ICRA ’08 Space Robotics Workshop:
Orbital Robotics

Grippers for Space Locomotion

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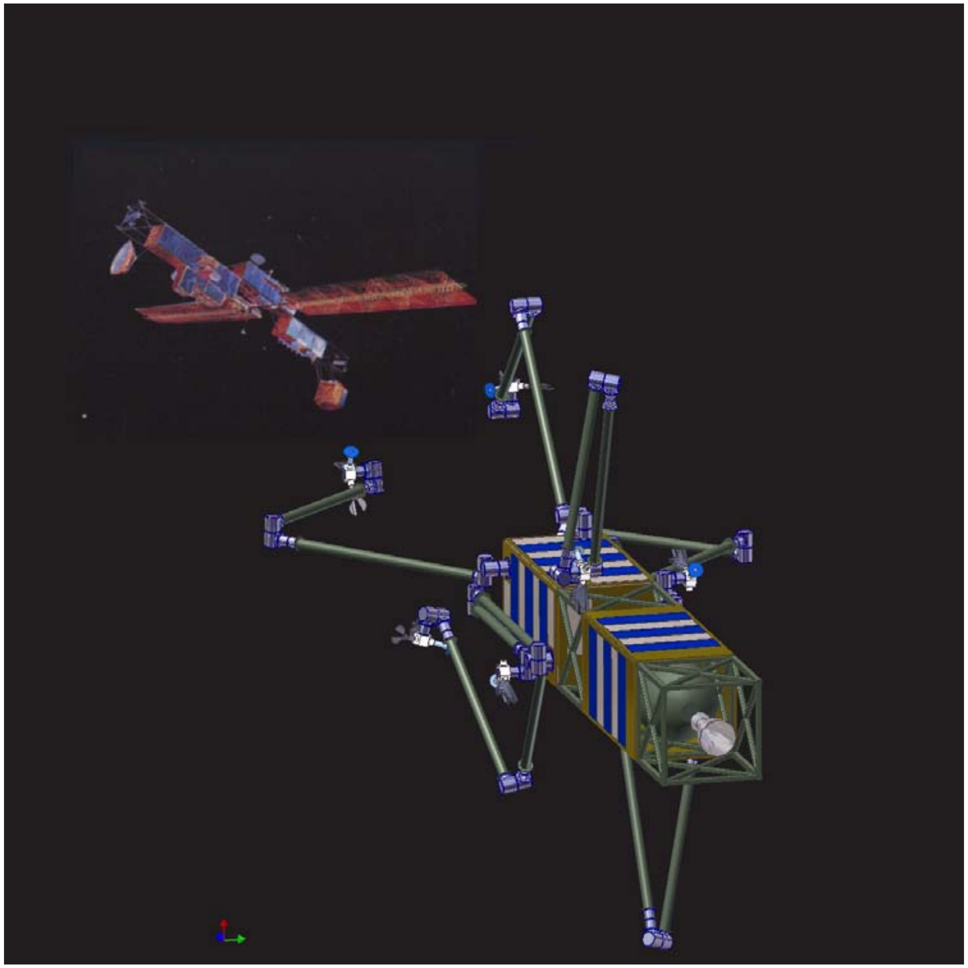
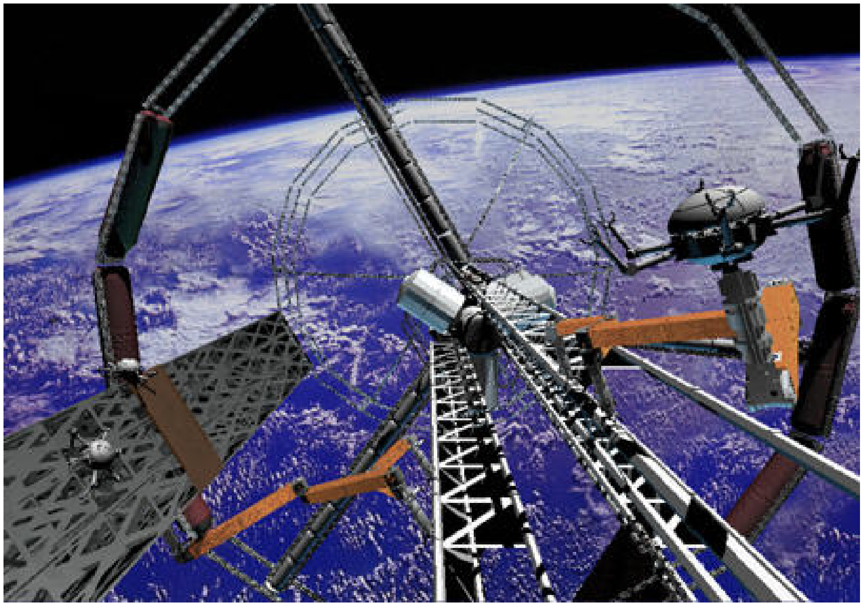


Introduction

- Locomotion in microgravity
  - Free flying: cold gas jet propulsion, 3-axis stabilization
  - Rail and wheels
  - Wheels or treads
  - Legged locomotion: walking, leaping
  - Tethers



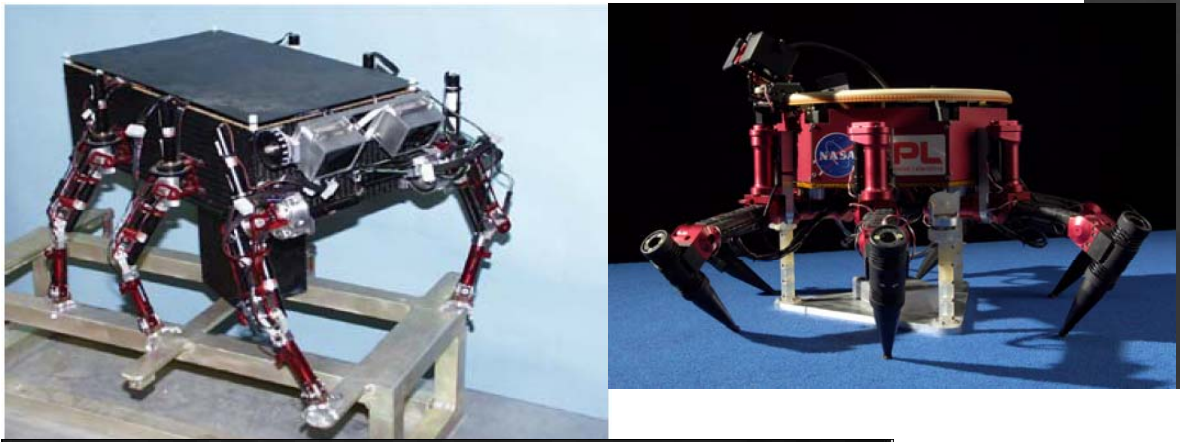
- Manipulation in microgravity
  - Gripping (grasping) of tools, work objects, retrieval
  - Handoff
    - Handoff of tools, materials
    - Astronaut assistance
    - Assisting other robots
  - Reacting forces
    - Tool forces
    - Component installation
    - Object stabilization
    - Vehicle ACS/RCS or delta-V propulsion dynamic forces

