Design of a Gecko Adhesive Climbing Robot

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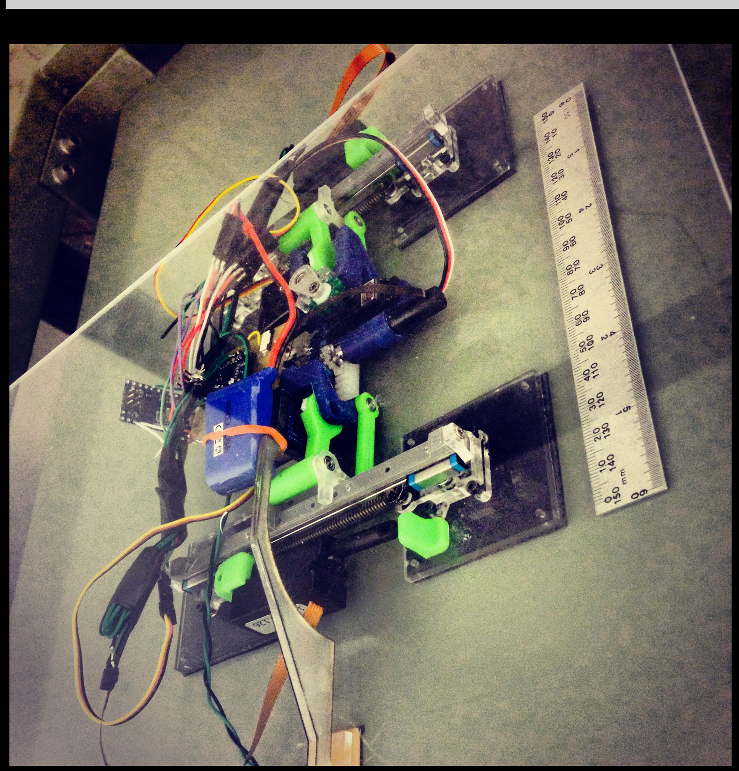
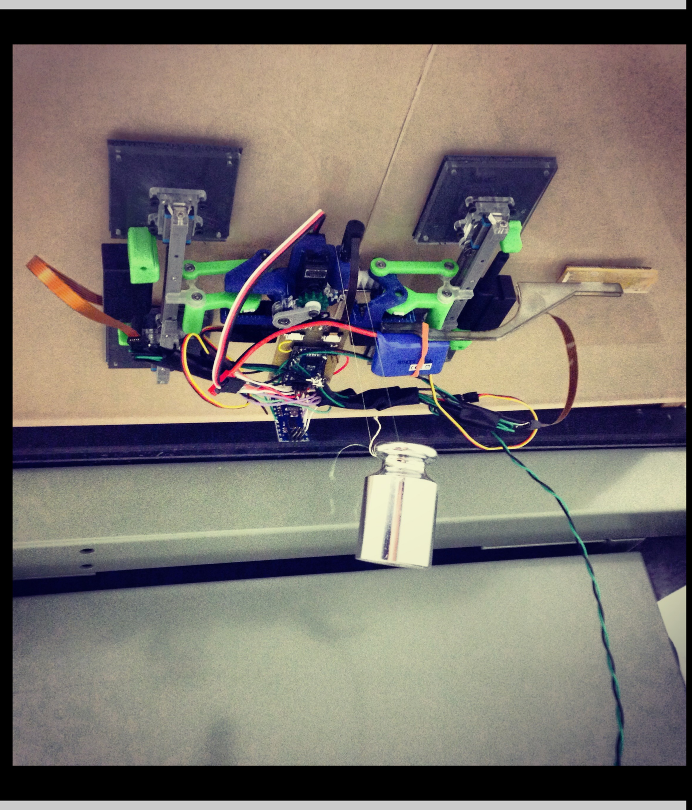
Abstract

