SRI International

Microrobot Inspectors

Electroadhesive wall Climbing Robots and more

Ron Pelrine
Chief Scientist, Robotics Program

SRI robotics : well-positioned for developing innovative and effective structural inspection tools

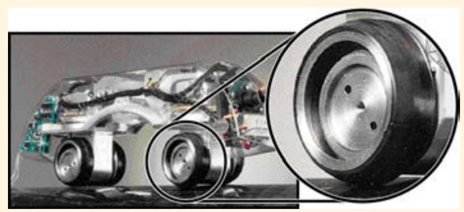
SRI breakthrough robotic components

Electroadhesive wall climbing robots

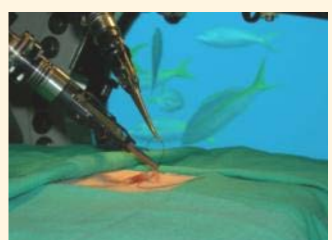
Innovative mobile robot actuation and sensing

SRI Robotics and Automation

M7 Remote Open Surgery System

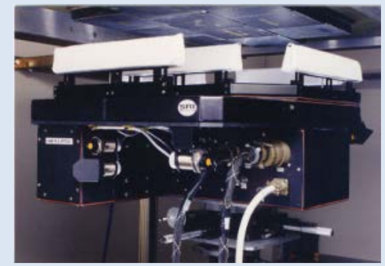


Magpipe gas pipeline inspection system

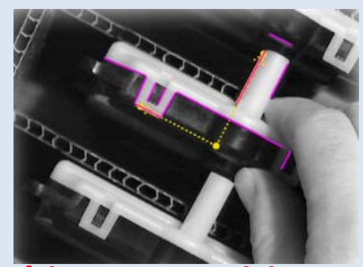


Extreme-Environment Telerobotics

SRI Machine vision



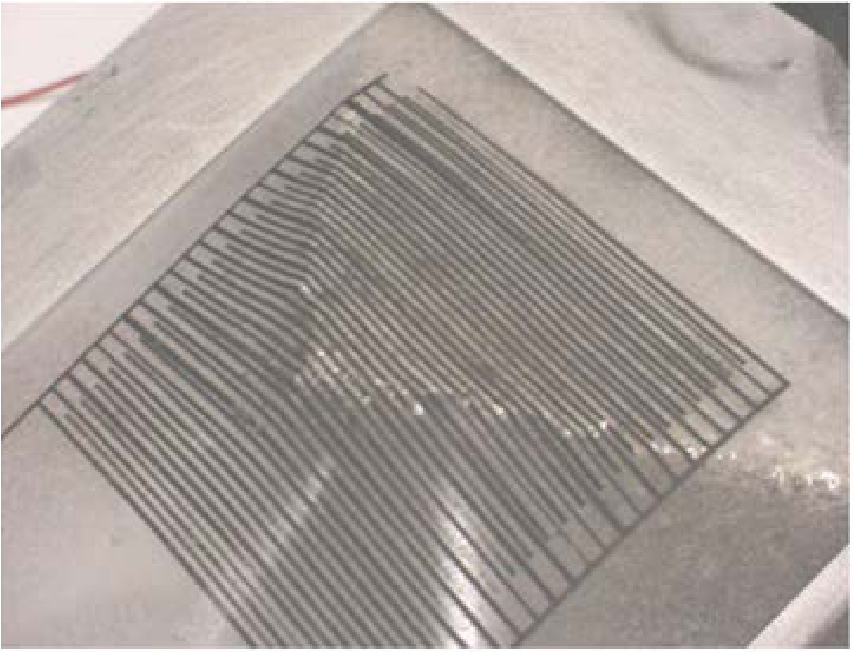
Space shuttle tile inspection experience

