VIBRISSA INSPIRED MECHANICAL OBSTACLE AVOIDANCE SENSOR FOR THE VENUS EXPLORATION ROVER AREE. R. S. Bhagwat[1*], B. H. Alva[2], B. D. Hartwell[3], E. O. Bernard[4], V. V. Rajesh[5]

[1]Department of Mechanical and Aerospace Engineering, The Ohio State University, bhagwat.14@osu.edu*
[2]Space Life Science Training Program, NASA Ames Research Center, benjamin.h.alva@nasa.gov
[3]Universities Space Research Association, NASA Ames Research Center, blake.d.hartwell@nasa.gov
[4]Department of Chemical Engineering and Materials Science, University of Minnesota, berna401@umn.edu
[5]Department of Chemical Engineering and Materials Science, University of Minnesota, rajesh009@umn.edu

Introduction: The Automaton Rover for Extreme Environments (AREE) is a NASA Innovative Advanced Concepts project to design a rover that can operate for six-months on the surface of Venus. To enable terrain traversal and navigation, AREE must be equipped with a robust obstacle avoidance sensor (OAS), however modern electronics cannot operate in the extreme surface temperature and pressure [1]. Therefore, as part of the NASA "Exploring Hell: Avoiding Obstacles on a Clockwork Rover" challenge, an OAS was developed with an array of mechanical sensors akin to mammalian vibrissae and associated electromagnetic actuators, shown in Figure 1 and 2. The obstacle detection method of the OAS can be described as a mechanical and electrical relay system.

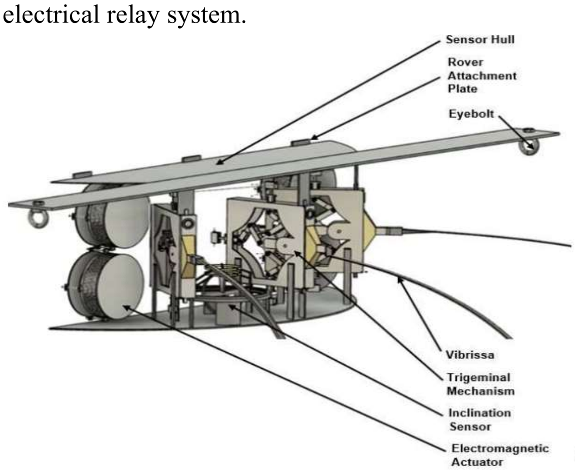

Figure 1: OAS, side hull removed for inner component visualization.

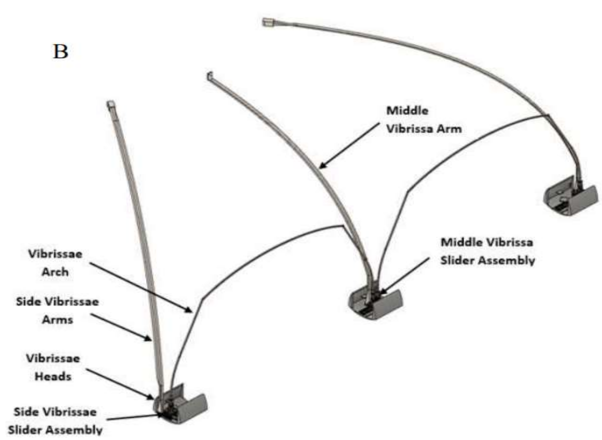

Figure 2: Vibrissae mechanism.

Vibrissae Mechanism: The first component of this relay is the vibrissae mechanism, an assembly of three mechanical vibrissa that extend from the front of the rover to the Venusian surface to detect obstacles. The outer two vibrissa are directly in front of the rover wheels, while the third is positioned in between the two. The ends of these vibrissae, which make direct contact with the Venusian surface, are characterized as vibrissa heads. The vibrissae are connected by rigid arches that allow motion hindering obstacles between the vibrissae heads to be detected, while allowing shorter obstacles to pass undetected. Rotary motion of these arches is possible through universal joints that connect the arches to the vibrissa heads. The impact of an obstacle on an arch or vibrissa head causes the entire vibrissa to translate backwards. Each individual vibrissa head is also capable of translating vertically by allowing the entire vibrissa to act as a lever which pivots about a fulcrum at the vibrissae base. Because the vibrissa arms are rigid and this fulcrum is fixed, the entire outer vibrissa will also have to yaw backwards via a bearing connection during this vertical translation of the vibrissa heads. To enable the outer vibrissa heads to be continuously stationed directly in front of the rover wheels, the arches are fixed to slider assemblies on the vibrissa heads, and non-extendible ceramic fiber loop bands are used to connect the outer vibrissa heads to eyebolts that are located on the underside of a rectangular plate atop the top-section of the OAS hull. During vertical extension of the vibrissa head, all sliders translate from their initial position towards the opposing ends of the vibrissa head as a result of centripetal force that acts towards the middle vibrissa and is induced by the rigid arch. However, any inward motion of the vibrissa head is prevented, because the aforementioned centripetal force is negated by the reaction force between the non-extendible ceramic-fiber loop band and the vibrissa head. The sliders are associated with self-retracting cord reels, which provide a spring force that allows all sliders to return to their initial position when backing away from obstacles upon detection.

