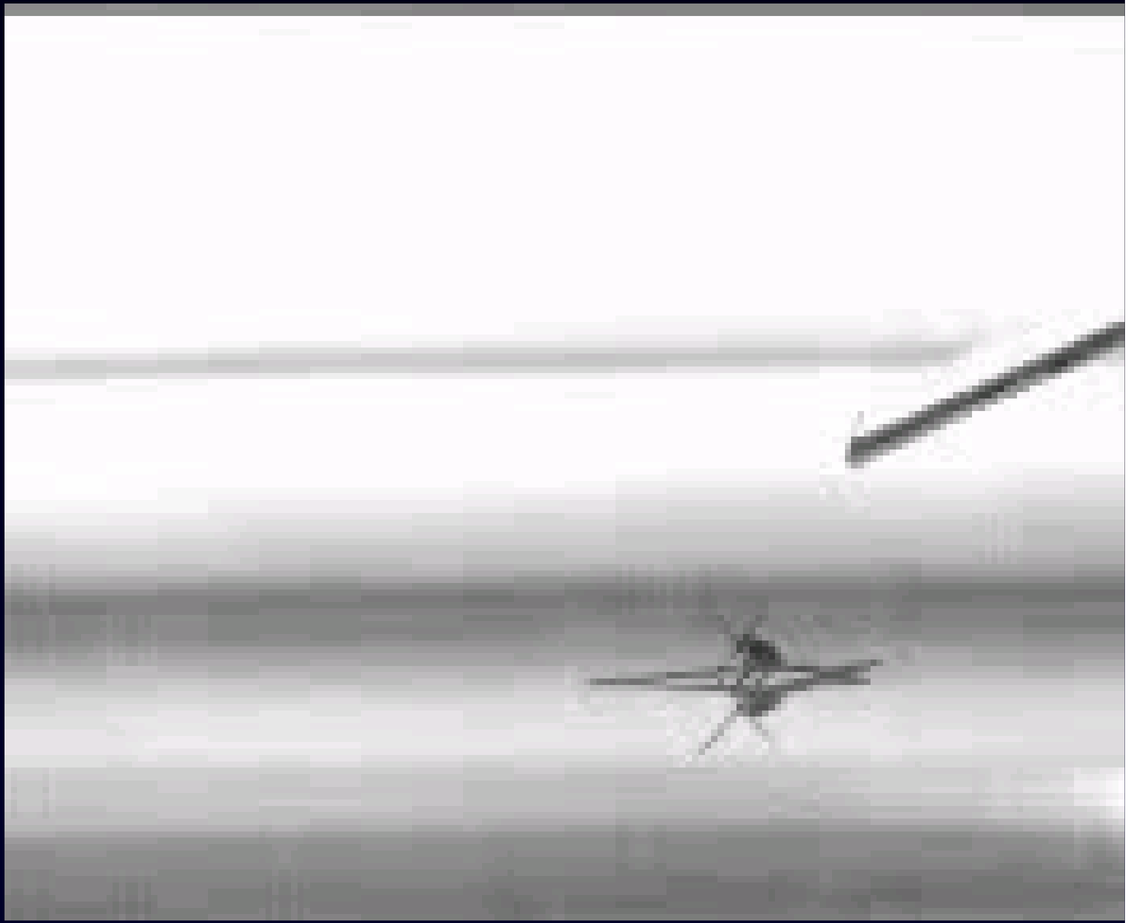
Water Striders in Nature

- Staying on water using surface tension
  - Surface tension $\propto L^1$
    >>
    Buoyancy $\propto L^3$
  - Super-hydrophobic legs using micro-hairs
    - One leg supports 15 times its body weight.
    - 0.1 mm diameter
    - Air pocket around the legs
  - Very light (10-100 mg)
  - 1-25 cm total length