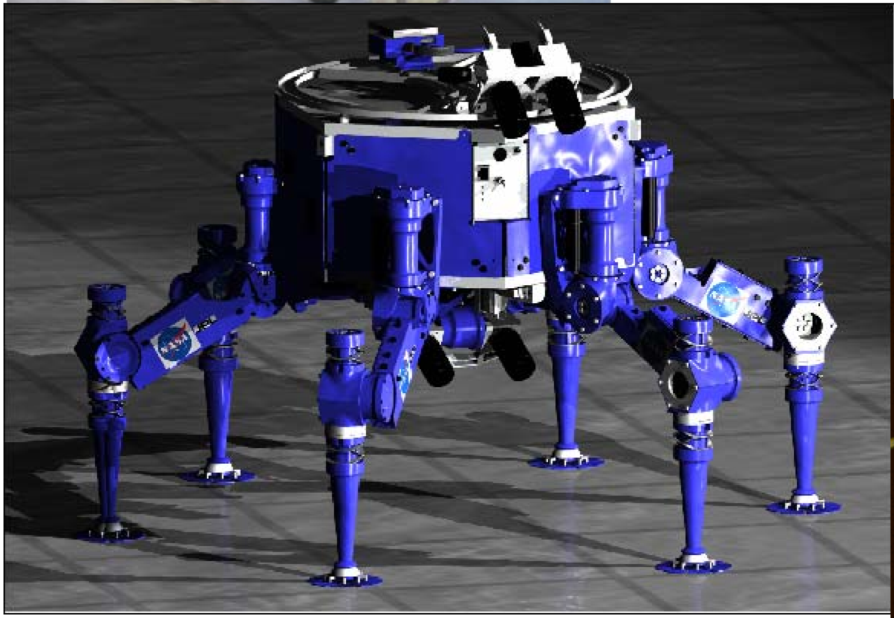
JSC’s mini AERcam

Related Work

JSC Robonaut

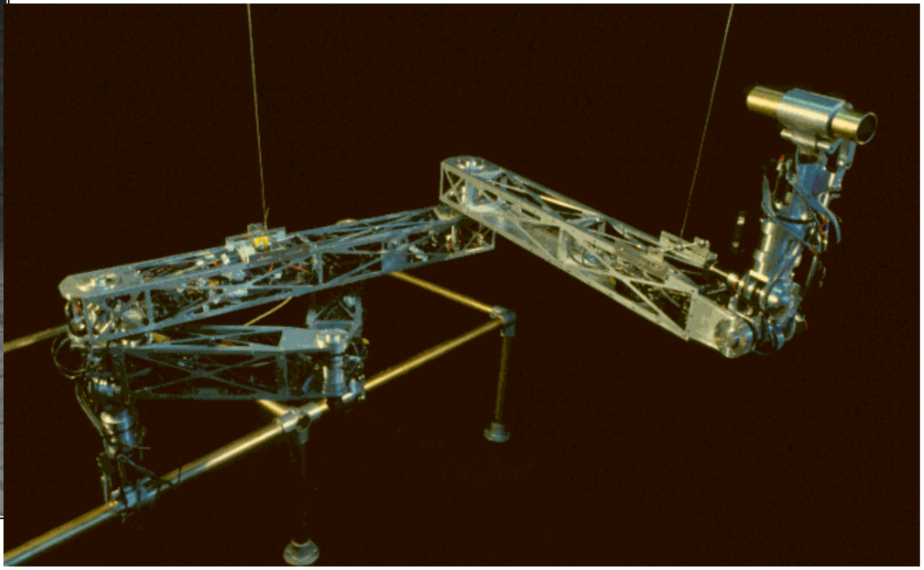
JPL LEMUR I and LEMUR II





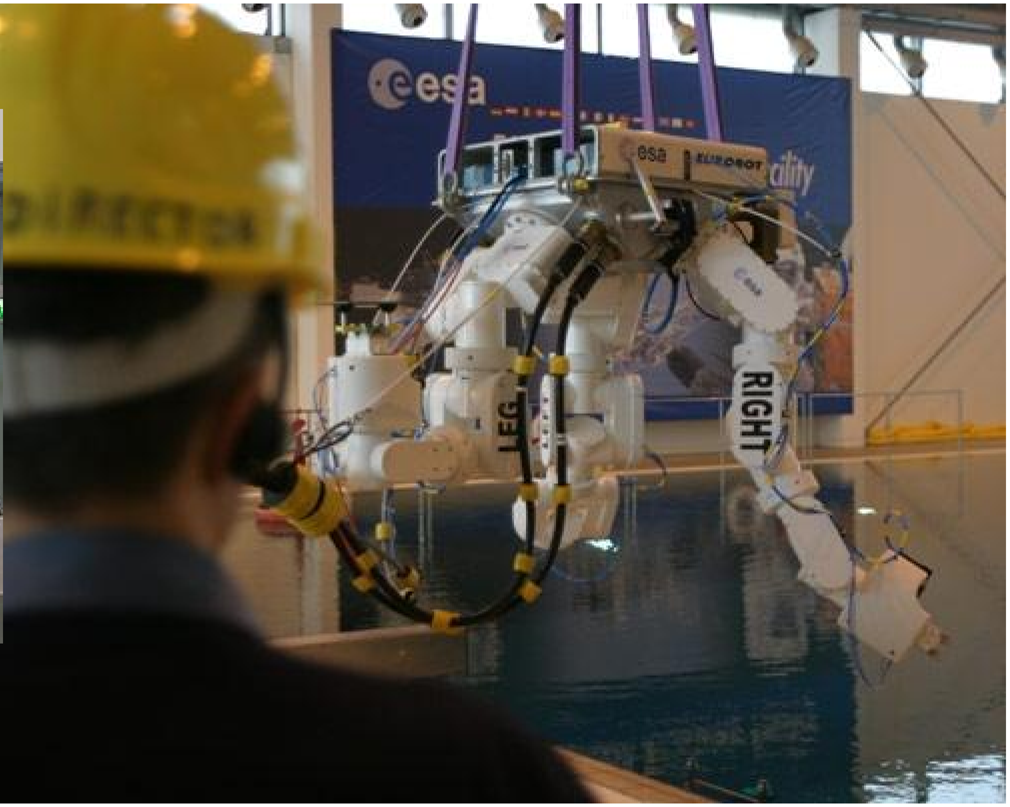
Northrop Grumman/JPL AWIMR

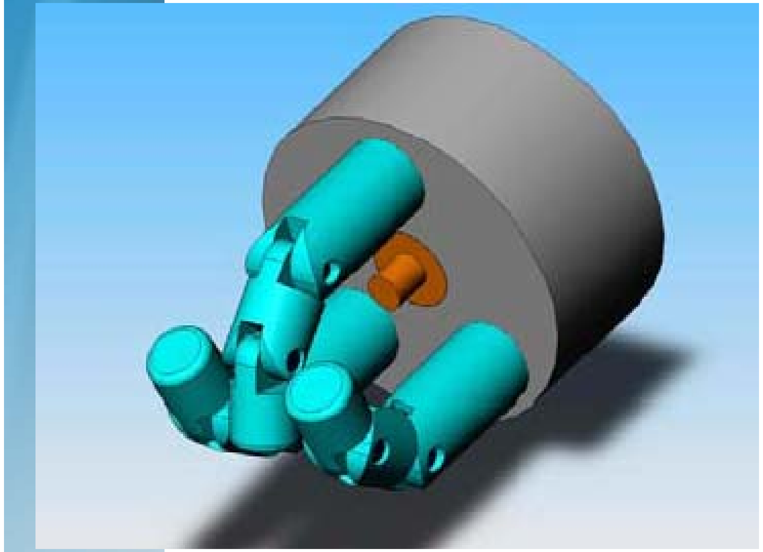
CMU Skyworker



Related Work (cont.)

Eurobot (ESA)





"Autonomous locomotion on ISS modules: the robot system is capable to walk on sections of real-scale modules of the ISS using handrails

Dexterous manipulation of ISS hardware: an operator, equipped with some human-machine interface, can command the robot to perform highly dexterous handling of objects."

From http://www.esa.int/TEC/Robotics/SEMUC68LURE_0.html and http://www.esa.int/esaHS/SEMI9TNSP3F_iss_0.html

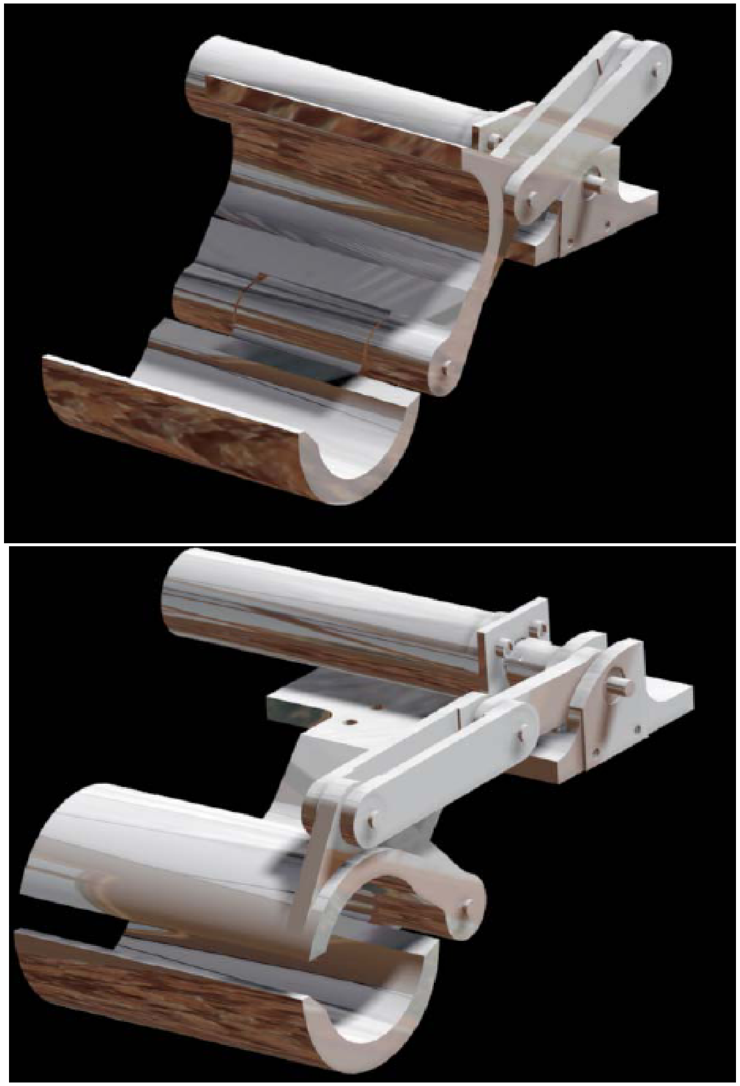
General Locomotion Requirements

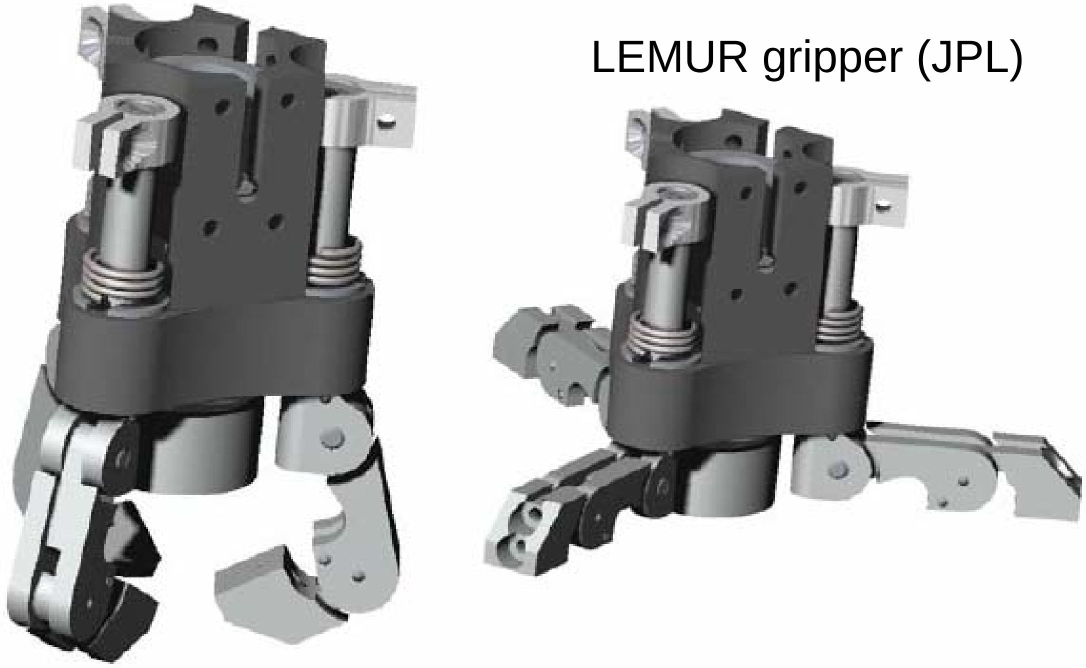
- Space microgravity "Prime Directive"
  - Maintain a positive grip on the space vehicle at all times!
    - Even on a tether, a drifting robot is not a good thing to have near a space vehicle
    - A free flyer walking robot hybrid is a possibility
      - Even better might be free flyer and walker docking collaboration
- Do not damage the host vehicle
- Speed of locomotion is usually important
- Sticky wheels or tracks are possible, but are not in the scope of this workshop presentation
  - Rails and wheels are also out of scope
  - We assume limbed (walking) locomotion
- A general microgravity walking algorithm is
  - Start with all feet gripping the structure
  - Ungrip one of more feet and relocate and regrip on the structure
  - Change the pose of the robot body in the direction of locomotion
  - Repeat

