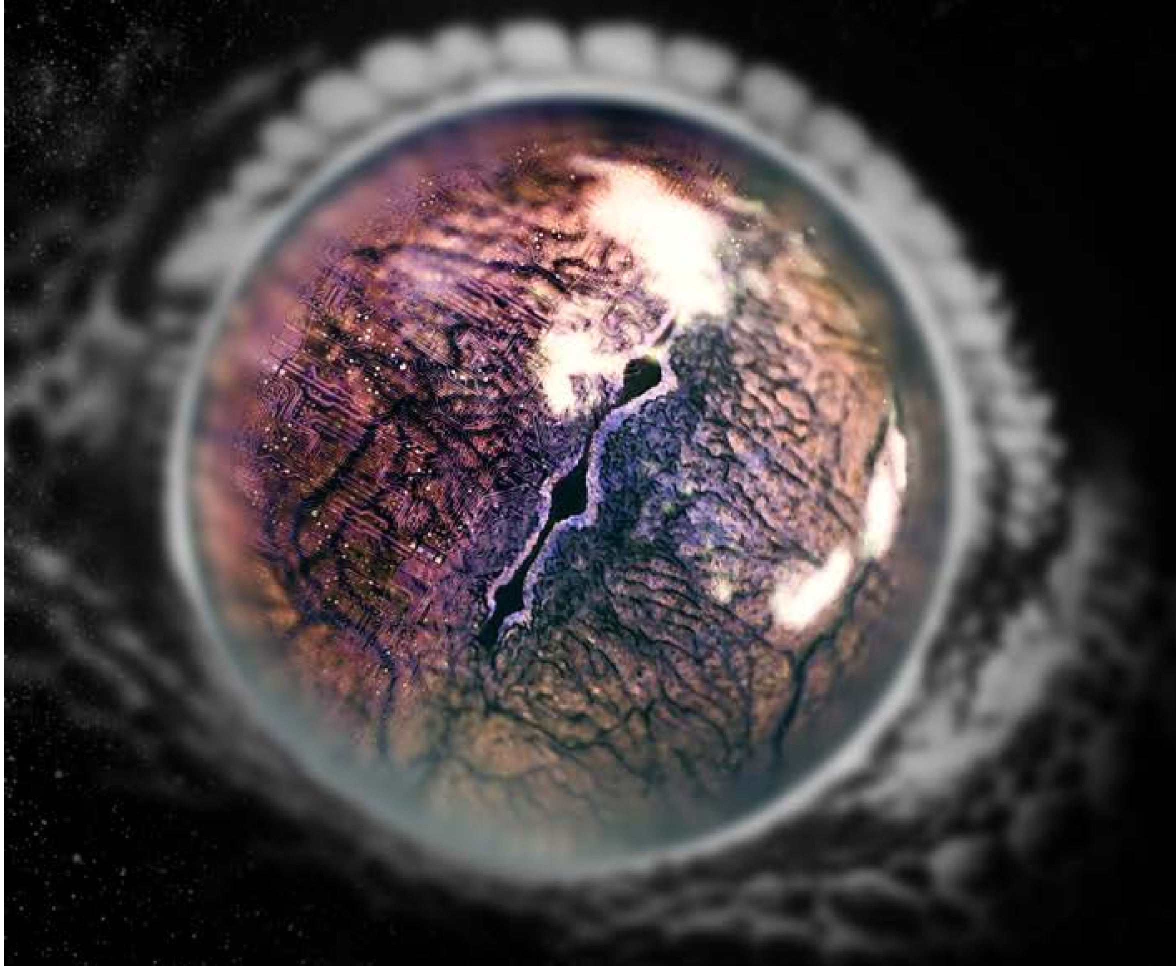

DESIGN OF A ZERO-GRAVITY CLIMBING ROBOT USING ON/OFF GECKO ADHESIVES.