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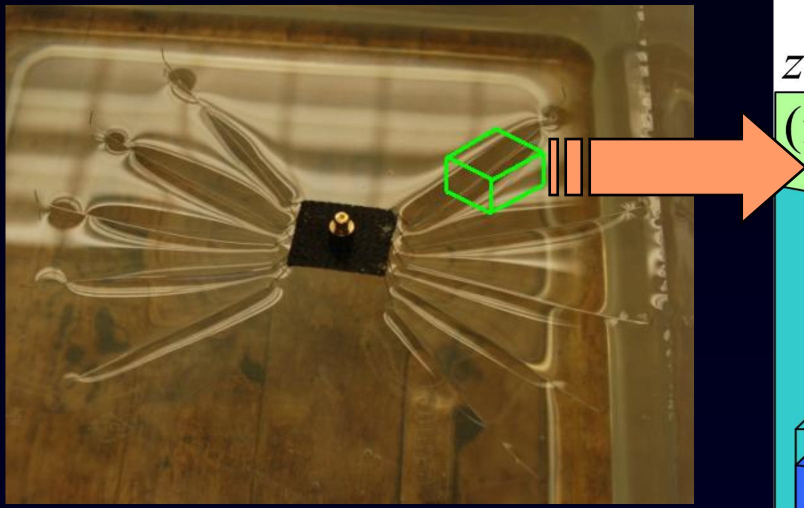
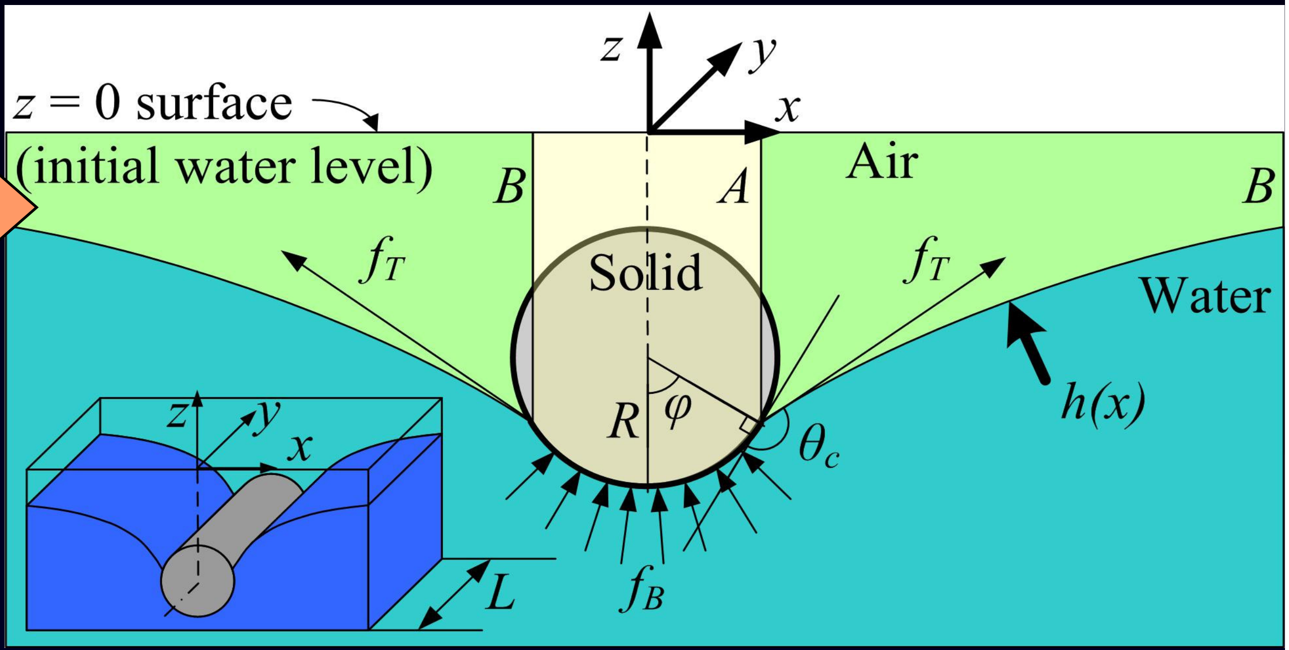
Balancing Legs: Modeling Leg Lift Forces





$$\rho \cdot g \cdot h(x) := \gamma \cdot \left[\frac{\frac{d^2}{dx^2} h(x)}{\left[1 + \left(\frac{d}{dx} h(x)\right)^2\right]^{\frac{3}{2}}} \right]$$

Young-Laplace equation:

Δ P between surfaces = γ /R

Boundary conditions of *h(x)*

$$\frac{dh}{dx}(x_0) = \tan(\theta_c + \varphi - \pi)$$

$$h(\infty) = 0$$

$$\frac{dh}{dx}(\infty) = 0$$

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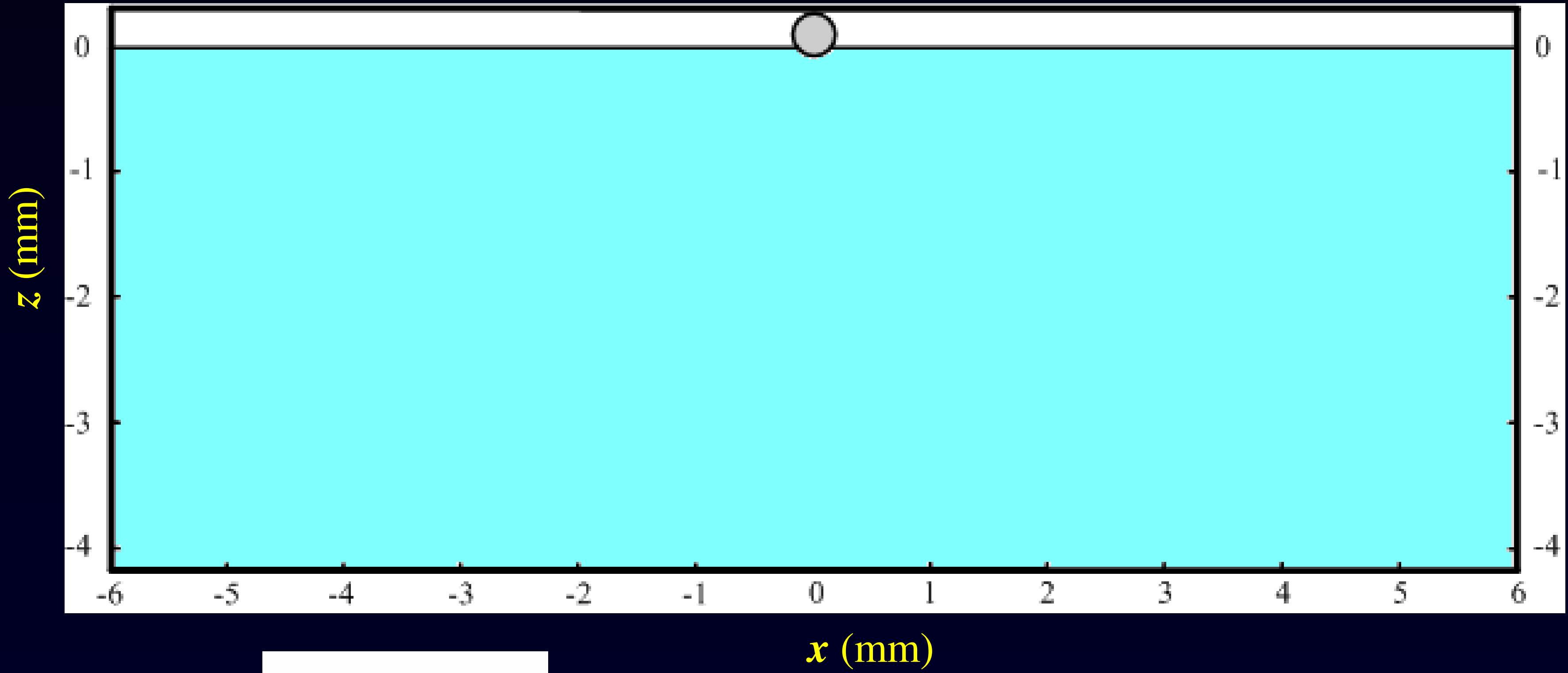
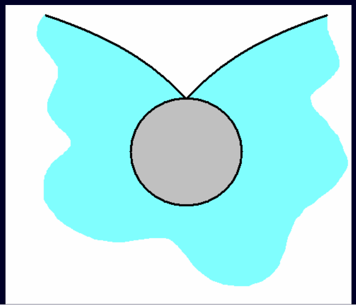
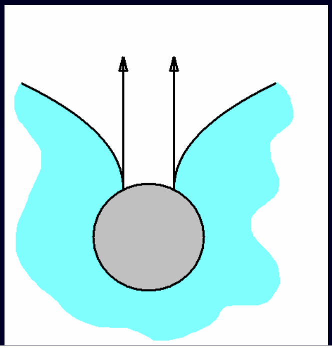
How Deep Can the Leg Go? (When Does the Surface Break?)







