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Zero Gravity Robotic Mobility Experiments with Electrostatic and Gecko-Like Adhesives Aboard NASA's Zero Gravity Airplane

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This paper presents the results of zero gravity adhesion and mobility experiments from two campaigns of flights aboard NASA's C9B zero-gravity airplane, totalling more than 300 parabolas. Two primary adhesion technologies were tested independently and as a hybrid system: gecko-like adhesives and electrostatic adhesives. Gecko-like adhesives use van der Waals forces generated by microscopic fibers or hairs to stick to surfaces; electrostatic adhesives create an electric field that both polarizes non-conductive surfaces to create adhesion and creates a capacitive clamping force on conductive surfaces where electrons are free to move. In zero gravity, grappling experiments were performed using a robotic gripper and a 10 kg target piece of debris to verify the performance of the adhesive materials. Based on these initial results, mobility experiments were devised for the second campaign of flights the following year. Experimental results from two mobile robots are presented. The first robot uses an inchworm style gait with two pairs of opposed gecko adhesive pads. The second robot uses adhesive wheels that contain flaps of the hybridized electro-gecko material. This robot can make transitions between perpendicular planes, and adheres to a much broader range of surface materials. Each robot weighs less than 200 grams and serves as a representative platform that was more easily deployed during the zero-gravity experiments. The technology can scale to much larger systems of 10s or even 100s of kg. Robots that can inch, roll, or crawl across surfaces in zero gravity could be used for inspection, repair, assembly, and photo/video documentation on satellites, space stations, and future long duration human spacecraft.

I. INTRODUCTION

Robotic mobility on the outside of spacecraft can provide unique inspection, repair, and videography capabilities. With the retirement of the Space Shuttle, the International Space Station has lost the ability to inspect the full exterior of the vehicle. Inspection capabilities are now limited to fixed cameras and the views possible through the use of the robotic arms. For this reason, when coolant leaks or micrometeorite damage occurs, as it has several times in past years, it can be very challenging to localize and repair the affected components. The only way to view certain exterior surfaces is through astronaut extra vehicular activity (EVA), which is time consuming and uses valuable consumable resources.

On future long-duration human missions to Mars, crew safety will be a priority, and the need to inspect the vehicles continuously and comprehensively is likely to be a high priority. One method to provide this complete coverage is through robotic crawlers that can maneuverer across the exterior of the vehicle.

Mobile assets can also perform valuable duties like filming docking operations or other critical activities from unique vantage points. These mobile robots could also reposition scientific payloads. With additional capabilities, these assets could also perform basic repairs and maintenance tasks, allowing astronauts to focus on science and exploration objectives.

Extravehicular robotic mobility may also play a role in the construction of very large space structures in the future, with the ability to move across the system to assemble structures too large to be launched in an assembled or deployable configuration such as large aperture telescopes.

Robotic crawlers have the key advantage that they can stay in place without expending any resources (like propellant) and can exert contact forces on the spacecraft. Certain non-destructive evaluation sensors commonly used in other aerospace applications require a slight preload with a surface to ensure a good signal. This class of sensors includes accelerometers, eddy current sensors, and contact acoustic sensors.

II. BACKGROUND

The microgravity environment requires that a robotic crawler actively anchor to the surface of the spacecraft. However, the space environment limits the use of many adhesive materials commonly applied on Earth. The vacuum environment precludes the use of suction-based grippers that are prevalent in the manufacturing industry, and many tacky materials such as tapes and glues outgas or cannot perform in the range of temperatures found in space. Further, many Earth-orbit applications require an adhesive that is reusable and can be turned ON and OFF. The danger of tip-off – where the object is bumped out of proximity or into a tumble accidentally – when adhering to a floating object means that small (or zero) preload forces are also a requirement. Both gecko-like adhesives and electrostatic adhesives meet these requirements:

1. Survive environment (vacuum, temp)
2. Turn ON/OFF; reusable
3. No significant preload forces

Combining the two technologies is also possible, and can lead to cooperative effects where the performance of the hybrid material is superior to the sum of each independent method[1].

Gecko-Like Adhesives

Geckos' adhesive ability has been a subject of academic interest since Aristotle[2]. However, it was not until the invention of scanning electron microscopy that the detailed structure of the gecko toe could be observed. Geckos grow a hierarchical fibrillar structure with features at the mm, um, and nm scale[3]. The smallest features make intimate contact with the climbing surface and utilize van der Waals forces as the dominant adhesive effect[4]. The larger structures in the hierarchy act as a suspension system to help the nanostructure conform to the surface, which may have roughness across several length scales, and to distribute the forces of climbing evenly among the many thousands or millions of independent surface contacts.