Mechanical Gripper

- Extensive literature exists on mechanical grippers for terrestrial use
- Space applications issues include thermal extremes, mechanism lubrication, and contact friction materials

Skyworker gripper (CMU)

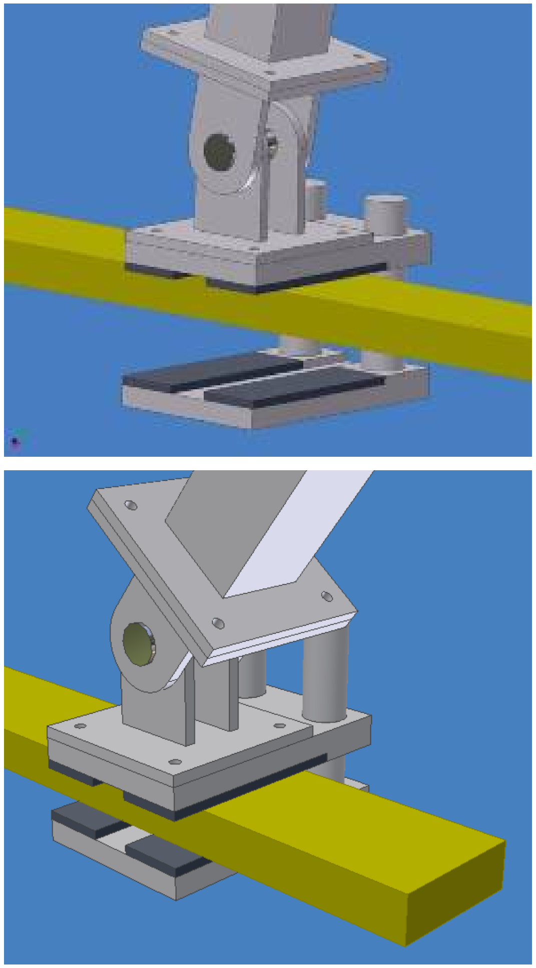




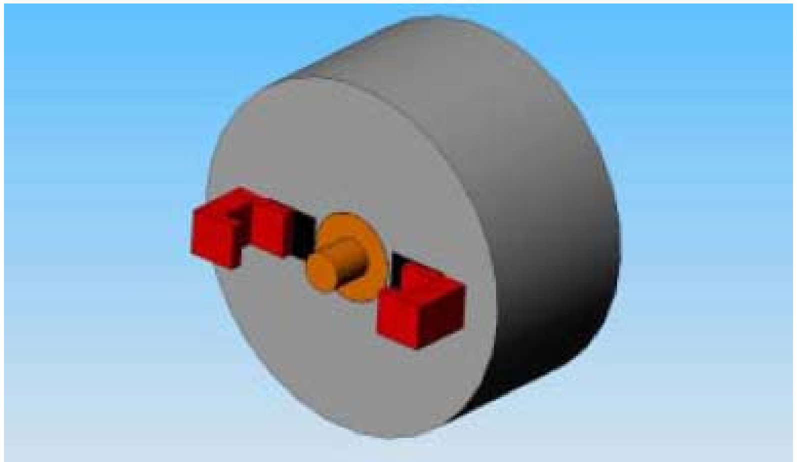
LEMUR gripper (JPL)

Gripping Astronaut Handrails

- Standard astronaut handrails are specified in a JSC document
  - Width, thickness, height above vehicle surface, and distance between standoffs (see references)
- Handrails are installed on the exterior of space vehicles wherever astronaut extra-vehicular activity (EVA) is planned
- Astronaut Story Musgrave told me that even though they were designed for a "power grip," astronauts actually use just their fingertips in traversing the handrails



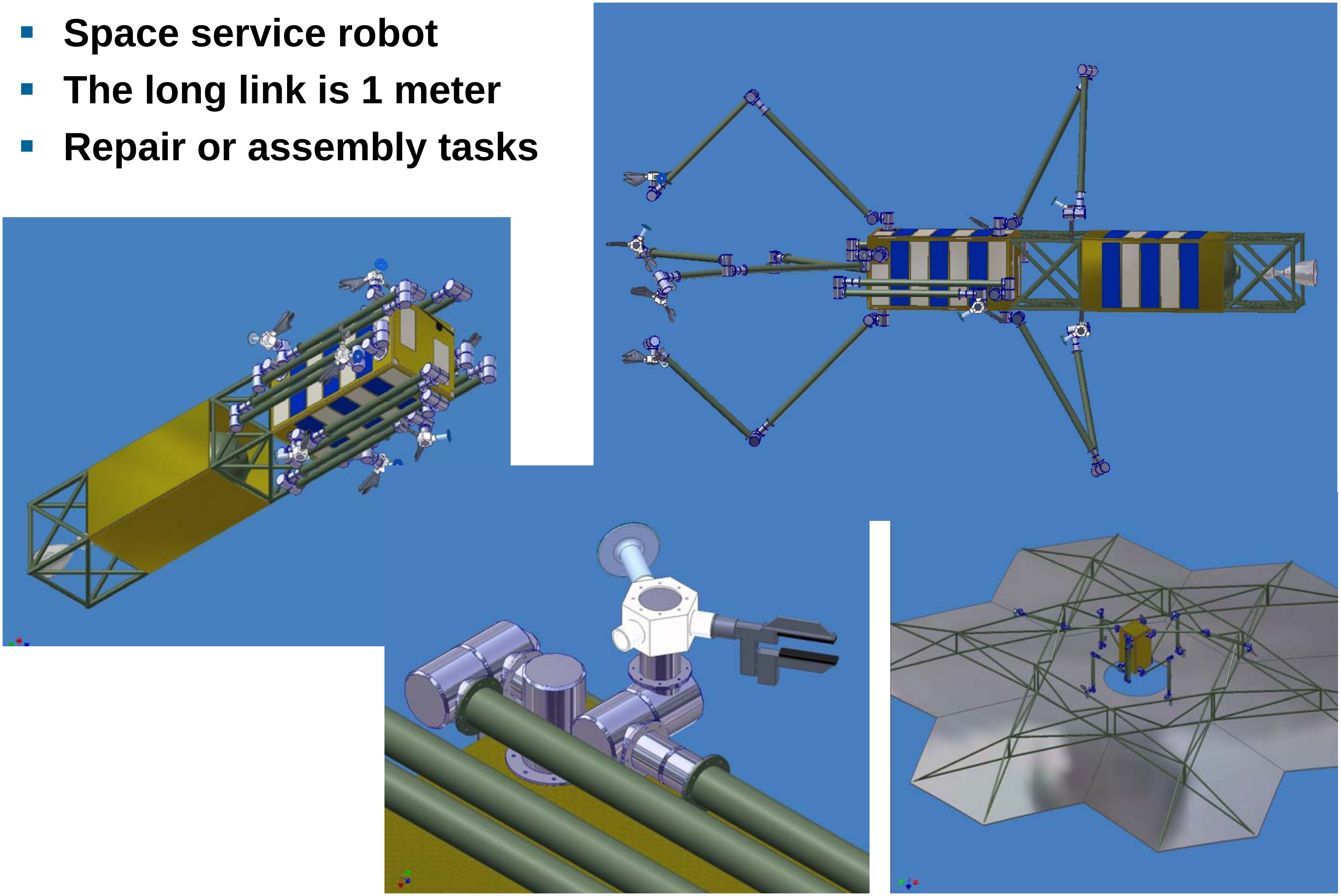
Friction clamp concept



Eurobot handrail gripper (ESA)

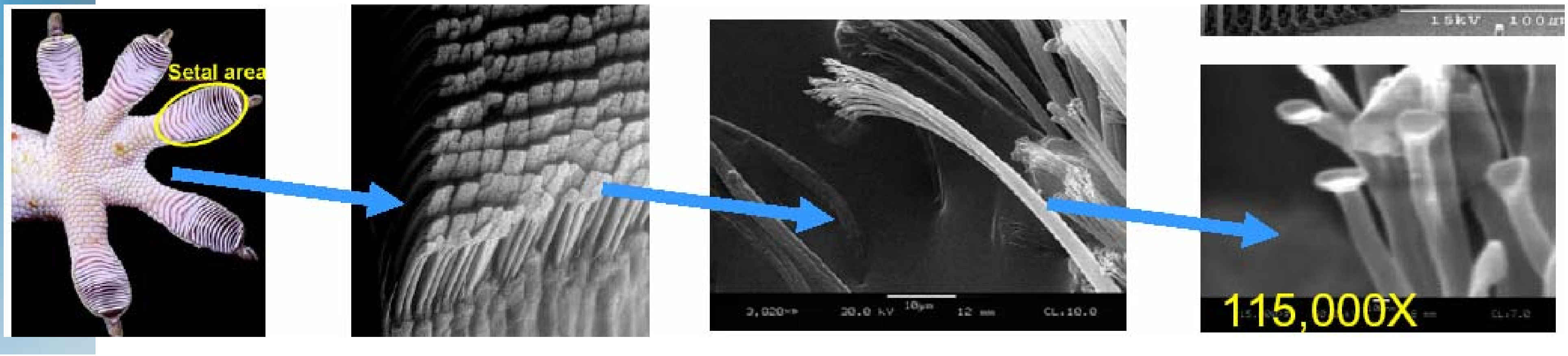
Hybrid Mechanical and Sticky Gripper Robot Concept

- Space service robot
- The long link is 1 meter
- Repair or assembly tasks



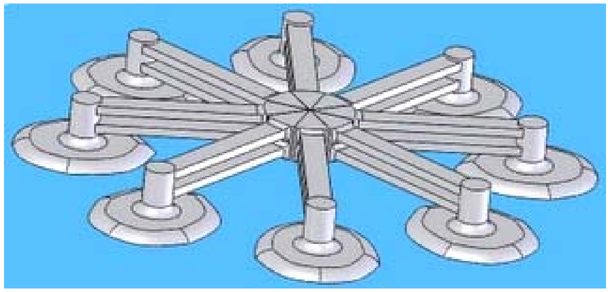
Dry adhesion (gecko feet)