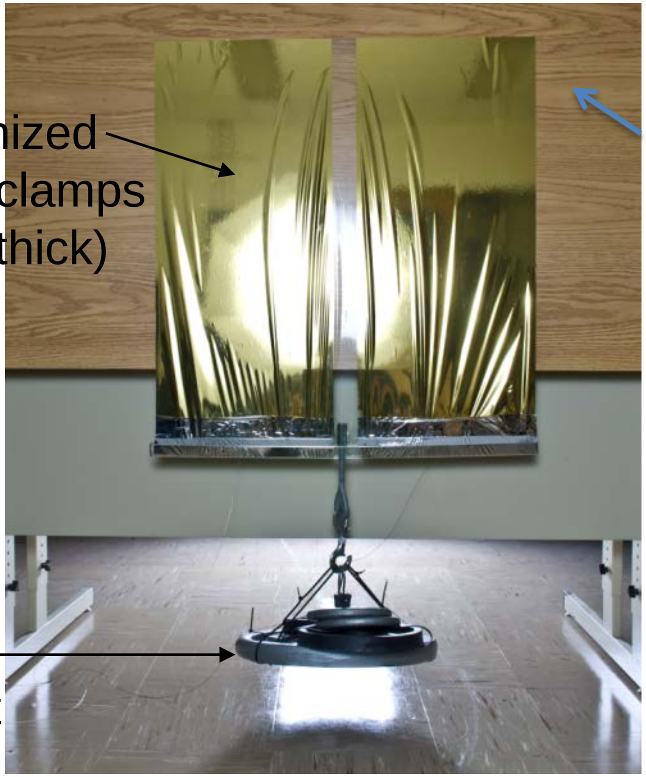


Object recognition

Video OCR

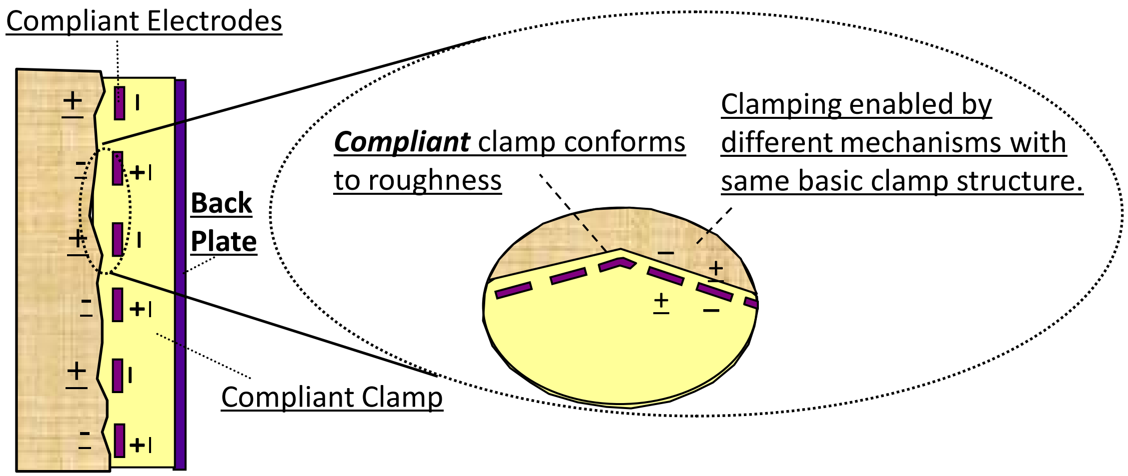
Electroadhesion : Electrically Controllable Adhesion





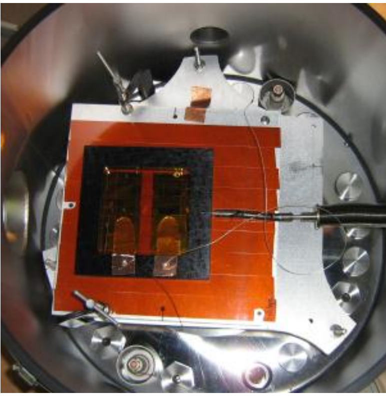
- Electrically controllable, reusable adhesion - Works by inducing electrostatic forces
- High clamping forces on glass, wood, metal, concrete, drywall, brick, granite etc.
- Compliance helps conform to irregular, curved or rough surfaces
- Robust clamping through dust and moisture
- Ultra-low power consumption (~0.02 mW/N of weight supported).