I present, ACROBOT, a gecko-adhesive enabled robot that can climb surfaces in any gravitational orientation or operate in full zero gravity. The robot is being developed as a prototype for inspection applications aboard the International Space Station (ISS) where current voids in inspection coverage both inside and outside the station pose risks to the vehicle. A specific area of interest for inspection is a narrow gap, approximately 1.5 inches wide, behind internal equipment racks. The prototype robot uses oppositional pairs of gecko adhesive pads that turn adhesion ON and OFF using an applied shear load. The robot is currently tele-operated and utilizes an inchworm style gait. The robot can turn in a tight circle, fits within a 1.5 inch gap, and can transition between orthogonal surfaces. Gecko adhesives leave no residue, are highly reusable, and create strong adhesion in vacuum and across a wide temperature range. The robot design and initial experimental results are presented including climbing vertical walls in Earth's gravity.





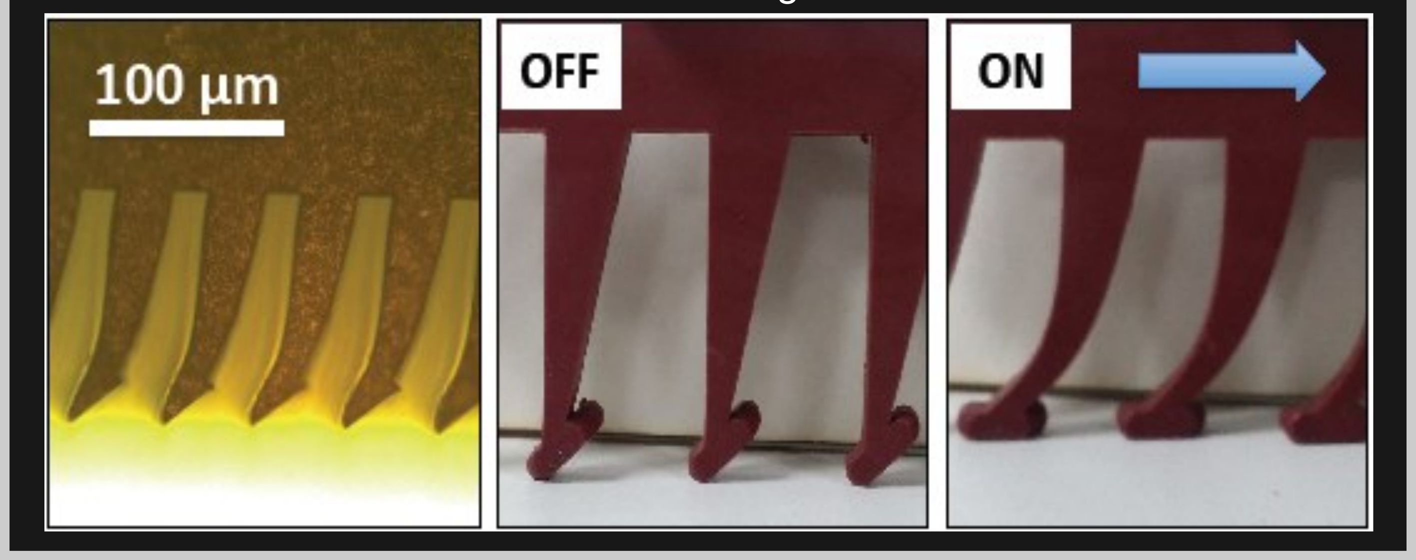
Introduction

Biomimetic Inspiration

- Geckos' toes are composed of a hierarchy of structures. On each toe, the gecko has tens of mm-sized flaps called lamellae on which arrays of millions of micron sized 'hairs' called setae grow. Setae branch further into thousands of nano-sized hairs called spatulae that make intimate contact with a surface and stick using predominantly van der Waals forces.