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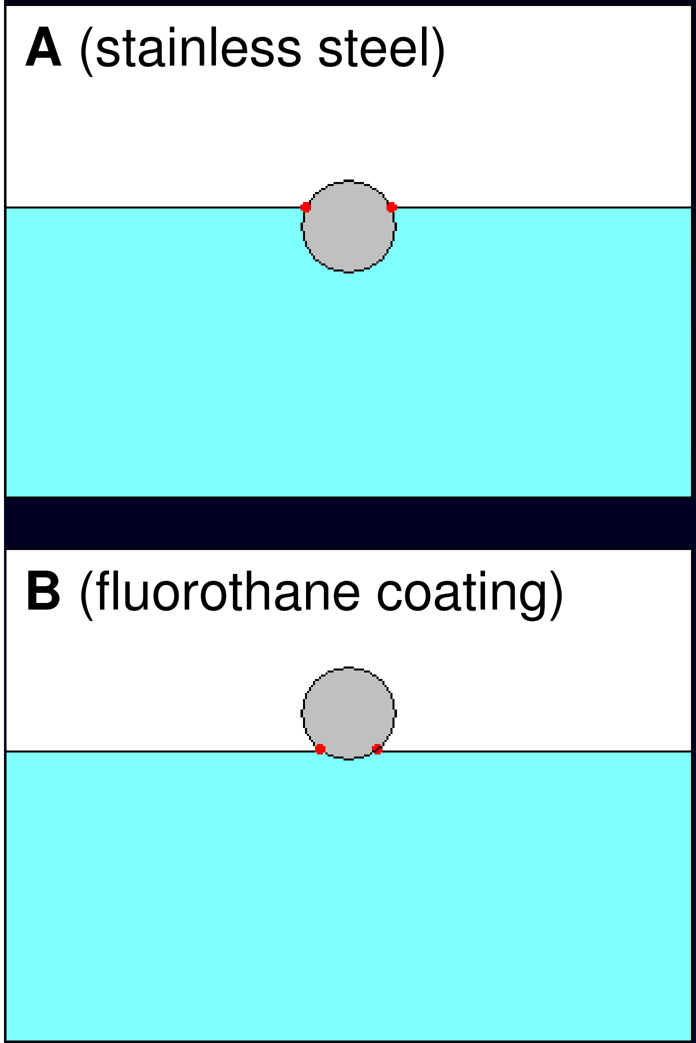
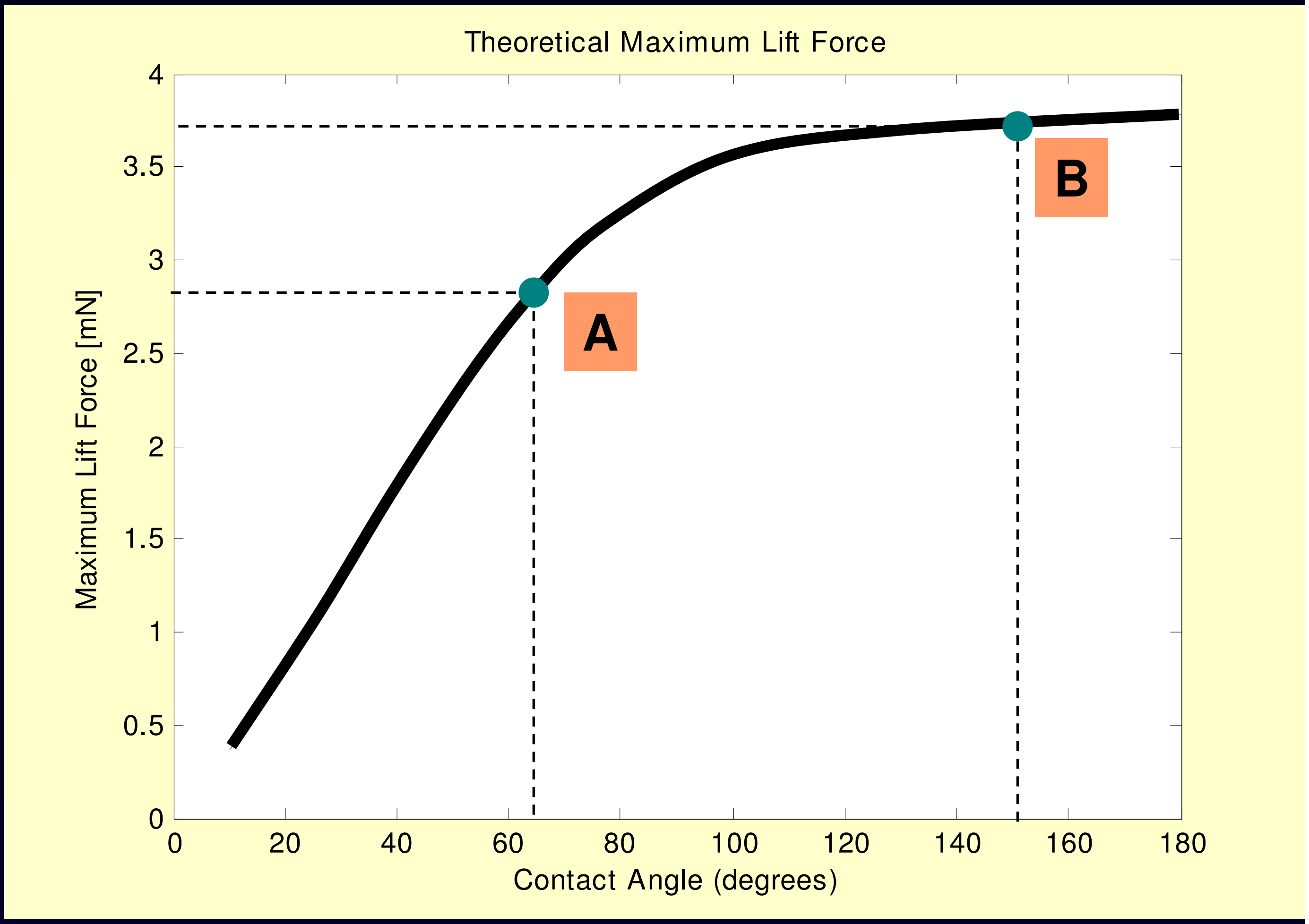
Simulation of Maximum Lift Forces