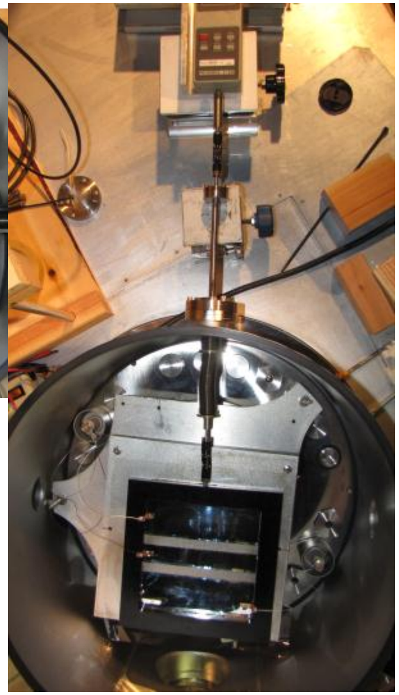
Electroadhesion

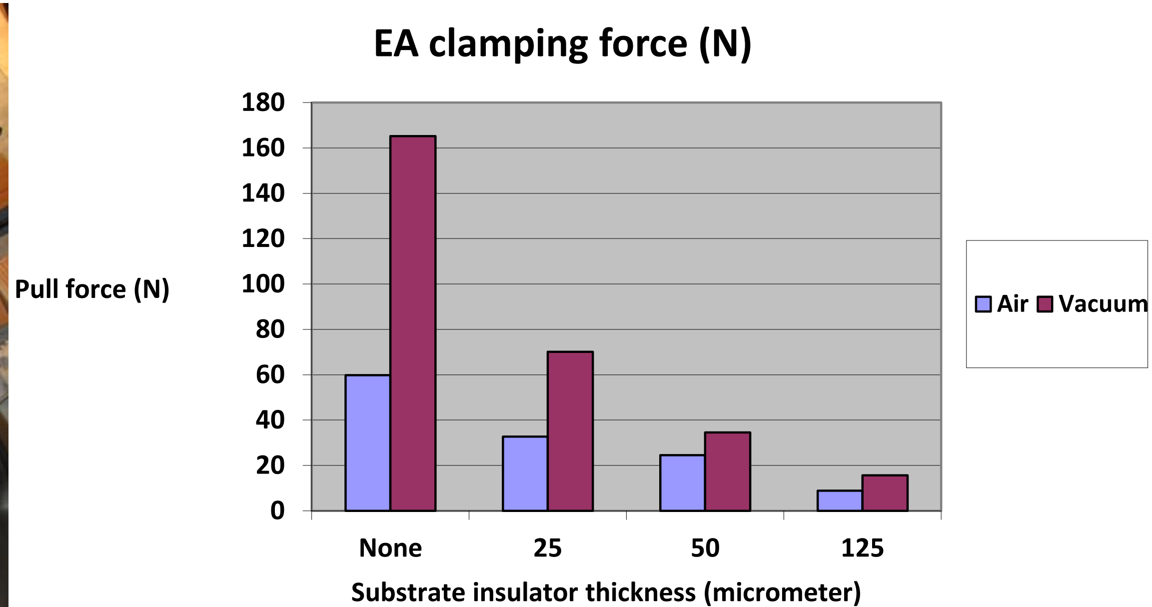


- Compliant films induce electrostatic charges on a wall using a low-power supply connected to the film electrode
- Space rated materials (e.g. gold coated kapton, aluminzed mylar etc.) can be used, further material optimization with funded efforts can dramatically improve performance
- Can be switched on or off quickly (<50 ms)
- Basic mechanism is electrostatic attraction, but it is *powered*
- Clamps onto both conductive and non-conductive substrates with same clamp geometry but with different mechanisms
  - With conductive substrates → clamping through Lorentz forces
  - With non-conductive substrates → clamping through polarization forces

Space Readiness Testing







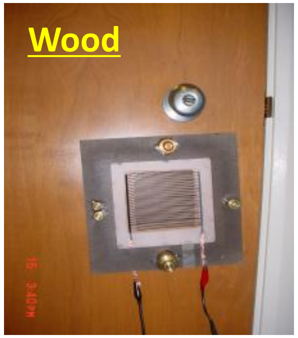
• So far, EA clamps have been successfully demonstrated in thermal vacuum (-40 to 150C, 10^{-6} torr), with UV exposure (1-5 suns) and with electron source

• Testing with substrate materials commonly found on spacecraft (Anodized or bare aluminum, Kapton, Polyimide, Mylar etc.)