Trigeminal Mechanism: The second set of components are the trigeminal mechanisms, which function via flexural-based mechanics to convert vibrissa displacement into an electrical signal, shown in Figure 3. The trigeminal mechanism, of which there are three included within the OAS, translates the two-dimensional movement of each vibrissae, which act as type one levers, into compressions or extensions of three sets of linkages and accompanying spring shafts.

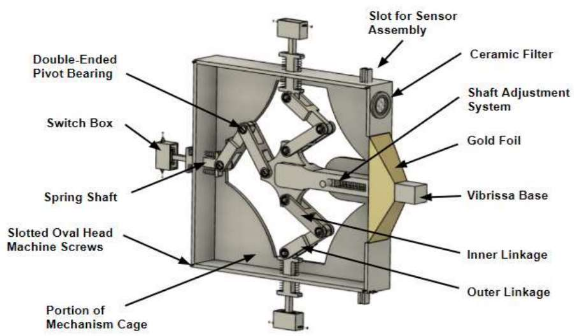

Figure 3: Trigeminal mechanism components with a section of the mechanism cage removed for improved interior visualization.

Much of the trigeminal mechanism is composed of Ti-6Al-4V, apart from the springs, foil, and screws. The linkages are constantly held in a resting state that resists displacement of the vibrissa head from level surface, where rover inclination acts as the reference, but are displaced by the slightest movements of the vibrissa. The restoring force is provided by nine Ti-6Al-4V double-ended pivot bearings, three per linkage, and the spring shafts that hold four springs that function to provide either a tension or compression force given the circumstance. The pivot bearings are a flexural-based device that employs three crossed internal flexure beam springs enclosed in a three-part cylindrical housing sleeve [2]. The system of nine differentiated double-ended pivot bearings provides precise rotation with low hysteresis that allow the trigeminal mechanism to resist inappreciable vibrissae movement, sustain a resting state, and allow angular displacement to specified degrees that define the pin actuating configurations. In addition, there is a shaft adjustment system that holds the circular shaft acting as the fulcrum for the vibrissae in place with two springs, which compress when against an obstacle of significant inclination, allowing for the aft linkage and spring shaft to fully compress.

Inclination Sensor: There are many obstacles that can be detected by the vibrissae and trigeminal mechanism. However, when inclination increases or decreases gradually, such as a slope on a hill or mountain, these systems will not detect this change since they are limited to sensing obstacles in reference to the plane tangent to the bottom of the rover wheels (i.e. rover inclination). Therefore, rover inclination in reference to the gravity of Venus must be monitored by the OAS and be able to detect when inclination maximums are exceeded to prevent the rover from losing surface traction or becoming overturned on a steep slope. To mitigate the risk that gradual inclines pose, a mechanical-based inclination sensor was designed for use in the OAS to detect gradual declines and inclines in any directions by referencing the orientation of gravity.

Electromagnetic Actuation System: The electromagnetic actuation system is the final component, containing four highly compact solenoids [3] Using two wires for power and ground connections, an electric circuit which is completed with sufficient compression of a trigeminal mechanism linkage and shaft was designed to pass current through the solenoids. Using a cylindrical, ferritic slug placed within the solenoid, the magnetic field generated by the energized coils exerts an axial force which actuates a pin via translation of the parallel slug to relay obstacle detection. This system allows the detection of a multitude of obstacles but can also differentiate them into four distinct signals, which include holes and negative 30-degree inclines, positive 30-degree inclines, 90-degree or near 90-degree inclines, and gradual inclination that accumulate to 30-degree in any direction. These signals trigger the rover to reverse and seek a different path forward upon obstacle contact.

Conclusion: The function of the various mechanisms, along with an extensive material trade study to determine the appropriate composition of OAS components, and failure modes with mitigation strategies, ensure that all problematical obstacles outlined by NASA are detected. The present OAS ensures that AREE is capable of operating in the extreme surface conditions of Venus for an extended period of time and was officially recognized by NASA as one of the top design solutions.

Acknowledgements: The authors would like to thank the NASA Jet Propulsion Laboratory, NASA Tournament Lab, and HeroX for organizing the NASA "Exploring Hell: Avoiding Obstacles on a Clockwork Rover" challenge, NASA Jet Propulsion Laboratory and NIAC for their extensive prior work on the AREE Rover, and NASA Ames Research Center for promoting the challenge.

References: [1] Sauder, J. AUTOMATON ROVER FOR EXTREME ENVIRONMENTS (Tech.). CA: NASA Jet Propulsion Laboratory, California Institute of Technology. 2016. [2] Riverhawk Company. (2018). Double-Ended Pivot Bearing. Retrieved July 19, 2020, https://flexpivots.com/flexural-pivot-products/double-ended-pivot-bearing/ [3] Schimpf, P., "A Detailed Explanation of Solenoid Force," International Journal on Recent Trends in Engineering and Technology, Vol. 8, No. 2, Jan 2013.