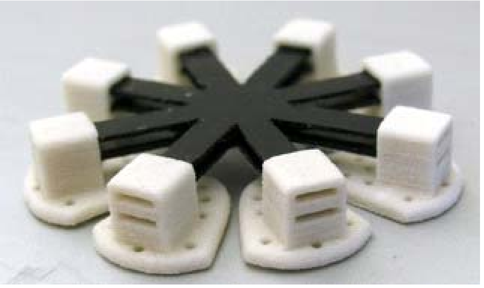
- Van der Waals forces of intermolecular attraction
- Good attachment strength, about 10 N/cm^2 for geckos
- Works in atmosphere and vacuum, low temperature and low humidity
- Compliant micro/nano-hairs adaptable to a multitude of smooth and rough surfaces
- Currently at NASA technology readiness level (TRL) 3
- Text and pictures adapted from a CMU document
    - CMU sticky foot work by Dimi Apostolopoulos and Metin Sitti
- Sticky feet are also under development at UC Berkeley

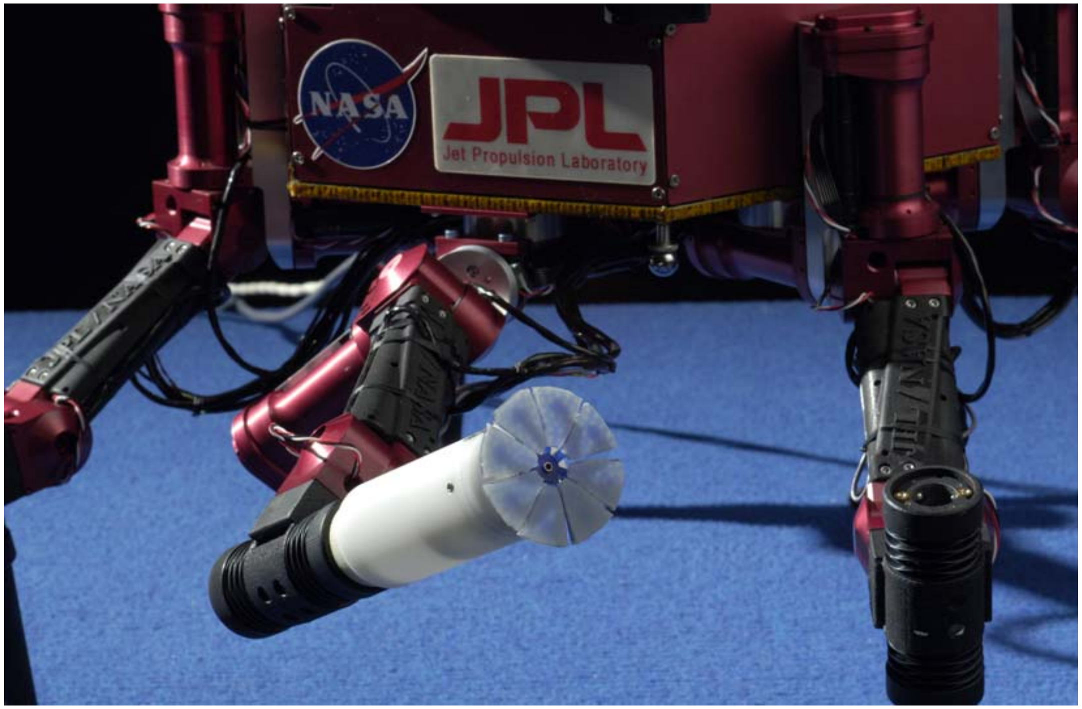


Sticky Foot for AWIMR

- CMU (Dimi Apostolopoulos and Metin Sitti) provided material samples and various prototypes of sticky feet for the AWIMR (Automated Walking Inspection and Maintenance Robot) project in 2005
- JPL (Brett Kennedy) installed a prototype sticky foot on LEMUR II (at right)

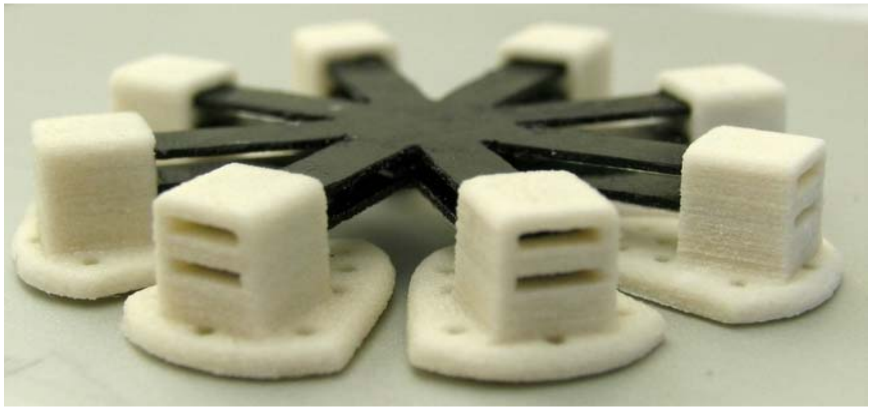






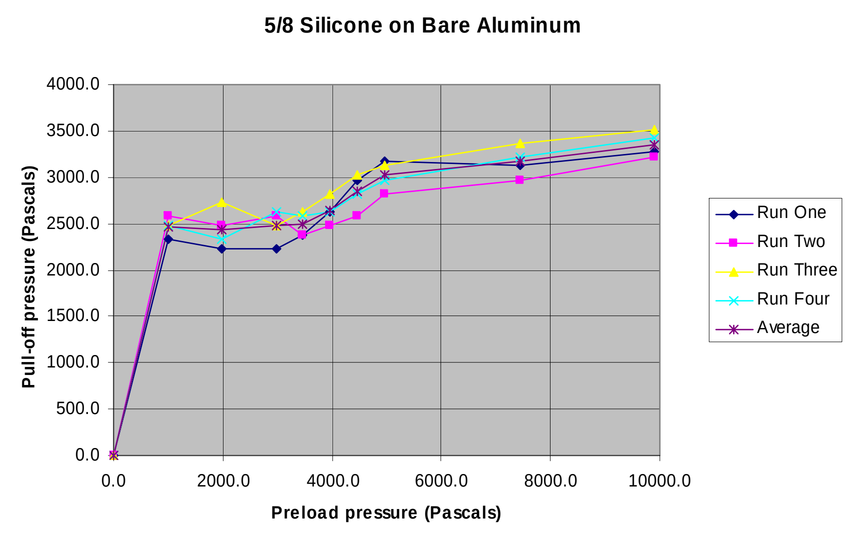
Stick Foot Material Tests

- In the summer of 2005 we received samples of sticky material for test from CMU
    - White silicone
    - Clear polydimethylsiloxane (PDMS)
    - PDMS with circular grooves
- We used various sizes of circular punches to create test specimens
- We used a weight and pulley apparatus to apply preload and pulloff forces

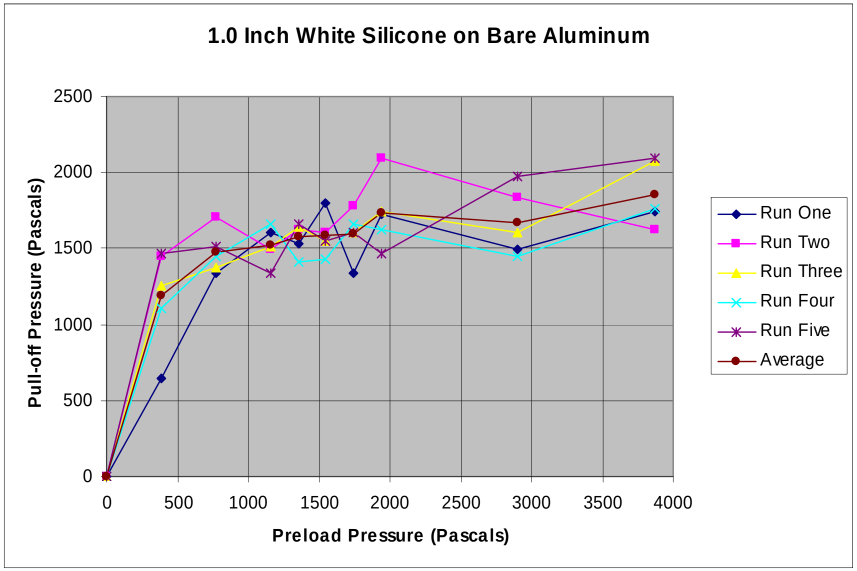


Sticky Silicone on Aluminum Tests

- Silicone on bare aluminum results
    - Better than 2:1 pull-off to preload force
- Aluminum Creep Test Results
    - We performed two trials with 2 kiloPascal preload and 0.5 kiloPascal pull load and measured the time for the aluminum plate to pull off:
        - 75 seconds
        - 50 seconds
- Storage test showed no degradation after two weeks

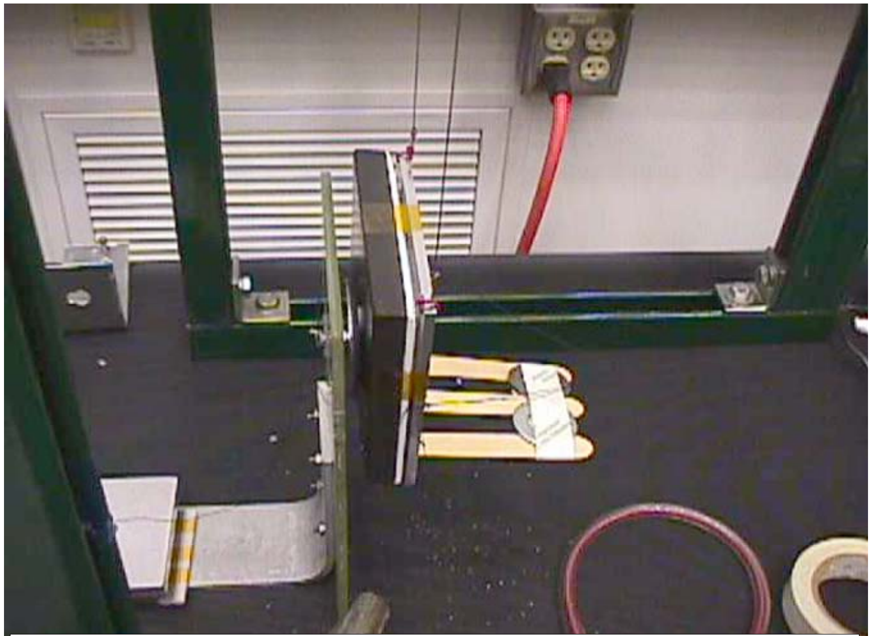


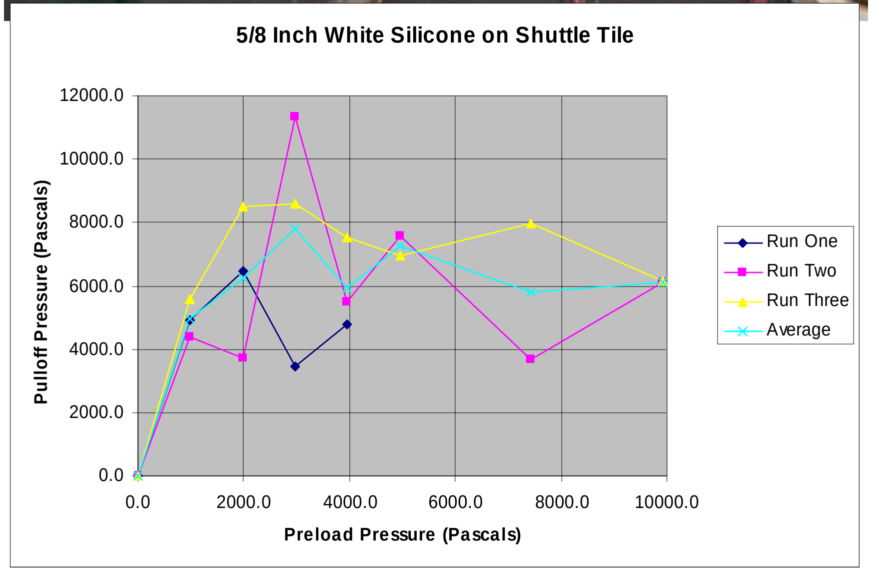
5/8 inch white silicone on bare aluminum. September 29, 2005