•Results are showing consistently better clamping forces under vacuum conditions than in air ~5×10^{-5} Torr

• Demonstration in LEO plasma is pending, modeling suggests that clamping forces will be similar but may may need special electrodes or electronics

Versatile Clamping



Material	Measured Lateral Force per Unit Area P_L (N/cm^2)	Measured Frictional Coefficient	Estimated Normal Pressure P_N (N/cm^2)
Finished wood	0.55	0.40	1.38
Drywall	0.21	0.4*	0.52
Paper	0.24	0.46	0.52
Glass	0.41	0.45	0.84
Concrete (dry)	0.17	0.57	0.30
Concrete (damp)	0.08	0.4*	0.20
Steel	.40	0.33	4.24

* estimated

Wall Climbing Technologies - Comparison

Technology	High forces ?	Repeated use on dusty surfaces ?	Works on rough AND smooth surfaces ?	Energy cost to peel / move	Energy cost for perching	Non-damaging / no residue ?	Space Rated Materials ?	Current Space TRL (Current terrestrial TRL)
Chemical adhesion (sticky feet)	Excellent	Poor	Excellent	Poor	Excellent	Moderate / Good	Poor	2/3 (4/5)
Suction cups	Excellent	Poor	Poor	Moderate / Good	Excellent	Excellent	Poor	0 (8/9)
Synthetic Gecko feet	Moderate / Good	Poor	Moderate / Good	Moderate / Good	Excellent	Excellent	Moderate / Good	2/3 (4/5)
Claws, microspines	Excellent	Excellent	Poor	Excellent	Excellent	Poor	Excellent	2/3 (5/6)
Electroadhesion	Moderate / Good	Excellent	Excellent	Excellent	Moderate / Good	Excellent	Excellent	4/5 (7/8)

Excellent performance

Moderate / Good performance

Poor performance

Electroadhesion allows robust electrically controlled adhesion that works on a variety of materials, surface morphologies and roughness and in the presence of dust.

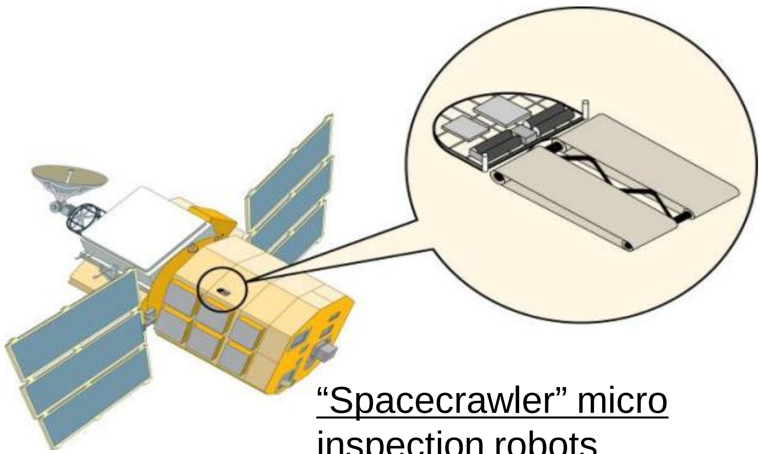
EA Terrestrial Applications : Overview

Industries				
Electroadhesion Product Categories	Industrial	Biomedical	Military	Consumer
Wall-Climbing Robots	Inspection robots		Surveillance robots	Toys
Sticky Pads	Automation	Bandages for sensitive skin, human tissue holders for surgeries, bleeding prevention bags	Temporary holding structures, surveillance patches	Hanging devices, temporary signeage and banners, skin-mounted consumer devices
Grippers	Robotic grippers, Automation	Lab automation		Consumer devices
Traction Enhancement Devices	Automation	Lab automation	Pads for wall-climbing soldiers, human restraint systems	Traction control for tires and shoes, safety devices
Other	Fittings and couplings, high-precision drives		Smart vehicle door seals, temporary truss structures	