0.3 mm diameter and 20 mm leg

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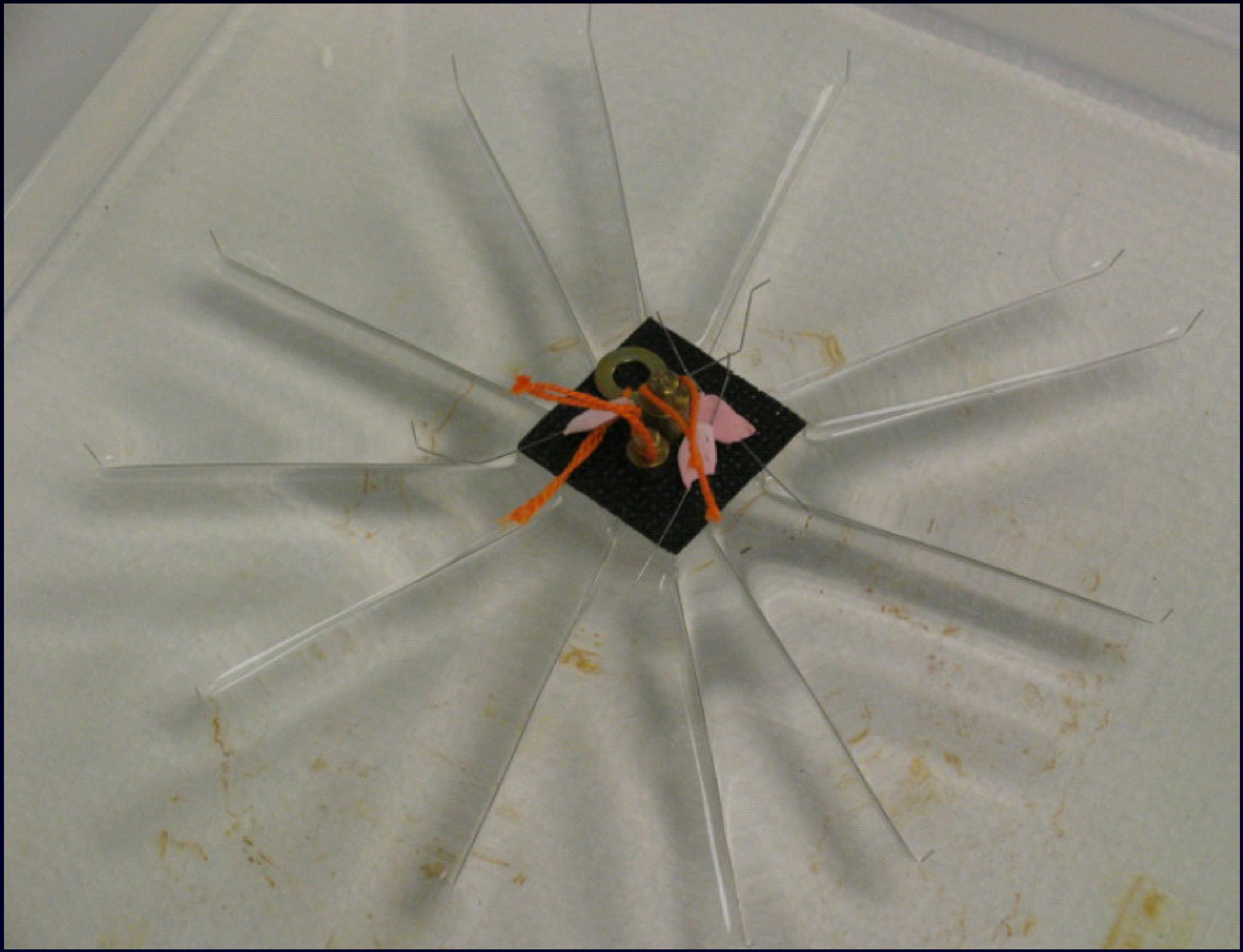
Improved Supporting Legs