JSC-Supplied Space Shuttle Tile

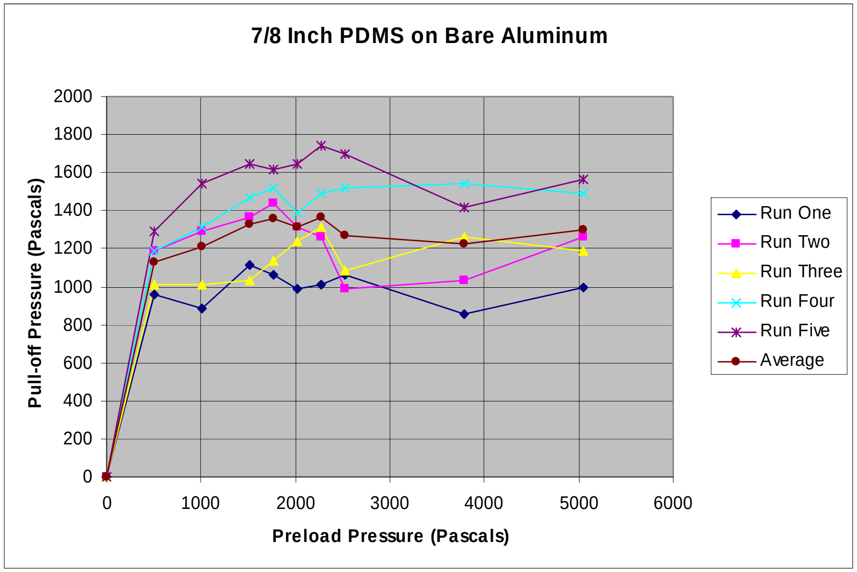
- Much higher pull-off forces were measured for the shuttle tile than for bare aluminum
- In general, smoother surfaces stick better than rough surfaces
  - The shuttle tile had a shiny surface finish
- No visible residue was evident with any of the CMU-supplied sticky materials we tested

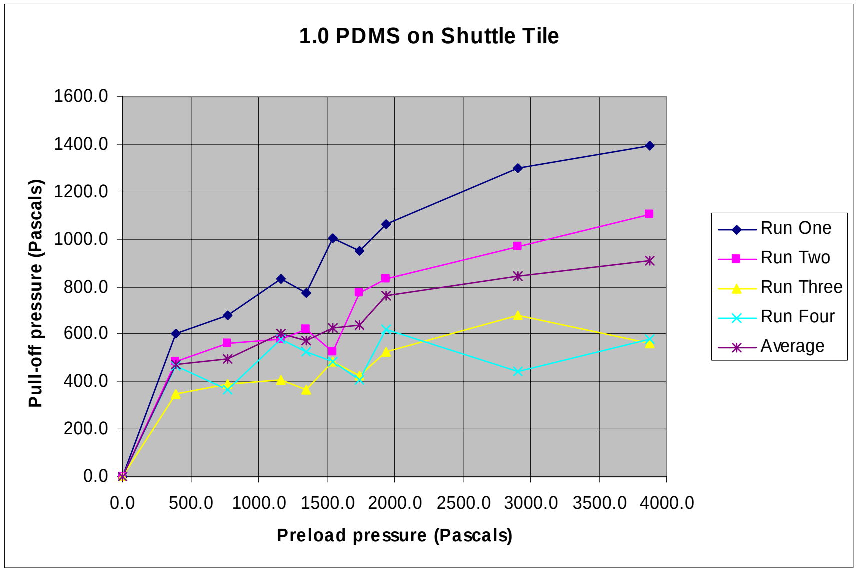


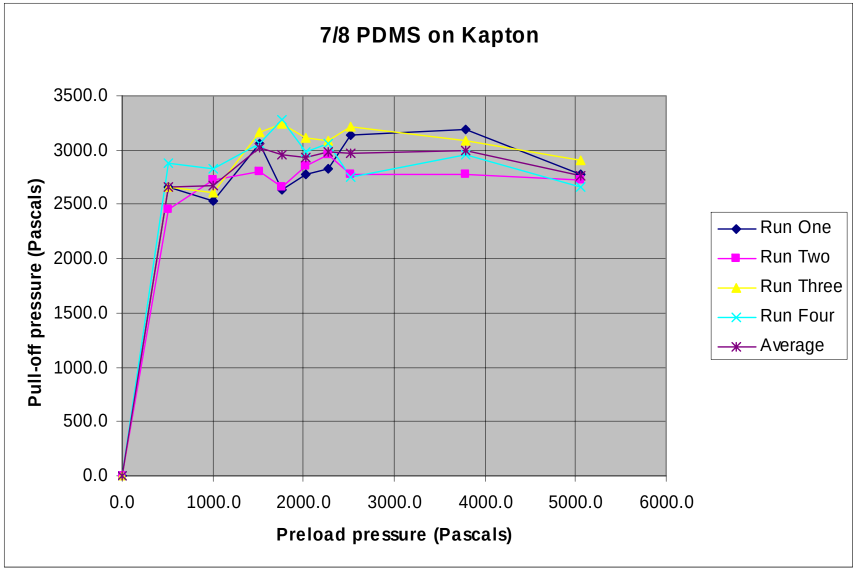


Polydimethylsiloxane (PDMS)

- The PDMS does not seem to have as much absolute adhesion pressure as the white silicone, but the preload sensitivity is high
- Pull-off pressure on Kapton for the PDMS sample was much higher than for bare aluminum