In the last decade, researchers have developed many synthetic gecko skins that mimic one or more of the gecko's properties. A review of many such materials can be found here[5].

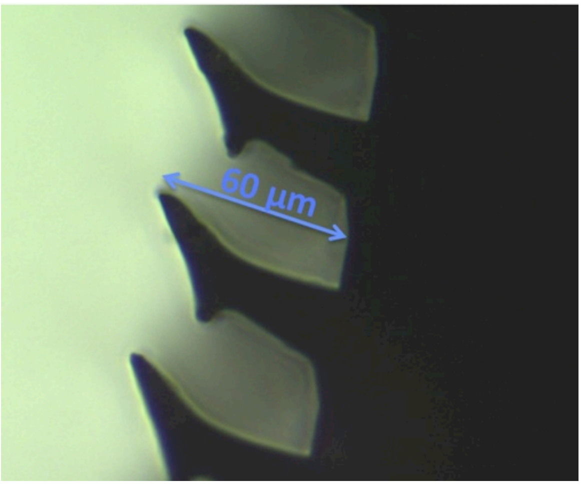

Fig. 1: Profile view of JPL's gecko-like adhesive microstructure with post-treated mushroom tips.

The material used at JPL was originally developed at Stanford University for the Stickybot climbing robots[6,7]. The material consists of right angle wedges that are

20um across the base, 70 um tall, and extend 200 um laterally. These wedges are post-treated using a dipping process to develop a mushroom-like cap structure on the tips that increases normal adhesive by a factor of two[8].

The gecko-like material has been tested over 30,000 cycles of ON/OFF[9], validated in a thermal vacuum chamber at full vacuum and -60C[10], and successfully performed static hang lifetime test of over a year followed by reuse[11].

Electrostatic Adhesives

Electrostatic adhesives use a high voltage potential across electrodes that are embedded in a dielectric to generate adhesion. These adhesives have been demonstrated for wall-climbing robots using tank treads made of the material[12].

On conductive surfaces, electrons in the substrate move to create matched opposition to the charge in the electrostatic pad creating a capacitive clamping force. On non-conductive surfaces, the molecules match the polarity of the electrodes in the pad, also creating an adhesive effect[13]. The adhesion force in most materials is proportional to the square of the electric field strength, so using high voltages is advantageous.

The electrostatic pads used in these robots consist of a comb pattern of copper electrodes that are mated to a Kapton surface. The silicone rubber of the gecko-like material encapsulates the exposed copper traces, acting as the dielectric. A DC voltage of 6kV is generated by a small DC-DC converter aboard the robot. Since the only currents needed in steady state are the leakage in the pads and the load on the converter, a small Lithium Polymer battery can power the pads for more than an hour.

III. EQUIPMENT DESCRIPTION

ACRobot

The Adhesive Climbing Robot (ACRobot) uses two pairs of opposed gecko adhesive pads to stick to surfaces and climbs using an inchworm style gait. The configuration of the pairs on orthogonal axes allows the robot to move in any direction on a flat surface. The robot is described in detail in a previous publication[14].

During the microgravity experiments, a Lithium-Polymer battery powered the robot. The robot was controlled from a laptop over a micro-USB cable. Because of the time required to grip and release a pair of gecko adhesive pads is on the order of 10 seconds, only single steps could be taken in the brief window of weightlessness aboard the aircraft. To demonstrate significant mobility, the robot was run over many consecutive periods of microgravity during which time the robot and panel were in free-float.

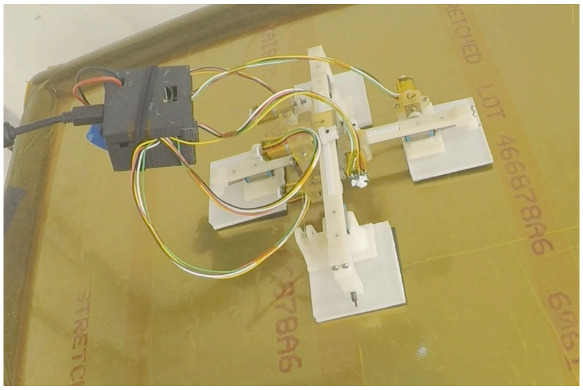

Fig. 2: The ACRobot platform.