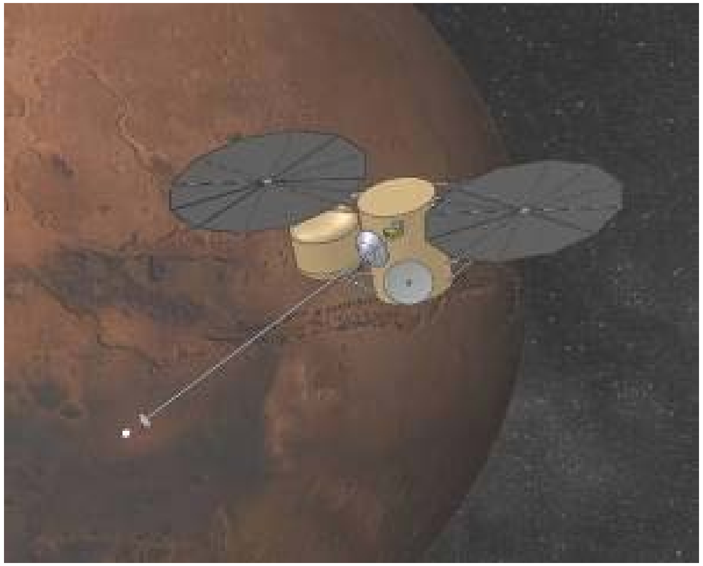
Electroadhesion markets, product categories, and applications

<u>Moderate / High Terrestrial TRL –</u>
<u>Commercialization efforts launched</u>

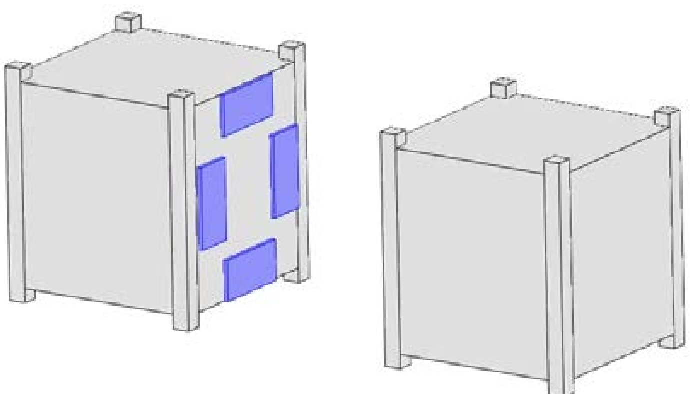
Potential Space Applications



“Spacecrawler” micro inspection robots



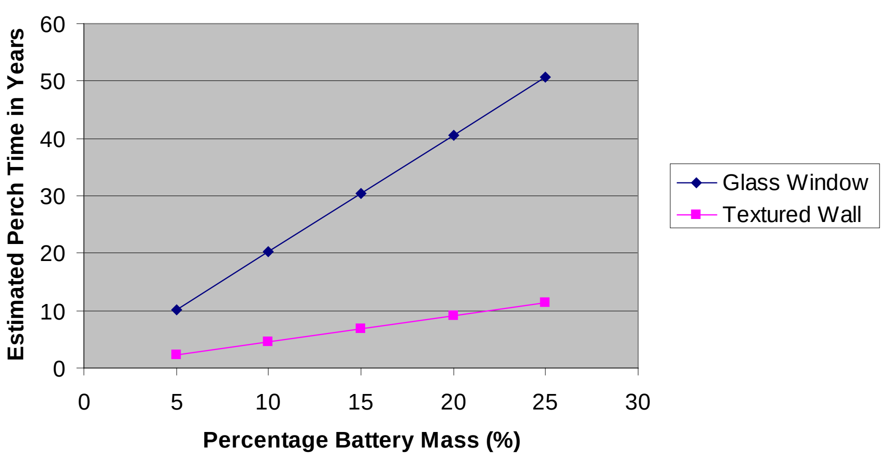
Gripper for applications such as Mars Sample Return (Courtesy: Altius Space Machines)



Docking of cubesats or to co-operative or non-coperative space objects

Anchoring tools for human EVA or internal to shuttle activities (traction enhancement in space station environments)

Wall Climbing Robot : DARPA Program



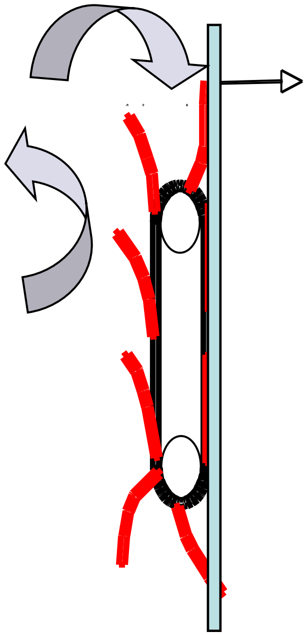
- Past DARPA program
- First generation climbing robots
- Showed basic technology, low power