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We present ACROBOT II, a gecko adhesive enabled robot capable of climbing surfaces of any gravitational orientation or in full zero gravity (W 1). ACROBOT II is being developed as a prototype for inspection of the International Space Station (ISS). There are current voids in the inspection coverage of the ISS due to the inaccessibility of certain areas to astronauts. Equipment in these areas that remains uninspected poses a risk of component failure and threatens the long-term success of the ISS. A specific area of interest for service and inspection is a narrow gap, approximately 2 inches wide, between the outer shell of the ISS and the external equipment racks. A small robotic platform, used in both autonomous and remote-controlled operation, would be advantageous for its ability to precisely navigate in tight spatial conditions. Due to the operating environment of a vacuum with no significant gravitational forces, a method of adhesion is required to ensure constant contact between the robot and the surface of the ISS. Gecko adhesives can be actuated ON and OFF by means of an applied shear force. They leave no residues, are highly reusable, and can create adhesion in a vacuum, making them a viable and promising option for space applications.

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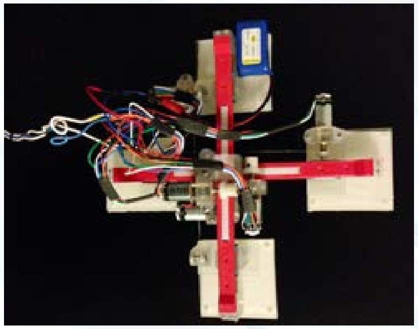

Figure 1: Complete functional, climbing, prototype of ACROBOT II.

I. MIMICKING THE SKIN OF GECKOS

Studying the biological structure of gecko's feet and toes led to the fabrication of a synthetic, gecko-like adhesive material. Gecko toes are composed of a hierarchy of several layers. Each toe has tens of millimeter-sized flaps called lamellae, on which grow arrays of millions of micron-sized 'hairs' called setae. Setae branch further at the tip into thousands of nano-sized hairs called spatulae. The setae add a layer of suspension to help conform to surface roughness of order 20-100 microns on the surface the gecko is climbing. The spatulae are then able to create very intimate contact with the surface being climbed, increasing the real area of contact (RAC) between the gecko's foot and the wall's surface.

As the RAC between the two surfaces increases, the net van der Waals intermolecular interactions subsequently increase, resulting in a significant adhesive force. To mimic this method of adhesion for climbing robots, synthetic gecko adhesives were fabricated. Using a complex multi exposure stereo lithography process, quartz molds were made with an array of 60-micron tall wedged-shaped structures. Silicone mixes were then poured into the mold, put into a vacuum, spun at a high rpm, and then set aside to cure. Post treatment processes were performed once the original molded silicone had cured to enhance the shape of the microfibrillar wedge's tips.

The synthetic gecko pads are a dual tiered structure. There exists a silicone foam suspension layer and an array of micro fibrillar wedges (the actual adhesive layer). The suspension layer allows the gecko-adhesive layer to conform to slight surface roughness and misalignments while evenly distributing loads across it. The micro fibrillar wedge shaped structure is composed of a 2-dimensional array of 60-micron tall directionally-biased wedges designed to increase RAC when under an applied directional shear force. The RAC between the synthetic gecko pad and the surface is small while no shear load is applied, as the only points of contact between the pad and the surface are the tips of the micron-sized wedges. However, when a shear force is applied to the gecko layer, the compliant wedges bend so that a much larger portion of the micro-fibrillar wedges are in intimate contact with the surface being adhered to, thus increasing the RAC by orders of magnitude and turning the adhesive ON. The microstructured adhesive can be seen in Figure 2 in both the ON and OFF states.

Gecko adhesives leave no residues, are highly reusable, have low sensitivity to temperature and pressure, are self-cleaning, and can operate within a vacuum—all ideal characteristics of an adhesion source for applications in space.