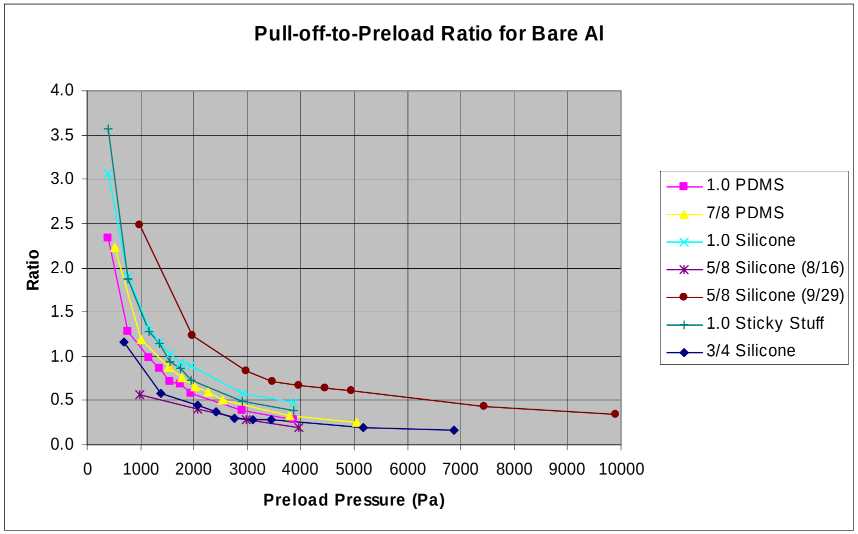

7/8 Inch PDMS on Bare Aluminum

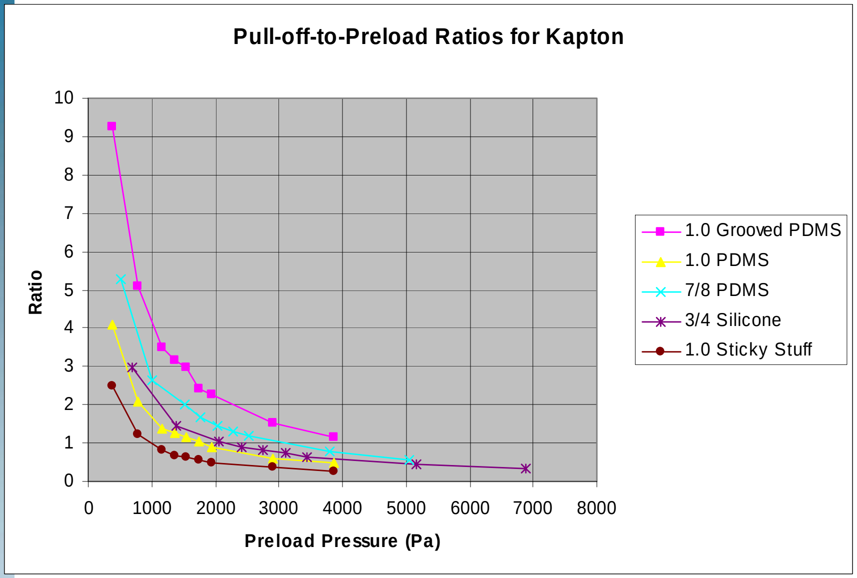

1.0 PDMS on Shuttle Tile

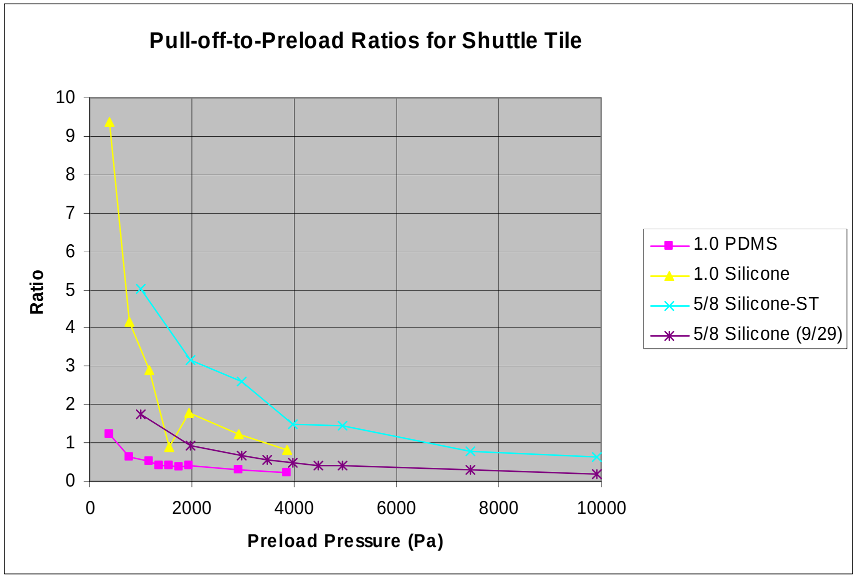

7/8 PDMS on Kapton

Sticky Foot Material Test Conclusion

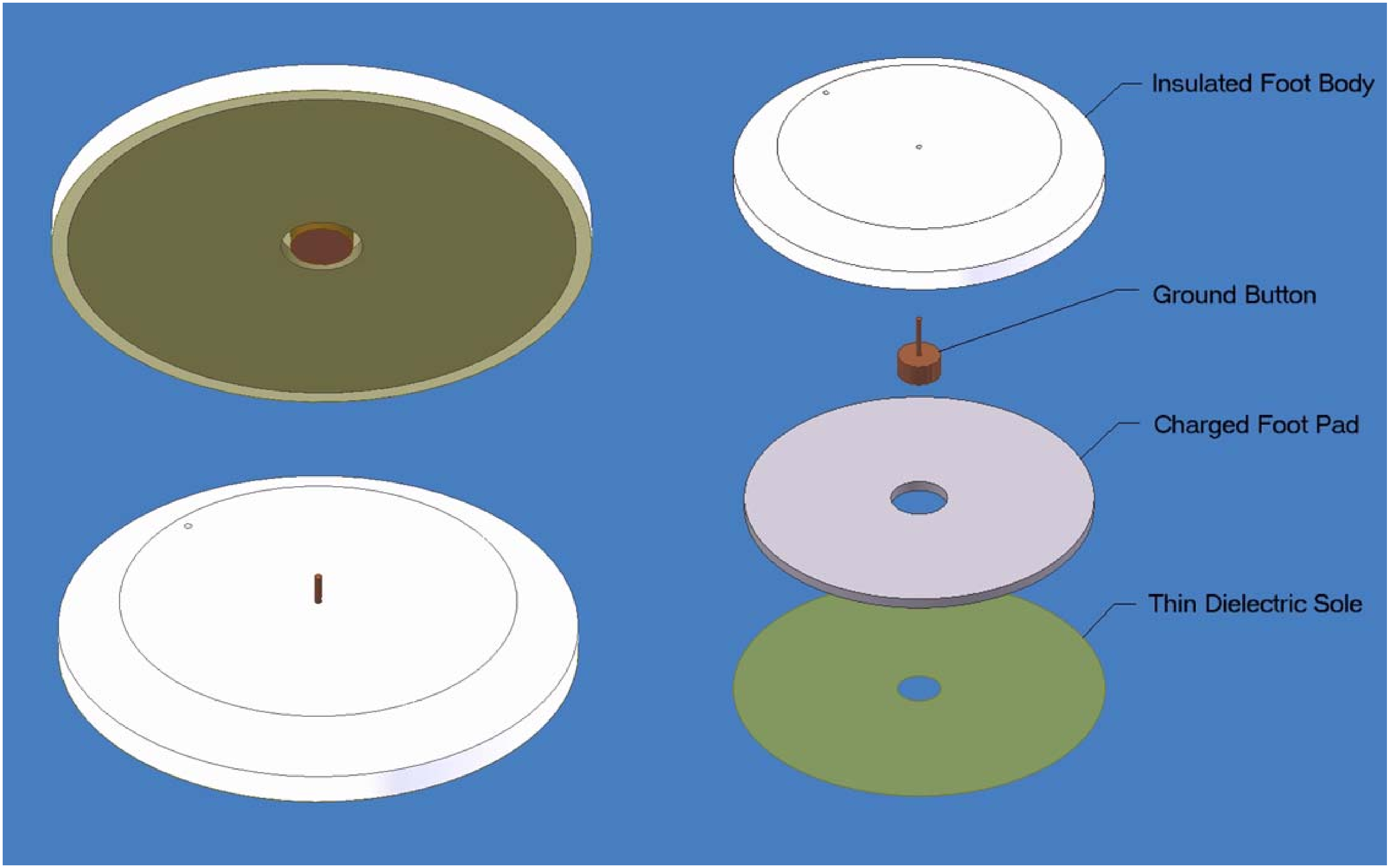
- General microgravity locomotion is feasible with sticky foot grippers
- May need to avoid areas of thermal insulation to avoid damaging







Electrostatic gripper for space use



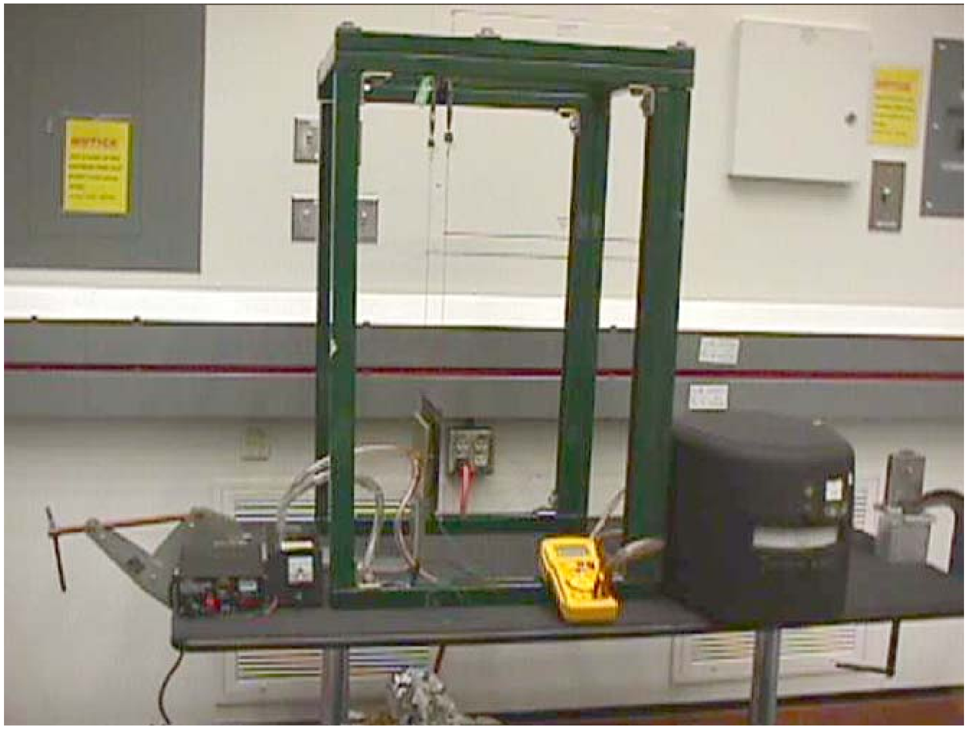
Conceptual model of an electrostatic attachment device. Left: lower and upper views of an assembled foot. Right: Exploded view.

Electrostatic Foot

- Capacitor plate force equation
    - We measured somewhat lower forces than the equation suggests
- Surface charge buildup effects were significant
- Humidity level was controlled at 50% RH
- Kapton punch-through voltage is about 3,000 volts per milli-inch
- Testing in vacuum is indicated for future work

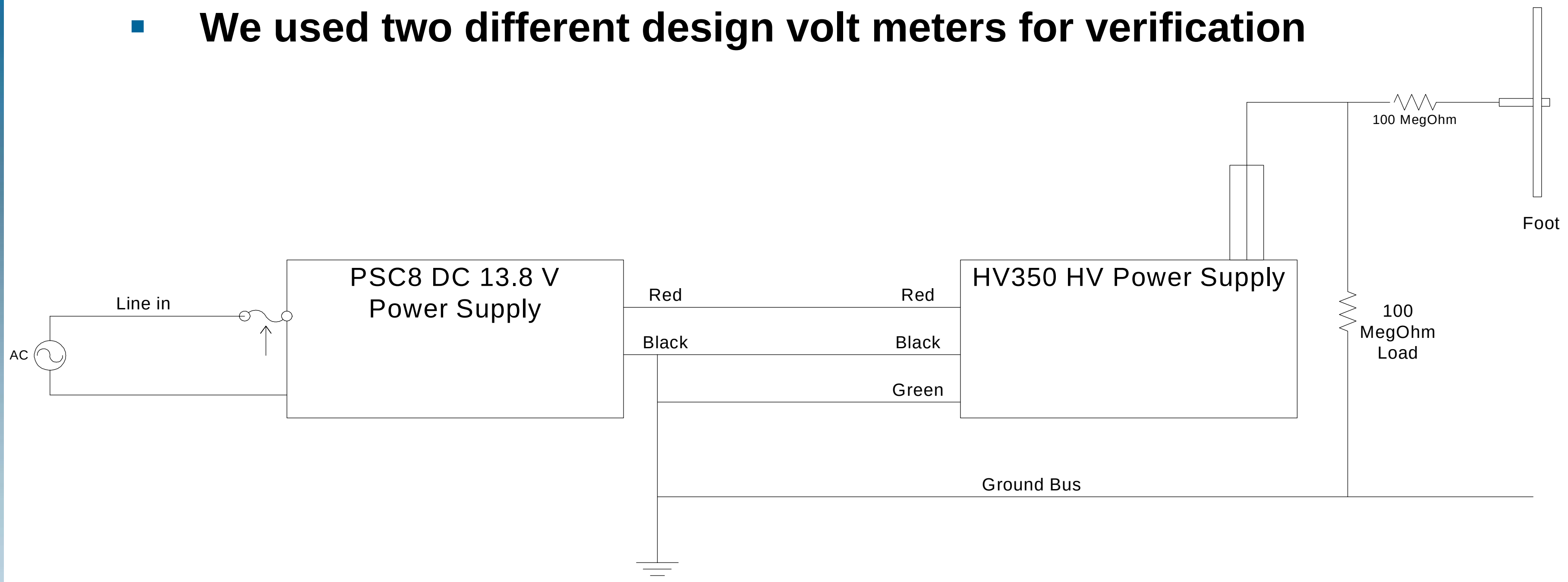
$$F = A\varepsilon_0 V^2/d^2$$

F is force of attraction in Newtons
A is area of the plates in square meters
V is voltage
d is the distance between the plates in meters
ε_0 is free-space permittivity (8.55×10^{-12})