Commercial Application : Structural Inspection

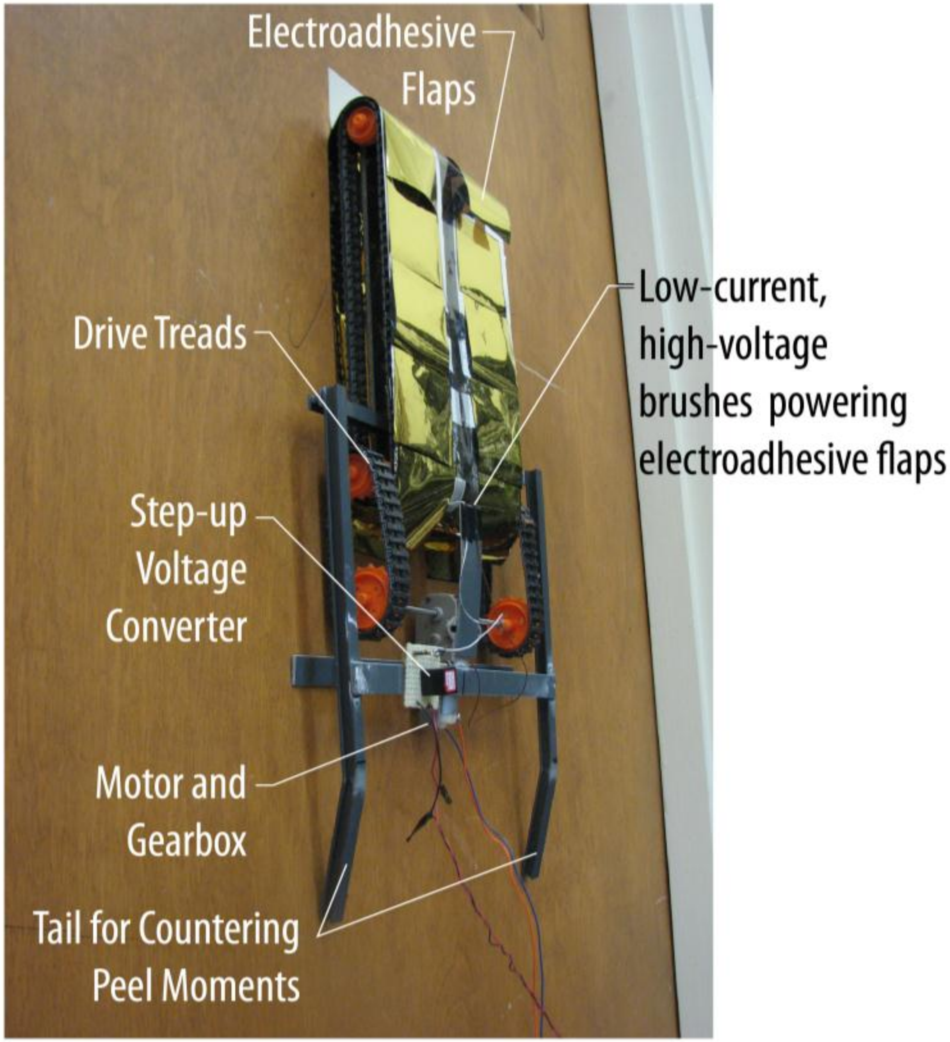
- Field application to inspection and cleaning of civil structures, especially concrete
- Current field robot weighs ~1.3kg, can carry payload of 1-1.5 Kg
- Ongoing commercial programs, primarily in Asia
- Useful Non Destructive Evaluation (NDE) payloads – Video cameras, ultrasound crack detectors, laser range finders, wireless transmitters

Treaded Flap - Robots

Peeling torque due to offset in robot Center of Gravity away from wall



Compliant flaps attached at base allow tensile loading while minimizing peel



- Most successful and robust design implemented so far
- Compliant flaps and tail help resist peel moments, can be retrofitted on conventional treaded robots
- Typical robots weighed 150-300g with full onboard power and RC control