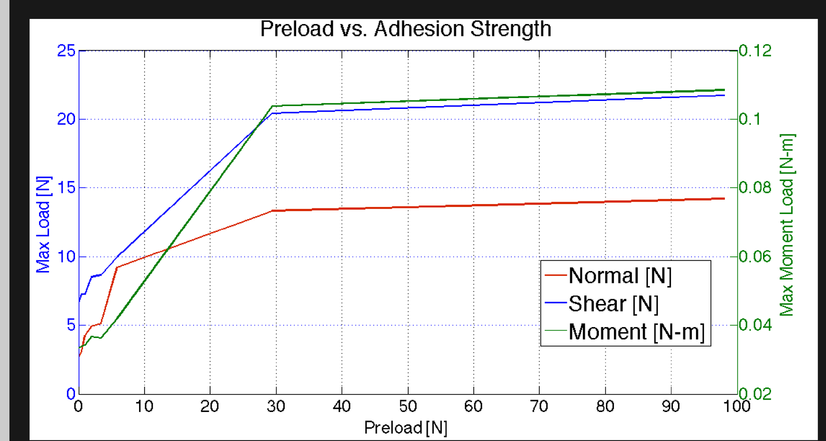
Directionally Controllable Adhesion

- Adhesive is an array of millions of compliant directionally biased wedges
- Adhesive turned **ON** by applying a shear force to pads in direction of bias
- Adhesive turned **OFF** by removing shear force
- Net van der Waals Intermolecular Force is directly proportional to real area of contact between adhesive and climbing surface



Adhesive Characterization

- Preload vs adhesion strength testing under normal, shear, & moment loads
- Performance characterization yields design parameter limits
- Results: Preload 'forces' out slight misalignments between pads & surface



MECHANISM VS. PRELOAD

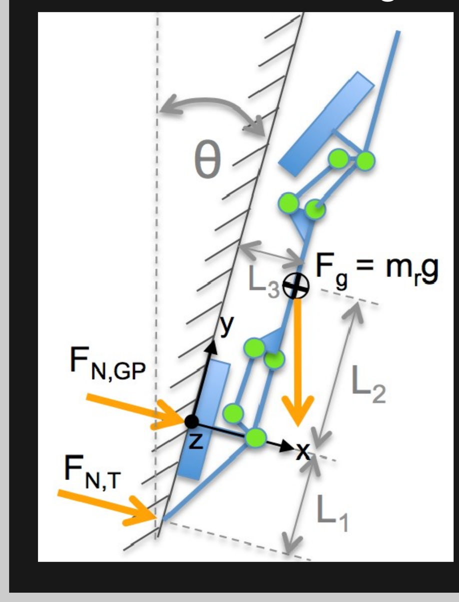
Mechanism	Preload Generated [N]
Robot Clamped/Fixed	5.0
Back Pads Adhered	0.4
Back Pads Adhered with Tail*	1.3

*Note: A maximum preload of 3.3N was attained when the pads did not maintain alignment with the surface

Robot & Mechanism Design

Synthesize collaborative mechanisms that allow the robot mobility along flat planes and the kinematic capability to execute orthogonal plane-to-plane transitions using an inchworm style gait.