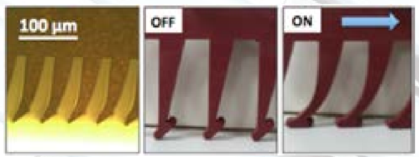

Figure 2: Gecko adhesive microstructure (left), 1000x mockup of adhesive in OFF state (center), and 1000x mockup of adhesive in ON state (right).

This synthetic gecko adhesive design provides a direct method of turning the adhesive ON and OFF. By simply applying a shear force in the direction of the wedge bending bias, the adhesive is turned ON. By applying a shear force in the opposite direction, against the bias of the micro wedges, the adhesive is turned OFF. Therefore, gecko adhesives are advantageous in comparison to traditional pressure sensitive adhesives (tape, glue, etc.) because large normal forces are not required to generate the adhesive forces, and a peeling motion is not required to remove the adhesive forces. Large normal forces are undesirable for climbing applications, because a large pull off force could potentially rip the whole robot off the wall; additionally, a large normal preload force would be very difficult to generate in space without the robot simply pushing itself off the surface. Gecko adhesives leave no residues, are highly reusable, have low sensitivity to temperature and pressure, are self-cleaning, and can operate within a vacuum—all ideal characteristics of an adhesion source for applications in space.

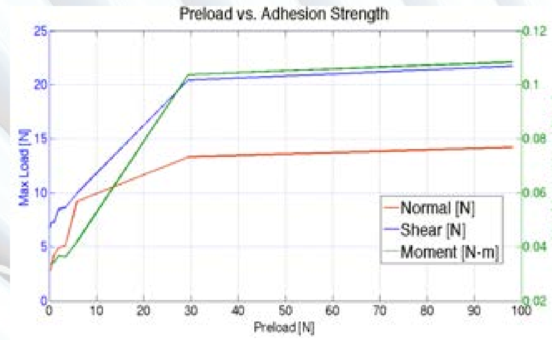

Figure 3: Characterization shows of the gecko adhesives show that adhesion is dependent on applied normal preload force when turning pads ON until about 30N, where the gecko layer is presumably coplanar with the climbing surface.

II. DESIGN

Robot Objectives and Design Approach

The main objective was to design a robot capable of climbing surfaces of any gravitational orientation and in full zero gravity. Because gecko adhesives require coplanar alignment to the climbing surface within 0.5 degrees, the mechanism responsible for placing the gecko pads onto the climbing surface must keep the pads parallel to the surface at all times or have a method for correcting angular misalignment. Gecko adhesive pads have a theoretical and experimental maximum carrying capacity under normal, shear, and moment loads. Load testing of the specific gecko pads being used has yielded the maximum load the pads can support before the adhesive fails for a given preload. As seen in Figure 3, the gecko adhesive's max load increases with increased initial preload. Theoretically, if the gecko pads are perfectly parallel and coplanar to the climbing surface, they do not require any normal preload force to turn the adhesive ON. However, slight manufacturing and assembly errors typically prevent the gecko pads from being coplanar with the surface; thus, applying a normal (into the climbing surface) preload force onto the gecko pad essentially forces out any slight misalignments by the foam suspension layer's passive distribution of the load. Therefore, a critical goal is to design a mechanism that can create high normal preload forces while maintaining coplanar pad-climbing surface alignment.

Another design goal is to minimize the mass of the robot so as to not exceed the adhesive's load carrying capacity, and to optimize the location of the robot's center of mass to minimize moment loads that could peel the gecko adhesive off the climbing surface. The maximum height of the robot is to be kept within a 2" limit to allow the robot to access areas inaccessible to astronauts aboard the ISS—the robot's main operating environment. Limiting the height of the robot will also reduce moment loads acting on the gecko pads in Earth gravity. To enable ACROBOT II to climb, a controllable mechanism must be designed that is capable of consistently toggling its adhesives between their ON and OFF state when desired. A power efficient mechanism is desired so as to use minimal actuation and allow for on-board power supply.