9.3 gr payload

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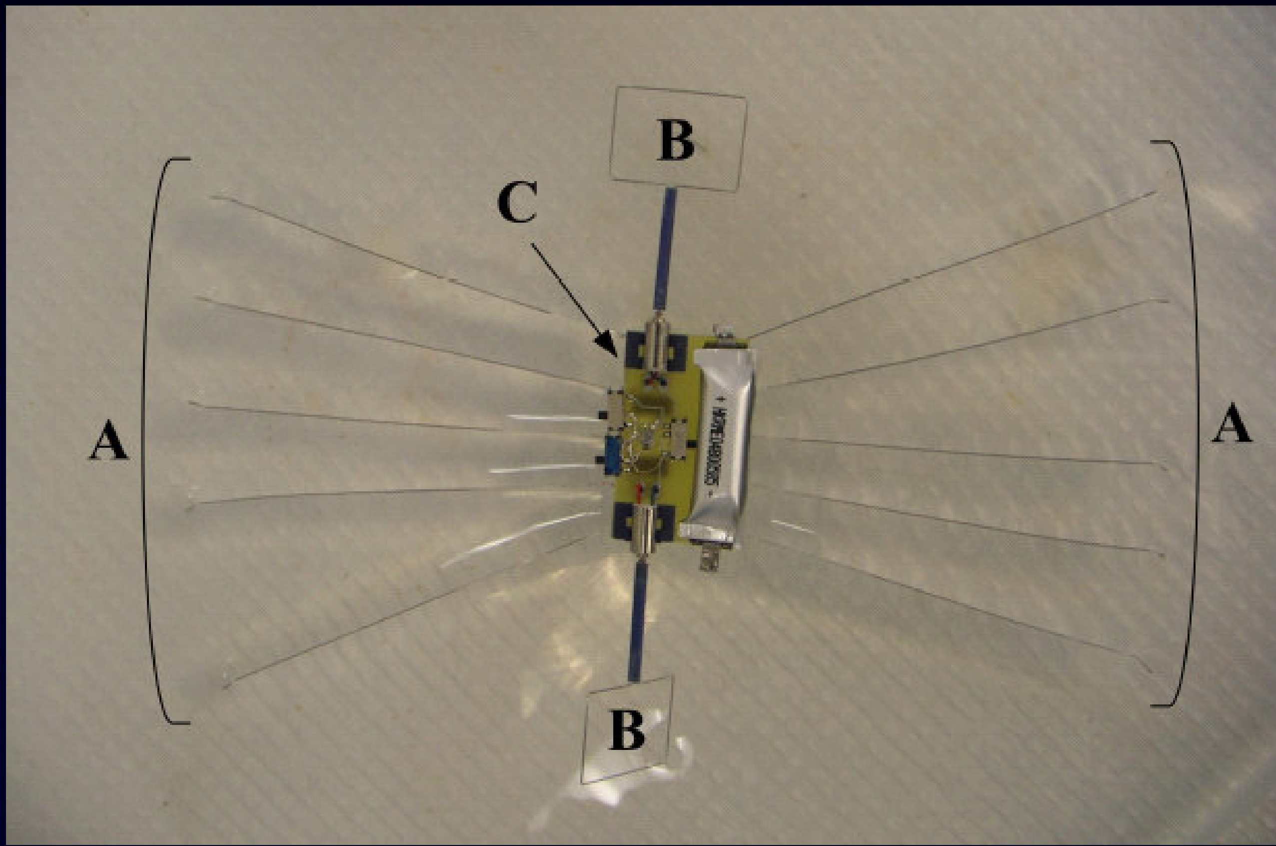
Motorized Water Strider Robot