- Optimize Center of mass
- Minimize weight



$$\sum F_x = F_{n,gp} + F_{n,t} + m_r g \sin\theta = F_{adh,x} \quad (1)$$

$$\sum F_y = m_r g \cos\theta = F_{adh,y} \quad (2)$$

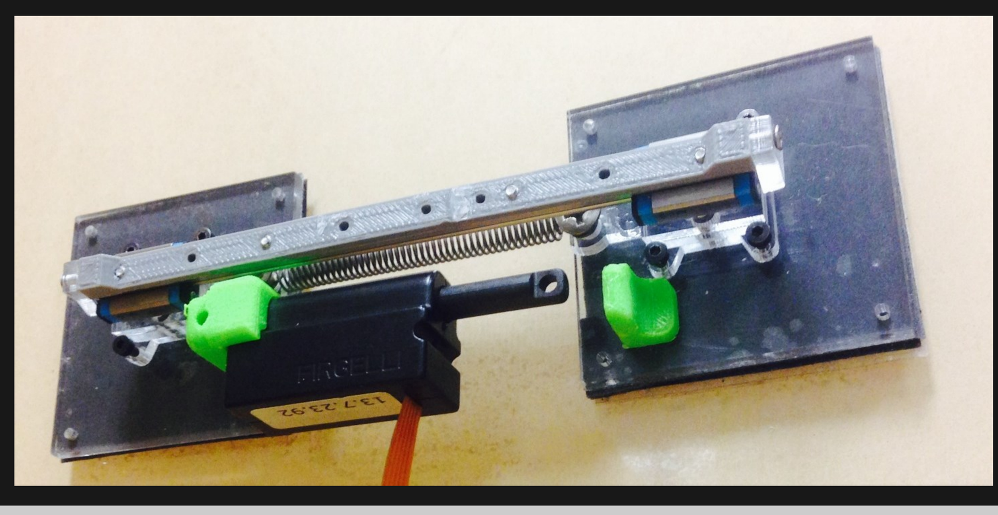
$$\sum F_{z,\ shear} = F_s = k(\delta x) \quad (3)$$

$$\sum M_z = L_1 F_{n,t} - F_g(L_3 \cos\theta + L_2 \sin\theta) = M_{adh} \quad (4)$$

Free body diagram showing all external forces acting on the robot during inverted θ > 0° climbing with only one module adhered to the surface. Solving the system of equations (1-4) for m_r, L_1, L_2, and L_{-3} given the limits of $F_{adh,x}$, $F_{adh,y}$, and M_{adh} with θ = 90° yields the robot's optimized parameters within the adhesive's loading capabilities.

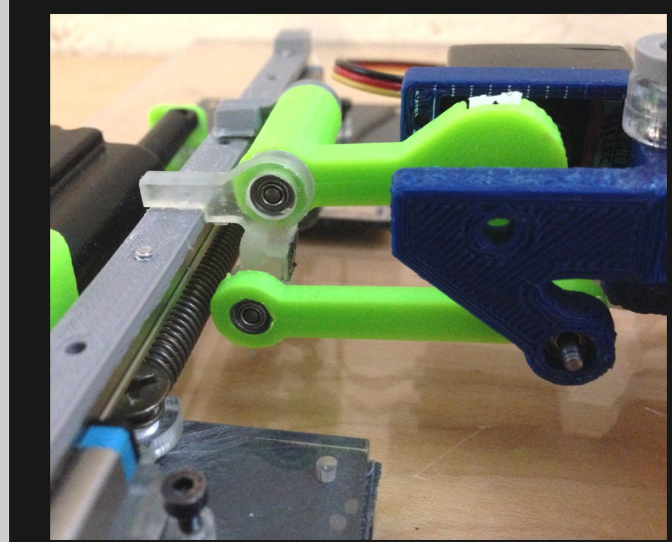
Adhesive Actuation Mechanism

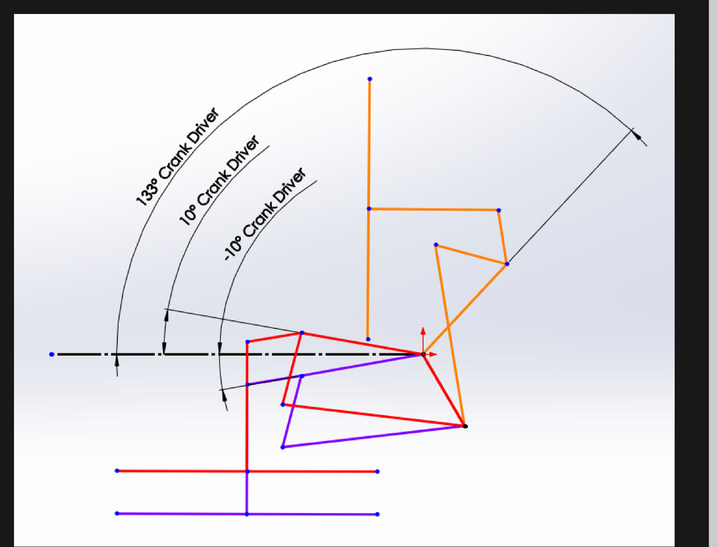
- Two gecko pads oriented in directionally biased opposition
- Tension spring configured in parallel with a linear actuator to apply shear
- Linear guide rail & bearings constrain pads & ensure coplanar alignment