Micro Climbing Robot

The Micro Climbing Robot use two wheels with flaps of adhesive material to traverse surfaces. The current platform is an evolution of the Durable Reconnaissance and Observation Platform[15] that has been modified for NASA applications.

Each wheel uses three pads of hybrid electrostatic-gecko adhesive material. The tail is essential in this architecture to react the torque created by the motors and cause the wheels to drive along the surface. The robot is powered by a small LiPo battery. Communication is done wirelessly using a DelTang transmitter-receiver chip set and an off the shelf remote control typically used for hobby airplanes. The robot carries a small payload in the form of a small camera and microphone that is mounted to a pan-tilt mechanism. This payload represents basic inspection capability, but could be replaced by any other payload of similar size, weight, and power specifications.

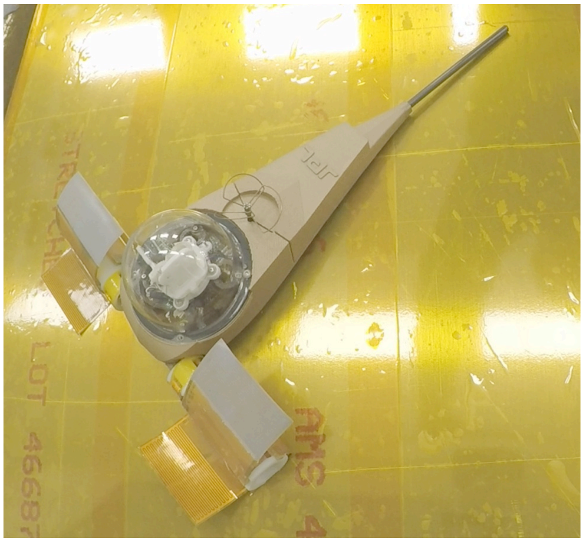

Fig. 3: The Micro Climbing Robot platform.

Flat Surface Gripper

A single flat surface gecko adhesive gripper was also tested as a representative foot for a larger walking robot. Due to the constraints of the test environment, it was not feasible to test the full LEMUR climbing robot for which these grippers are intended during this campaign[16].

The flat surface gripper uses 8 gecko adhesive pads that are arranged in four oppositional pairs. These pads are engaged and disengaged using a single actuated lead screw with three positions: gripped, home, and detached. The design considerations and development of these grippers are well documented in prior publications[17,18].

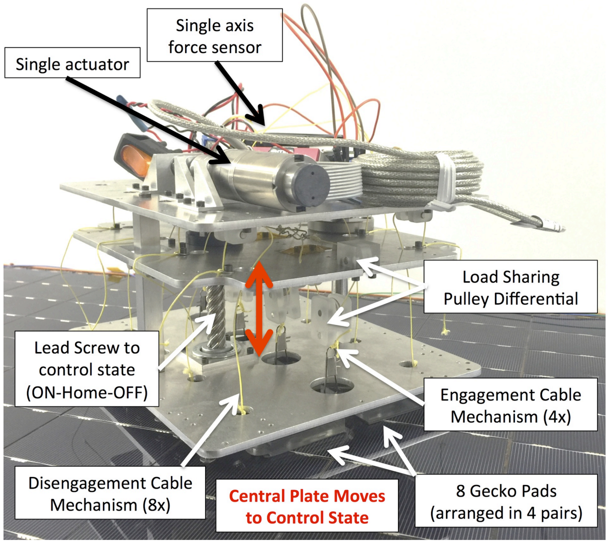

Fig. 4: The Flat Surface Gripper with all key parts annotated.

IV. RESULTS

ACRobot

A camera was mounted to the climbing panel on which ACRobot was moving and recorded video of the robot over a consecutive sequence of 20 parabolas during which time the robot took 20 steps in microgravity.

Micro Climbing Robot

The Micro Climbing Robot was tested in four separate scenarios. First, the robot was driven across a flat, rigid panel. This simulates the traverse of a solar panel or exterior structure of a spacecraft. Second, the robot was driven across a flexible mylar film that is representative of the multi-layer insulation (MLI) that is common as a thermal blanket material on spacecraft. Third, the robot was driven on the inside of a 1-meter diameter aluminium cylinder, demonstrating the ability to move across the interior structures of a space station that may have curvature. Fourth, the robot was driven around the exterior of the 1-meter diameter cylinder. This test simulates the ability of the robot to maneuver on the exterior of pressure vessels or fuel tanks that commonly take the form of large cylinders.