It is desired for ACROBOT II to have complete 2-dimensional mobility across a single plane. It is also desirable that the robot be designed to have future capabilities enabling the transition between orthogonal planes (i.e. wall to ceiling, floor to wall, etc.).

Adhesive Actuation Mechanism

The mechanism responsible for actuating the gecko adhesives between their ON and OFF states was designed to use a guide rail and carriage where a pair of gecko pads were oriented in directionally biased opposition. Using a single guide rail with a carriage or linear bearing mounted to each gecko pad ensures the two pads are always coplanar and parallel with respect to the other. The linear rail also constrains the motion of the pads to 1 translational degree of freedom. Extension springs are fixed to each of the gecko pads on one end and onto the end of the rail at the other end. A winch system was designed to wind up a tendon that couples both the gecko pads as seen in Figure 4. By coupling the two gecko pads (aligned in directional opposition), the pair of pads can be toggled between their ON and OFF states via one actuator rather than two. The use of extension springs creatively allows for a shear force to be applied to the gecko pads indefinitely without the use of any power. This allows the robot to remain adhered to a surface indefinitely without the need to consume energy or actuate any motors.

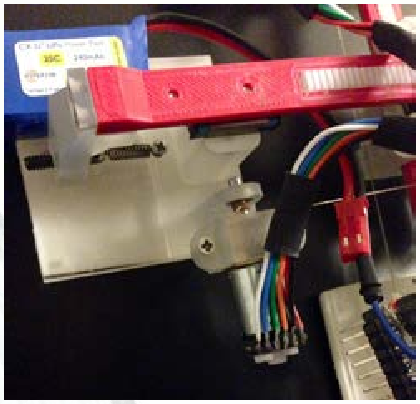

Figure 4: The winch mechanism responsible for turning the adhesives ON and OFF. The brushed DC micro-gearmotor has a tendon wrapped around its shaft and can wind it up to put the extension springs into tension.

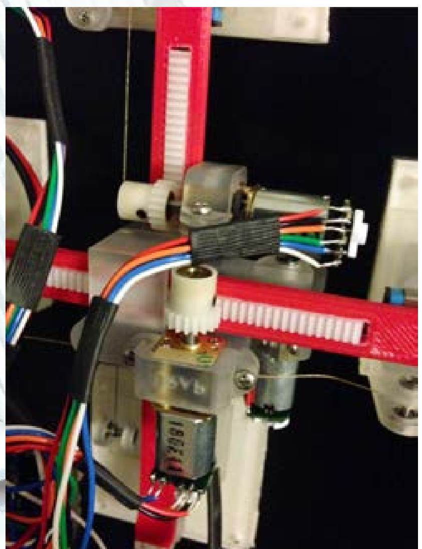

Figure 5: Prototype of ACROBOT II showing the 2 orthogonal rack and pinion inch-worm mechanisms actuated by identical brushed DC 298:1 micro-gearmotors.

Mobility Mechanisms

ACROBOT II can achieve translational inch-worm style locomotion in two perpendicular directions using two micro rack and pinion systems aligned orthogonally to one another as seen in Figure 5. A central unit composed of two components (upper and lower) was designed to house three motors which actuate both upper and lower rack and pinions and the cam motor. By actuating only one rack and pinion, ACROBOT II will travel linearly in one direction (e.g. vertical). If the other rack and pinion is actuated, ACROBOT II will travel in a direction perpendicular to the other rack and pinion (e.g. horizontal). To travel along a diagonal line, the two rack and pinions can be actuated in an alternating pattern to achieve complete 2-dimensional mobility.