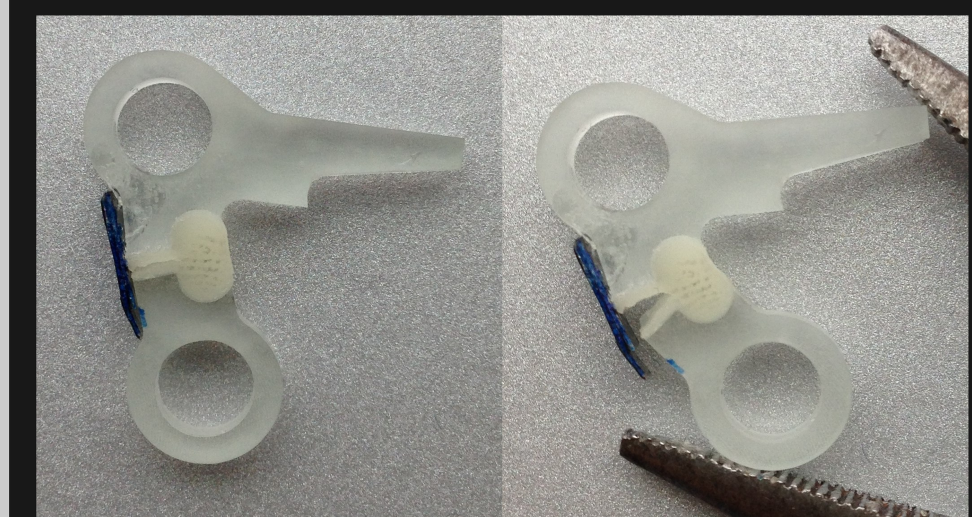
Metamorphic Compliant 4-bar Mechanism

- Synthesized 3-positon, 4-bar linkage to lift gecko pads onto and off of climbing surface
- For ±10° crank angle the linkage maintains pads at parallel alignment with climbing surface for optimal adhesion generation





- Compliant, contact-aided, anisotropic coupler link passively adjusts to slight misalignments with climbing surface
    - Compliant in bending in one direction and stiff in the other
    - Coupler link fabricated using **shape deposition manufacturing (SDM)**, an iterative milling and casting process yielding multi-material, embedded component parts