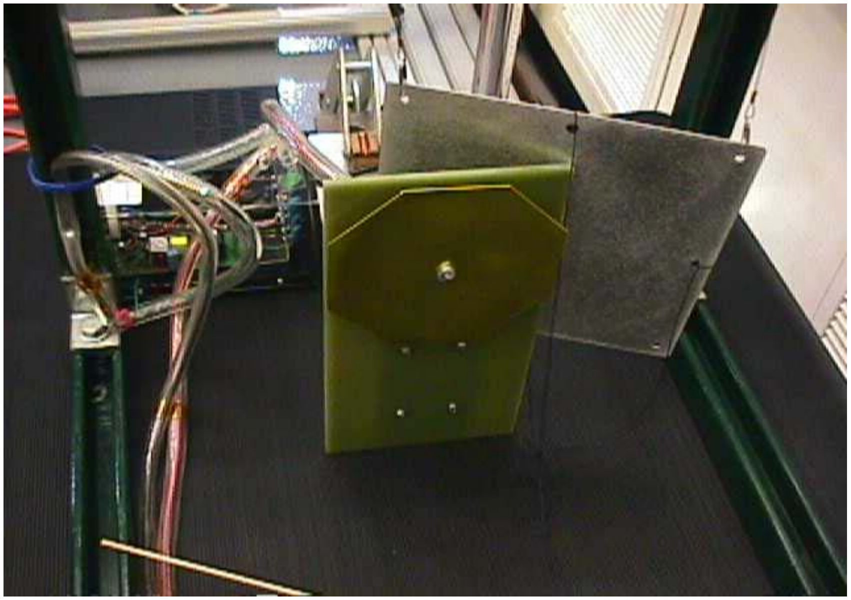


Electrostatic Foot Testing

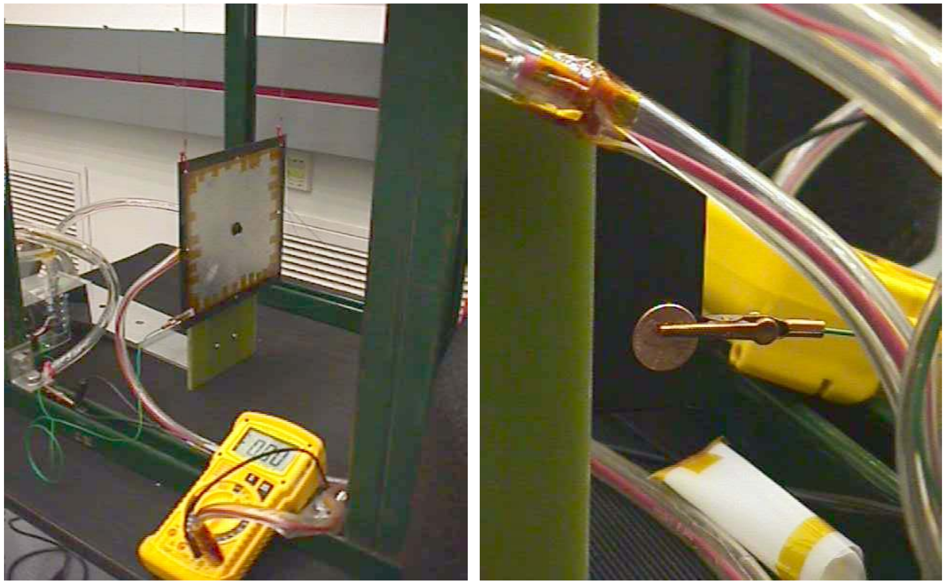
- Test Objectives
  - Evaluate the electrostatic model (area, voltage, force, and dielectric thickness relationship) for real materials
  - Establish the foot's sensitivity to surface irregularities
  - Evaluate the suitability of the foot to microgravity locomotion in a space environment
- Test Setup
  - Fixed electrostatic foot with suspended test surface at ground potential
  - We used two different design volt meters for verification



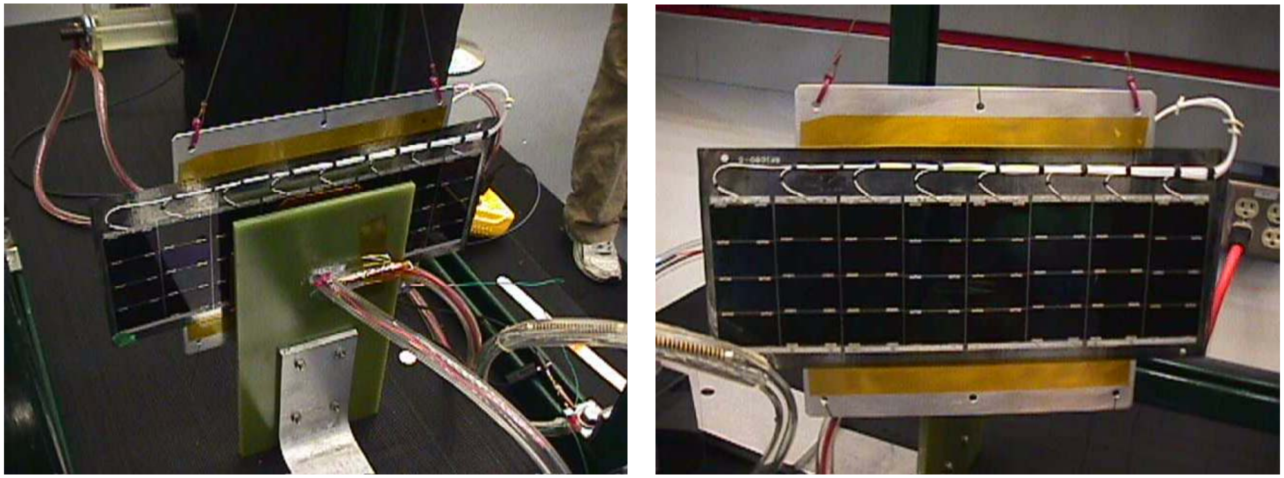
Electrostatic Foot Test (four inch foot)



Four inch diameter octagonal foot wrapped with half mil Kapton

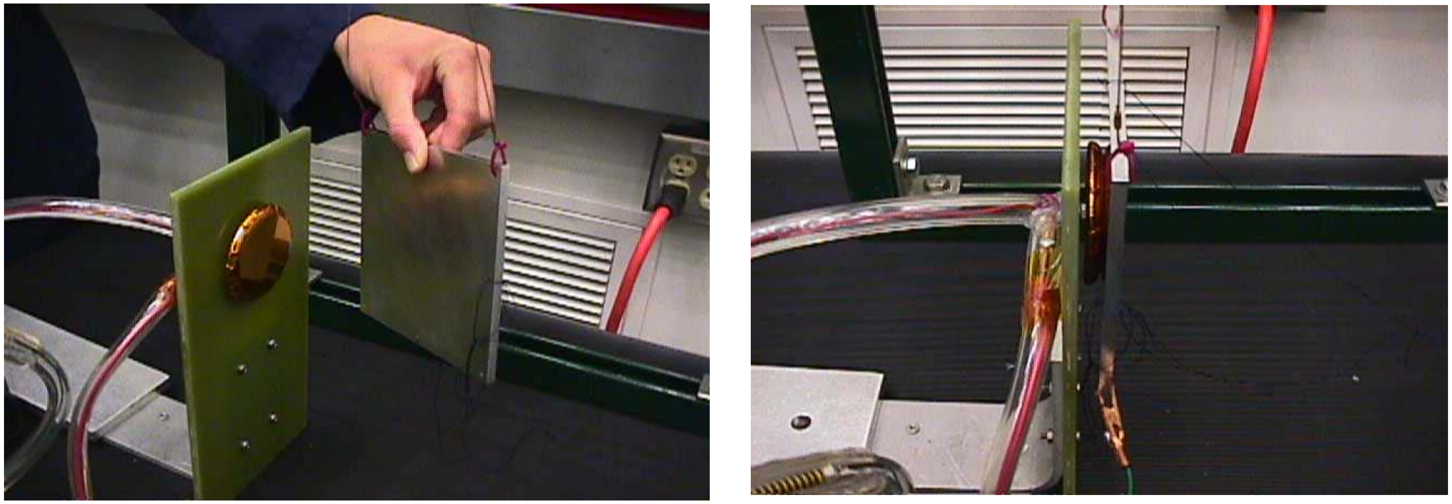


Black kapton ground plane

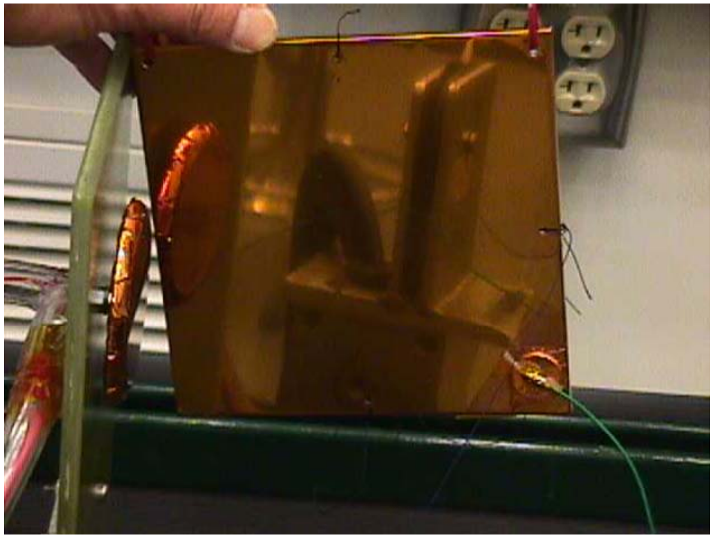


Solar cells on ground plane

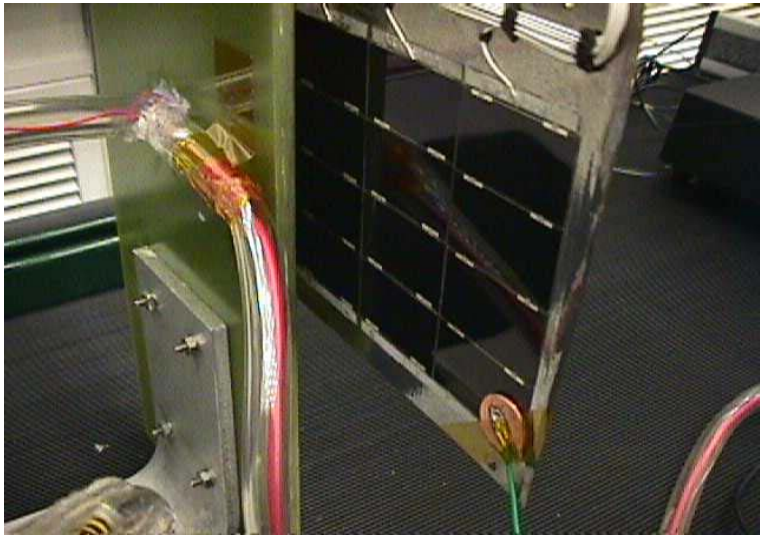
Electrostatic Foot Tests (2.5 inch foot)