A cam is used to raise and lower each pad-pair onto and off of the climbing surface. The orientation of the cam determines which pair of pads is in contact with the surface and which pair of pads is lifted off the surface so that it can translate forward without sliding or rubbing on the climbing surface. The cam has 4 dwells designed for 4 static positions: (1) upper rack and pinion pad-pair in contact with surface, (2) both rack and pinion pad-pairs in contact with the surface, (3) lower rack and pinion pad pair in contact with the surface, (4) both rack and pinion pad-pairs in contact with the surface. This cam allows for the cam motor to be only actuated in one direction while the sequence of dwells corresponds to the appropriate sequence needed for taking a step.

This design addresses and fulfills the major design criteria assessed in the preliminary design stages. The two components in the central unit are constrained to 1 translational degree of freedom relative to one another. The cam mechanism controls this single degree of freedom by translating rotary motion from the motor into linear motion between the two central unit components. By constraining the two rack and pinions to one relative, translational, degree of freedom, the design ensures that the pads will always be parallel to each other and to the climbing surface. Furthermore, this design ensures that the pads will be placed onto the climbing surface with an ideal normal preload force. To maximize effective preload force, the cam and winch mechanisms can be actuated in a manner that allows the set of un-adhered pads to be preloaded with a force less than or equal to the maximum normal load of the adhesive pad pair that would be currently turned ON. Therefore, rather than simply turning OFF the pad-pair by removing the shear load from extension spring with the winch, the cam can rotate to the position in which the pair of pads that is currently ON would be lifted off the surface and the pair of that is currently OFF would be pressed onto the surface. This would effectively use the maximum normal load capacity of the gecko pads to preload the non-adhered pair while pulling off the adhered pair.

Modular Design and Future Mobility

ACROBOT II has a modular design in that it uses the same motor to actuate all of its mechanisms. The motor used is a Pololu Micro Metal gearmotor, which outputs nearly 1.5 times the torque offered by servo of comparable size. The use of an optical sensor for shaft encoding allows the motor to be smaller than available hobby servos, able to produce more torque, and have equivalent resolution for angular positioning tasks.

ACROBOT II's design is also modular in its ability to operate in parallel with one or more identical robots, making each individual robot a module in a multi-robot system. When large structures are assembled on Earth, the construction is done in a parallel manner by small units that move as the structure grows, for instance, a colony of termites building a 10 m mound or construction workers on moveable scaffolds building a skyscraper. The proposed is a similar approach where swarms of hundreds or thousands of microrobots autonomously maneuver the various components of the structure into position. These segments would then be mated with a passive connector (ball and socket, magnetic, TBD) or, less optimally, delivered to a traditional dexterous robot arm and manipulator for final integration into the assembly. Using this approach, massive apertures, solar arrays, or mirror assemblies could be constructed in days instead of years – with the components literally walking themselves into place and plugging in.

Two or more ACROBOT II robots could also be coupled by a high degree of freedom (DOF) serial arm allowing for this configuration to achieve mobility across orthogonal planes such as inner and outer edges. This modular configuration could also allow for manipulative tasks where the robots would essentially act as grippers in the overall system rather than individual climbers.

The symmetrical architecture and design of ACROBOT II is also conducive to the implementation of four rotors above each gecko pad, essentially making this robot a quadrotor flying and climbing, mulit-modal mobility platform. This architecture could allow for short periods of flying and long periods of perching, effectively elongating the mission time of currently existing quadrotors for terrestrial applications.

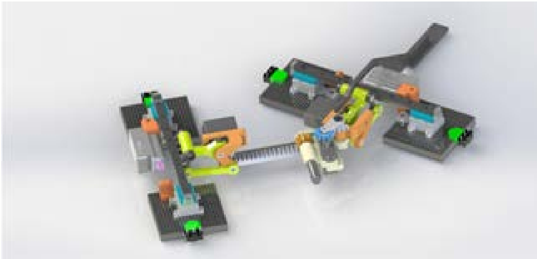

Figure 6: ACROBOT I used kinematically synthesized compliant 4-bar linkages to lift pads onto and off of the climbing surface.