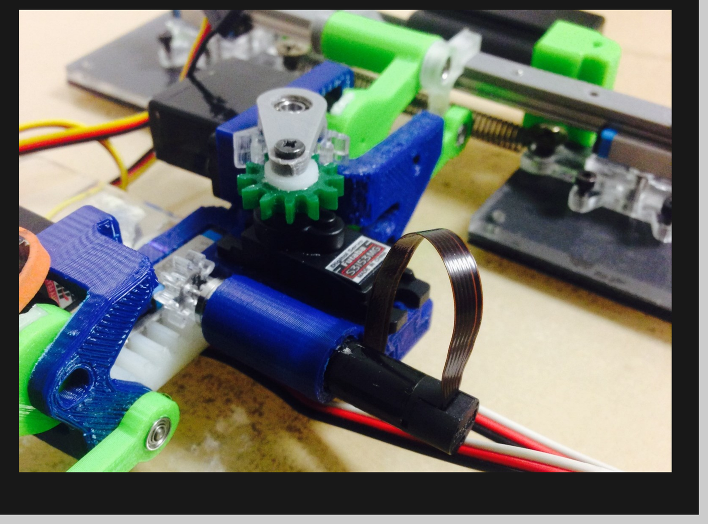


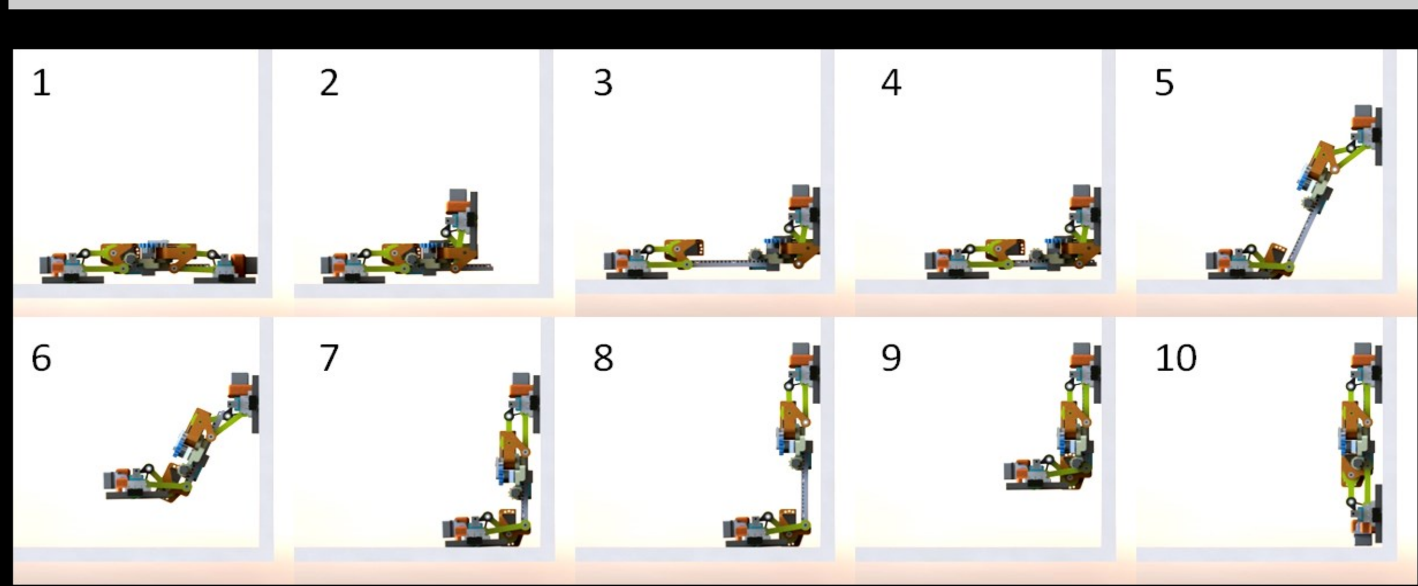
$$k_\theta = \frac{EI}{l} = \frac{E(\frac{1}{12}bh^3)}{l}$$

Mobility and Tail Mechanism

- Micro rack and pinion system for extension and contraction inch-worm locomotion
- Servo-actuated gear system for turning
- Passive tail counteracts gravity induced moment when only one gecko module is adhered to the climbing surface
- Tail used to preload gecko pads