2.5 inch diameter circular foot wrapped with 2 mil Kapton



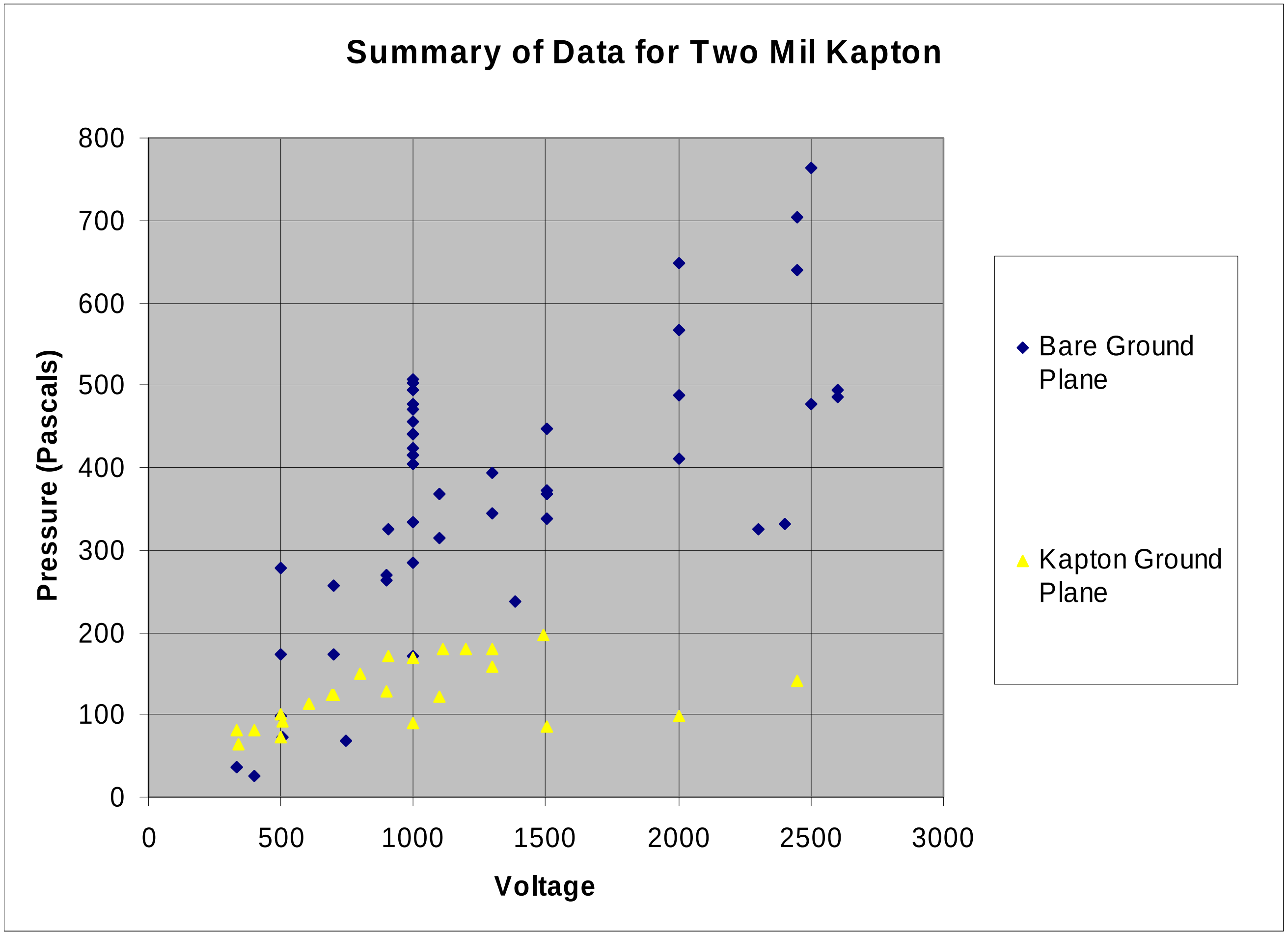
Aluminized Kapton ground plane



2.5 inch diameter circular foot test with solar cells

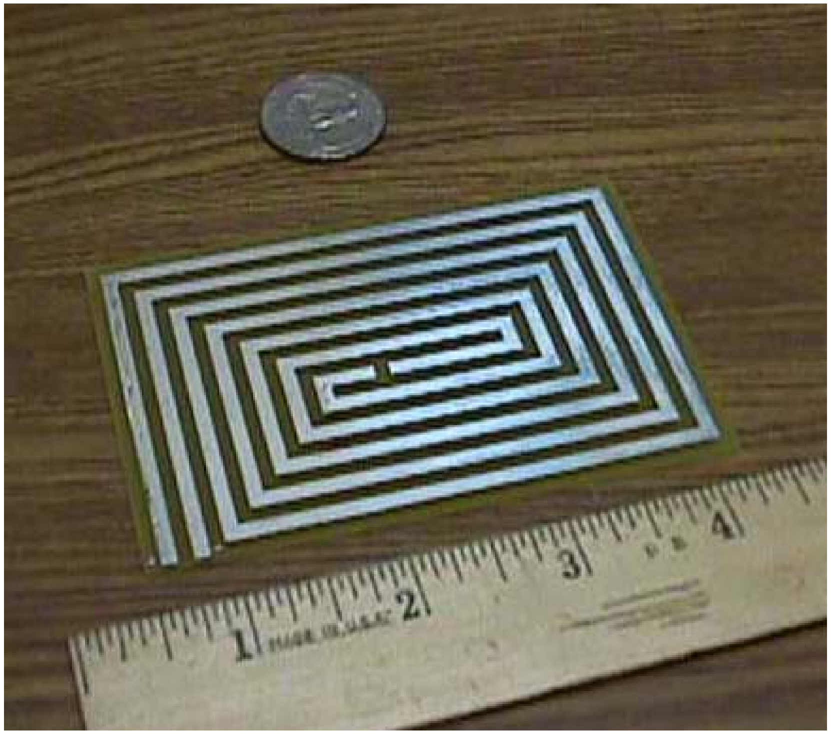
Electrostatic Foot Results

- Summary of Test Data
  - Foot with two mil Kapton
  - Includes both 4-inch and 2.5 inch foot data



Electrostatic Foot Conclusion

- Shear capability was found to be an order of magnitude greater than normal pull force
    - This is a known effect as a result of polarization of surface molecules
- We tested the analytical electrostatic model with real materials and found that an empirical model is more suitable for use as a guide to design
- We established the foot's sensitivity to surface irregularities and evaluated the suitability of the foot to microgravity locomotion and other uses in a space environment
- Future work
    - Vacuum Testing
    - Polarity Reversal Testing
    - Bi-Polar Device Testing (at right, by Hobson Lane, Northrop Grumman)



Algorithmic Considerations

- Sticky feet require some preload which is reacted in tension by the other feet
    - With the tripod gait in a hexapod robot, preload reactions are roughly equal to the preload: pull-off to preload ratio must be greater than 1.0
    - Pairwise opposed gait gives twice the pull-off margin during foot preloading (but with 2/3 the walking speed)
- Sticky foot preload can be refreshed by a force pumping action of the legs in a hexapod robot
    - Push down triples alternately to overcome relaxation creep
- Force sensing at the feet is probably necessary to detect marginal adhesion during locomotion
    - Applies to both sticky and electrostatic feet

Space Locomotion Gripper Conclusion

- For reacting high tool forces, mechanical grippers are indicated
    - Requires astronaut handrails or other vehicle design features for gripping
- For minimal complexity for locomotion, sticky foot grippers are indicated
    - May need to avoid thermal insulation and solar cells to avoid damage
- For locomotion on thermal insulation and solar cells, electrostatic grippers are a possibility
    - Much work remains to be done, e.g., time dependent surface charge phenomena need investigating (especially in vacuum)
    - Robustness of dielectric materials needs to be demonstrated
    - Vacuum may improve performance (but may lead to unanticipated problems, e.g. corona)
    - Bipolar and/or polarity reversing devices are interesting

References

- **JSC 26626A, Extravehicular Activity (EVA) Hardware Generic Design Requirements Document, EVA and Crew Equipment Projects Office, May 1995**
- **The Challenges of Extra-Vehicular Robotic Locomotion Aboard Orbiting Spacecraft, Fredrik Rehnmark, Robert O. Ambrose, and Michael Goza, proceedings of the 2004 IEEE International Conference on Robotics and Automation (ICRA), New Orleans, LA, April 2004, http://ieeexplore.ieee.org/iel5/9126/29025/01308135.pdf**
- **Eurobot End-Effectors, S. Michaud *et al.*, Proceedings of the 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation, November 2004, http://robotics.estec.esa.int/ASTRA/Astra2004/Papers/astra2004_C-03.pdf**
- **Brett Kennedy, *et al.*, "Limbed Excursion Mechanical Utility Rover (LEMUR)," JPL Technical Report, Jet Propulsion Laboratory, California Institute of Technology, 2003**
- **Mark Showalter, *et al.*, "Development and Comparison of Gait Generation Algorithms for Hexapedal Robots Based on Kinematics with Considerations for Workspace," ASME IDET/CIE, August 2008 (to appear)**