ACROBOT II has successfully demonstrated climbing on sloped, vertical, and 30 degree inverted planes in Earth's gravity during tele-operation.

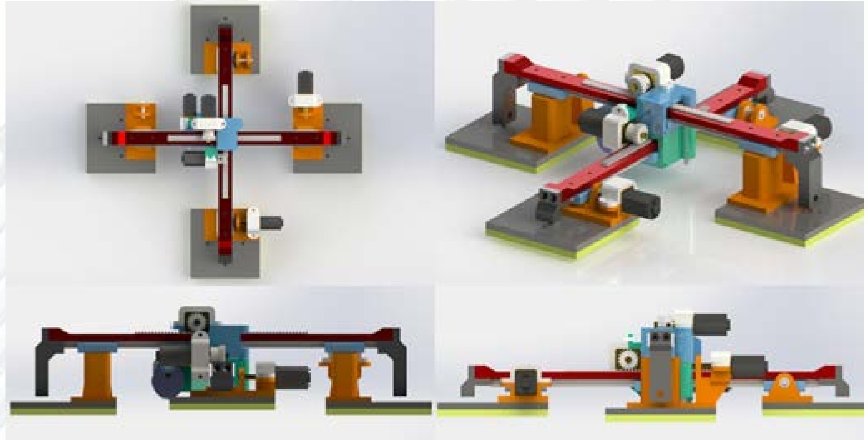

Figure 7: Top, front, right side, and isometric views of ACROBOT II. The top view shows all five of the actuators and their locations within the robot.

III. CONTROL & SENSING

Controller

ACROBOT II uses a Pololu Baby Orangutan robot controller which houses an Atmel ATmega328P microcontroller, offers two internal channel bidirectional motor drivers, 16 general purpose digital I/O pins (8 of which can be used as analog input channels). Six of the digital I/O pins are used to send Pulse Width Modulation (PWM) signals to external dual h-bridge motor drivers to power three additional motors. With this configuration, up to 6 actuators can be powered; however only 5 are needed in ACROBOT's current architecture.

Sensors

ACROBOT II is equipped with several sensors to provide feedback on internal motion and position to close the loops on motor actuation. Each of ACROBOT II's 5 identical brushed DC micro gear motors is configured with an optical sensor used for shaft encoding. The motors have an extended shaft, which spins at the frequency of the motor output (before the gearbox). Using a three tooth encoder wheel, the optical sensor has a resolution of 6 ticks or increments per motor output revolution. Thus, the output gearbox shaft has a resolution of 6 times 298, which is 1,788 increments per 360 degrees or 1 revolution of the gearbox shaft. This resolution is more than sufficient for this application.

Hall effect sensors are also used in parallel with the motor encoders for the two winch mechanisms to determine the displacement in the extension springs which would allow for ACROBOT II to generate the optimized shear load onto the gecko layer which differs when climbing on different materials or using different pad sizes. The Hall effect sensors are also being implemented to sense whether or not adhesion was created when attempting to turn the gecko pads ON.

Future work may include the implementation of novel, soft multi-axis force sensors, using a multi-layered array of channels containing conductive liquid metal. Changes in resistance due to deformations in the cross section of the fluid channels can provide force data at the gecko layer. This can be used to determine an optimized cam actuation pattern so as to not exceed the load carrying capacity of the adhered pair of pads while preloading the non-adhered pair.

Software

ACROBOT's control software is written in C via the Arduino environment. Code has been written to print sensor output data to a serial window, to allow for serial control and tele-operation of each of the motors individually, and to allow ACROBOT II to climb autonomously and execute multiple step sequences. ACROBOT II can currently climb vertical and slightly inverted walls autonomously using open-loop control; however, climbing is not yet robust at this point. Implementation of the aforementioned sensors would close the loop on applied force data at the gecko layer. This would enable optimal adhesion to be generated and maintained during climbing.