The robot was able to successfully drive in all four cases, including the ability to steer and turn. The wireless camera payload was not operated in flight due to spectrum interference concerns with the aircraft, but functions perfectly on the ground in simulated tests.

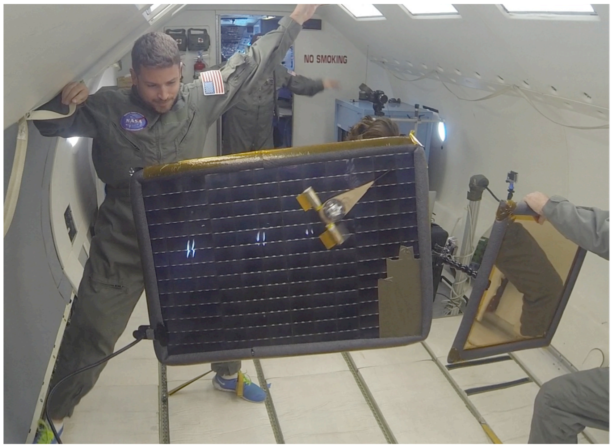

Fig. 5: The Micro Climbing Robot driving across a flat solar panel in free float.

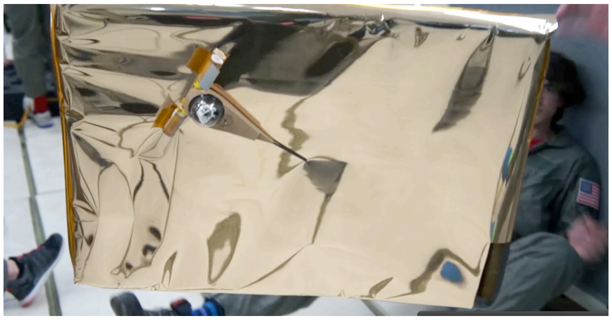

Fig. 6: The Micro Climbing Robot driving across a flexible mylar blanket in free float.

Fig. 7: The Micro Climbing Robot driving on the inner portion of a 1 meter diameter aluminium cylinder in free float.

Fig. 8: The Micro Climbing Robot driving on the outer portion of a 1 meter diameter aluminium cylinder in free float.

Flat Surface Gripper

The Flat Surface Gripper was used successfully to grip a free-floating cube of 10 kg mass. The gripper was able to anchor with less than 6 N of preload force and support the loads of manipulating the cube during free-float. The cube could also be detached with near-zero detachment force. This demonstrated the ability for a larger limbed robot, such as LEMUR 3, to take a step on a locally flat surface. A limbed robot would have, by far, the most capability in a complex environment like the exterior of the International Space Station.

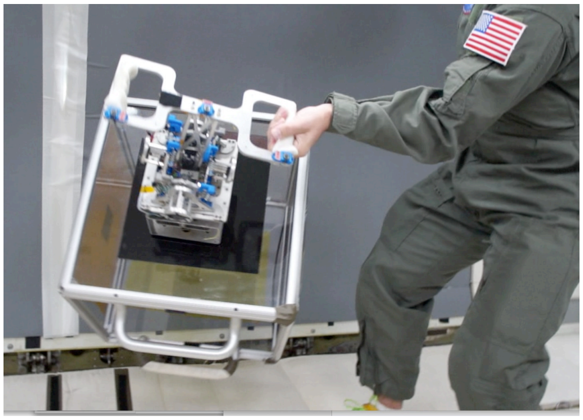

Fig. 9: The Flat Surface Gripper grappling a free floating cube on a carbon fiber surface.

V. CONCLUSIONS

This paper presented the results of a campaign of experiments conducted in microgravity aboard NASA's C9B aircraft flying parabolic trajectories. Three types of robotic attachment were demonstrated including an inchworm style robot, a wheeled robot, and the foot of a larger limbed robot. These robots used either gecko-like adhesives or hybrid gecko-electrostatic adhesives that are compatible with the space environment. We hope that these demonstrations prove to be the first steps towards robotic crawlers with the capability to inspect, repair, and document events on the International Space Station or future long-duration spacecraft.

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