Climbing on Variety of Surfaces

Concrete.avi

CONCRETE

Wood_Beam.avi

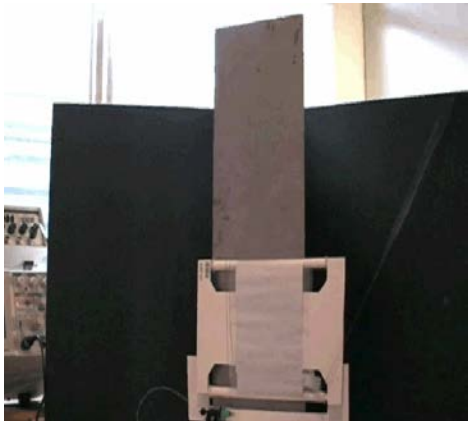
WOOD

Fast Window.avi

GLASS

CERAMIC TILE

Edited version of Bath tiles.avi



STEEL

Metal Climber.avi

DRYWALL

Drywall Front2.avi

Coping with Real Surfaces : Dirt

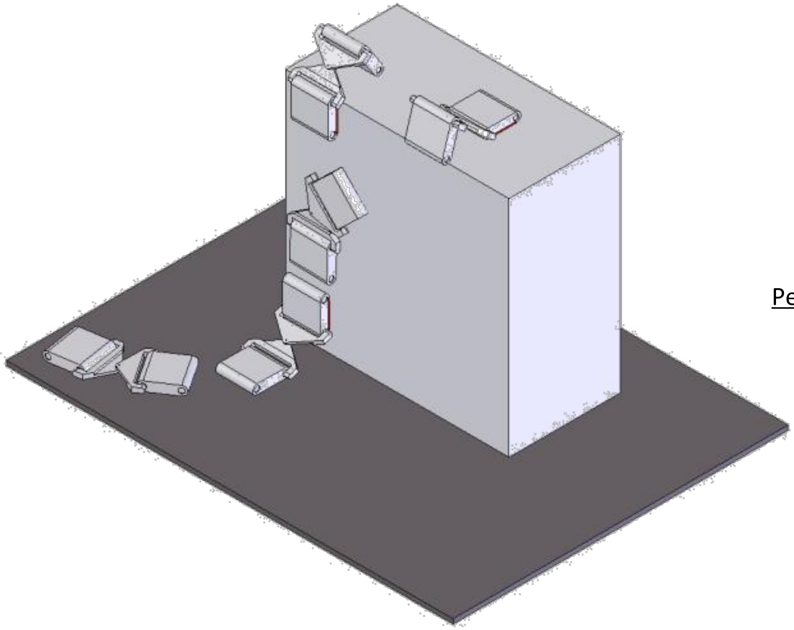
Video of robot on concrete wall after both robot and wall area coated with talcum powder

Electroadhesion clamps through dust to the wall

Obstacle Clearance and Advanced Mobility Tests

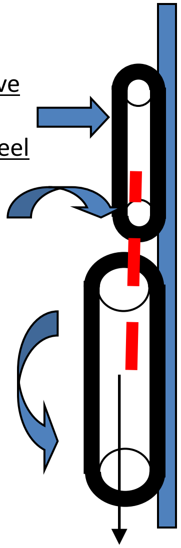
Mirror.avi

Wood_Bump.avi

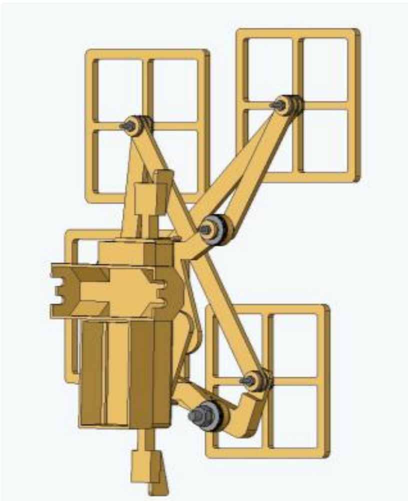


- Transitions (floor to wall, wall to orthogonal wall, wall to ceiling etc,) can be accomplished using articulated tank robots
- Double tread design improves peel