IV. TESTING & RESULTS

Gecko Pad Suspension Testing

In controlled laboratory tests, the directional gecko adhesive requires almost no preload to engage. However, on the robot, tolerances and manufacturing imperfections lead to slight pad-surface and pad-pad misalignments that are significant at the micro-scale of the adhesive. Using a hierarchical suspension layer and a slight preload orthogonal to the climbing surface can overcome these misalignments; however, maximum adhesive performance is sacrificed. Testing of pad pairs shows adhesion strength increases with preload until reaching a critical value, presumably due to good alignment. Therefore, ACROBOT II was designed using mechanisms synthesized to maintain parallel pad-surface interface while producing sufficient normal preload forces. Figure 3 shows the characterization of a pair of 4 in^2 gecko pads under applied normal, shear, and moment loads as a function of applied normal preload force.

ACROBOT II Climbing Tests

ACROBOT II has successfully demonstrated climbing on sloped, vertical, and 30 degree inverted planes in Earth's gravity during tele-operation. While tele-operation produces more robust climbing, due to operator feedback and control adjustment, the climbing is significantly slower as each actuator needs to be actuated independently. ACROBOT II is also programmed to climb autonomously in all orthogonal directions in any sequence. Climbing performance in autonomous mode, however, is not robust due to the current lack of feedback at the gecko layer. The robot operates open-loop, meaning it has no sensing capability between itself and its environment at this point in development. ACROBOT II's only sensing capabilities are the encoders and Hall-effect sensors, which are used to sense internal kinematic orientations of its actuation mechanisms. Future sensor implementations will close the loop on force sensing at the gecko layer which can significantly improve autonomous climbing performance to match that of tele-operated performance.

Improvements Over Previous Design

The previous generation ACROBOT I (see Figure 6), was designed, iterated, and tested thoroughly before the design of ACROBOT II (see Figure 7). ACROBOT I used similar actuation mechanisms to toggle between the adhesives ON and OFF states using springs to apply indefinite actuating shear forces on the gecko layer. This conserved significant amounts of energy and elongated mission time, thus this mechanism design was incorporated in a similar way into ACROBOT II. ACROBOT II uses a winch and tendon rather than a linear actuator to put a spring in tensions. ACROBOT I used two compliant, kinematically synthesized, 4-bar linkages to place and lift the adhesive pads onto and off of the climbing surface. The 4-bar linkage was synthesized to rotate the gecko pads through 3 task positions. The first two kept the gecko pads nearly parallel to the climbing surface for single plane locomotion while the 3rd task position rotated the gecko pads to be orthogonal to the original climbing surface for plane-to-plane transitions. ACROBOT II uses a cam to alternate between which orthogonal pair of pads is in contact with the surface. ACROBOT II solves angular misalignment issues by constraining the pads to 1 translational degree of freedom with the pads parallel to the climbing surface at all times. ACROBOT I turns while ACROBOT II has orthogonal bi-directional mobility. Both versions of the robot use a stable inchworm style gait. ACROBOT II's main advantages are that it keeps its gecko pads parallel to the climbing surface and that its center of gravity is always between the pair of pads that is adhered at all positions during climbing sequences. This minimizes the adhesives main failure mode caused by applied moment loads.

V. FUTURE WORK

The next step in progressing to a further flight readiness level for this robotic platform would be to continue testing and slightly modifying the design to increase performance on surfaces of all gravitational orientations (i.e. vertical, inverted, etc.). Once ACROBOT is climbing consistently in Earth gravity, testing will be done on climbing in micro gravity via NASA's reduced gravity simulating parabolic flights. ACROBOT is expected to perform better under zero gravity due to the absence of gravity induced loads and moments on the gecko pads. Cameras, LEDs, and other inspection tools will eventually be mounted onto the robot for testing readiness of inspecting the ISS.

VI. ACKNOWLEDGMENTS

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VII. FURTHER READING

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