6.8 gr
5 cm/s
2 motors + poly-Li battery



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Forward Motion

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Rotation

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Free Water-Walker…

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Legged Locomotion on Water #2: *Running on Water* (Basilisk/Jesus Lizard)

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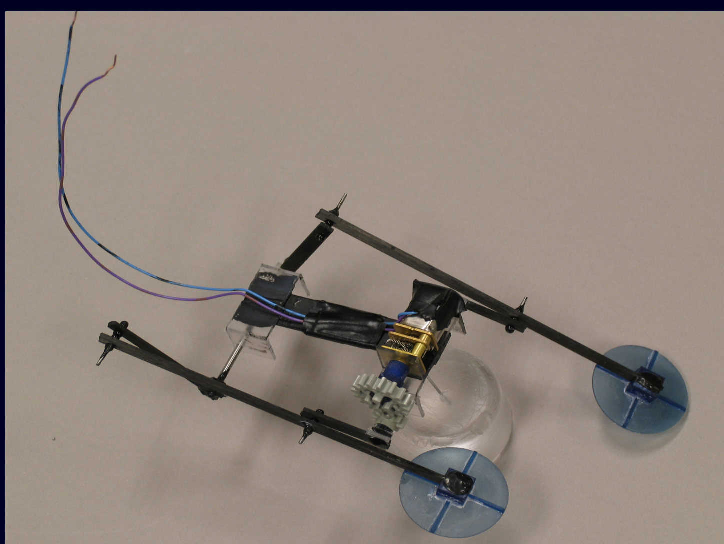
Current Prototype

- **Current specs:**
  - **4 (and 2) legged**
  - **~80 gr tethered**
  - **6-10 rps**
  - **50 g/W lift**



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Leonardo's Float Design…

For a 70 kg person:

To walk on water:

10 km foot perimeter

To run on water:

10 m/s speed
with 1 m^2 foot area

Conclusions

- **Demonstrated miniature robots with various unique locomotion inspired by geckos, water striders, and basilisk lizards**
- **Bio-inspired miniature robots**
  - **Going beyond nature: Backward motion, more legs, etc.**
  - **Designing and implementing robots inspired by nature, and understanding the nature better by the developed robots**
- **Enhancing the welfare of our society by applications in:**
  - **Health-care, space, environmental monitoring, entertainment, education, homeland security, search and rescue, etc.**
- **Future Direction:**
  - **Autonomous, dynamic, agile, and all-terrain swarm of miniature robots**