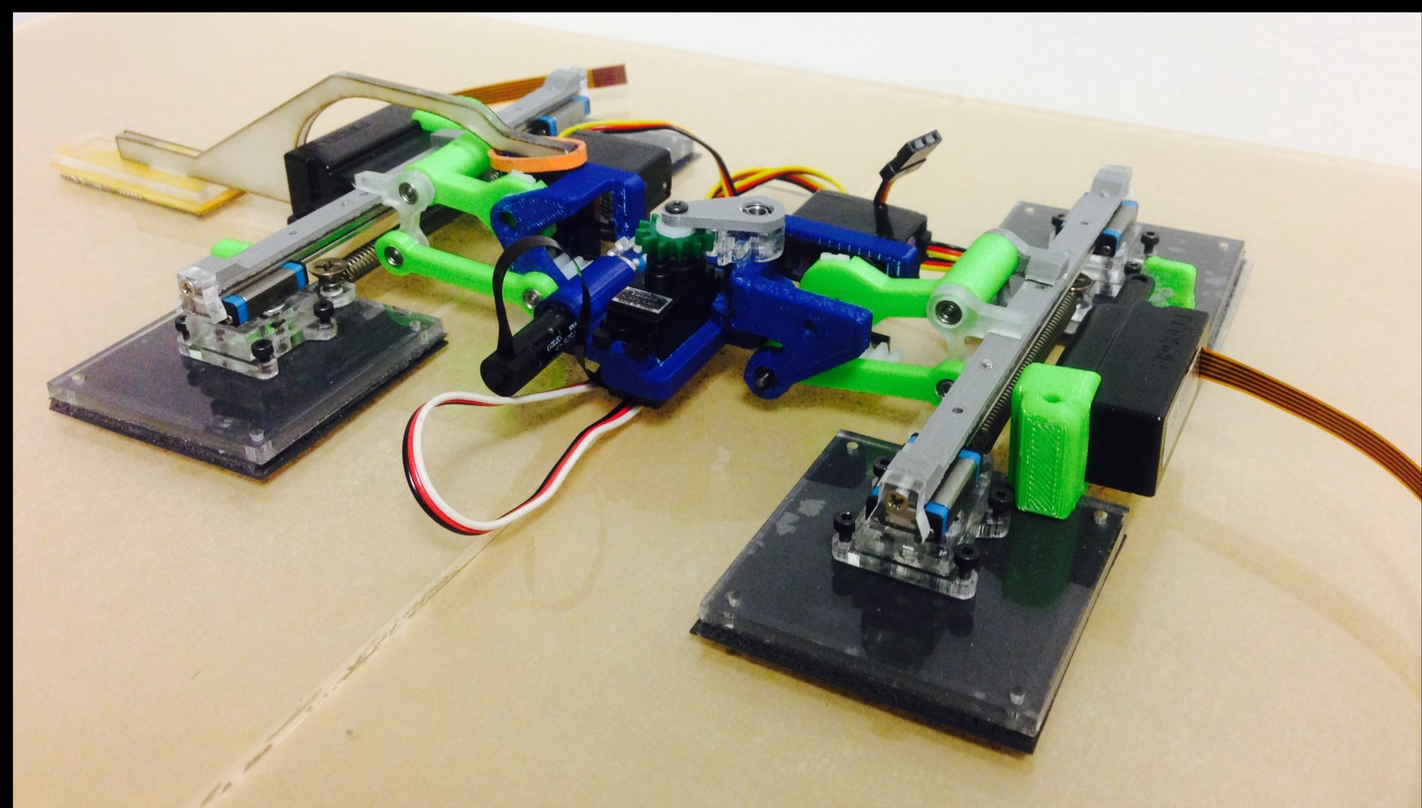
$$M_{gravity} = m_{robot} g(L_3 \cos\theta + L_2 \sin\theta)$$





Control, Sensing, & Actuation

- Two Pololu Baby Orangutan micro-controllers arranged in master/slave configuration control 2 linear actuators, 3 servos, & 1 brushed DC motor.
- Microswitch sensors used to determine if pads are in contact with surface
- Linear potentiometers and encoders used for motor position feedback
- Hall effect proximity sensors are being implemented on each pad-pair to determine if adhesion was created when attempting to turn pads ON
- Currently implementing control for autonomous step sequence climbing



Climbing Test Results

- Successful climbing on sloped & vertical surfaces in Earth gravity
- Can climb supporting own mass (0.323 kg) plus 0.2 kg payload
- Inverted hang using tail supporting additional 0.6 kg payload
- Inverted hang with only 1 module adhered supporting 0.075 kg

Future Testing

- Inverted climbing
- Plane-to-plane transitions

References/Acknowledgements

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[1] S. Kalouche, N. Wiltsie, H. Su, A. Parness. "Inchworm Style Gecko Adhesive Climbing Robot." IROS, Chicago, USA 2014.