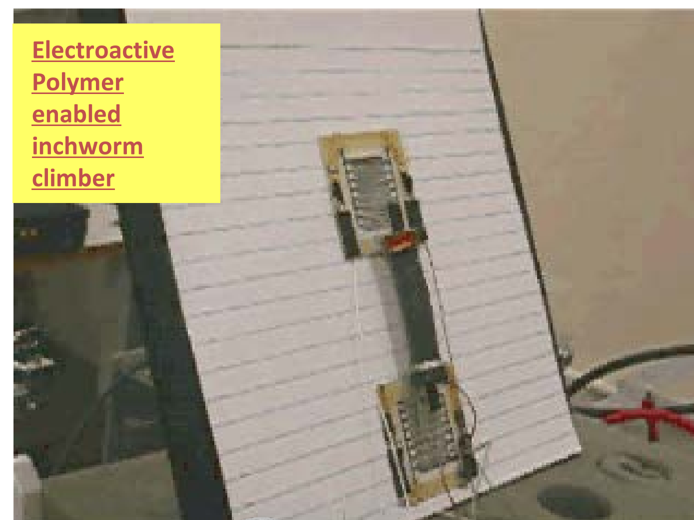
Double tread design



Biomimetic Walking Robots

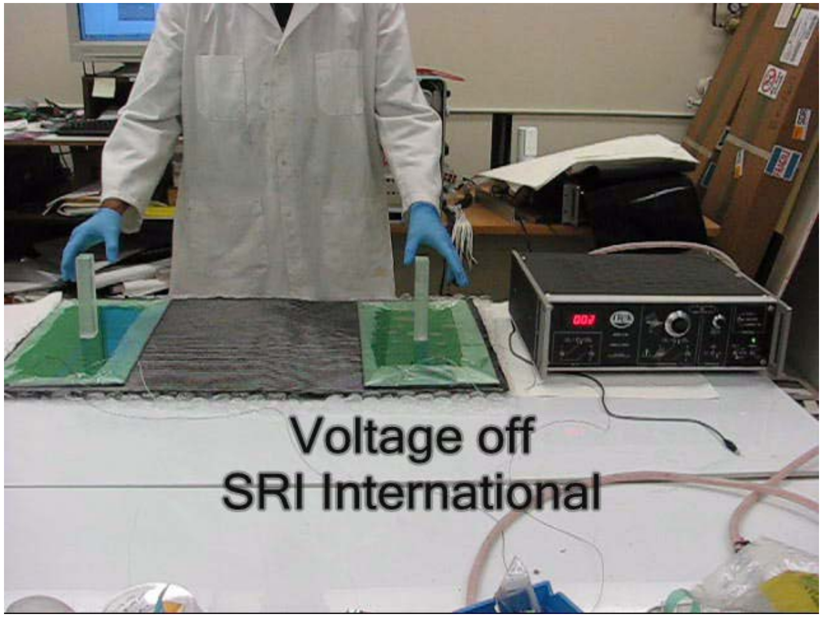


- In some designs that have been demonstrated (inchworm, skid designs), only inplane motion is required.
- In other designs, pads move out-of plane to come in contact with wall, but then move in-plane to drag the robot forward
- Pads can be switched off during movement to minimize energy for peeling
- Biomimetic designs are fundamentally sound and can be implemented with electroadhesion, but tracked robots were emphasized because of simplicity and speed



Edited version of Electro_Gecko_29Mar.avi

Other applications : Electroadhesive Gripping



Application of electroadhesion to gripping complex-shaped objects

- **Ongoing program with DARPA (ARM-H)**
- **Business development activities with industrial robotics companies and energy / aerospace companies for material handling**

Levitated Micro Robots – new systems for inspection (and repair?)

- **Levitated using diamagnetic materials (graphite)**
- **Freely mobile within workspace; uses PCB or flex circuit for electromagnetic drive force**
- **1 – 10 mm typical; larger sizes possible**
- **High performance (high speeds, excellent precision, etc.)**
- **Limited space-rated testing, but vacuum compatible and can use space-rated materials**
- **Applications as end effector on larger robot:**
  - Surface mapping
  - Electrical probing
  - Repair processes

Conclusion

- **Electroadhesion offers exciting opportunities for space-based inspection systems**
  - More work to be done, but results to date on space compatibility are encouraging
  - Several earth-based systems demonstrated and in commercial development

- **Various possible target applications in space**
  - Tile inspection
  - Solar array inspection
  - Also possible applications within spacecraft for temporary and semi-permanent adhesion, traction, etc.

- **New early stage micro robot technology (mobile but not autonomous) is promising as an inspection and repair tool**
  - Able to deploy multiple independent micro robots as end effectors

Thank You!