SOFT ROBOTICS FOR SPACE APPLICATIONS: TECHNOLOGIES FOR RESOURCE UTILIZATION IN EXTREME ENVIRONMENTS.

W. Foster-Hall[1] and D. J. Harvey[1], [1]william.foster-hall@adelaide.edu.au, School of Electrical and Mechanical Engineering, The University of Adelaide, SA 5005, Australia.

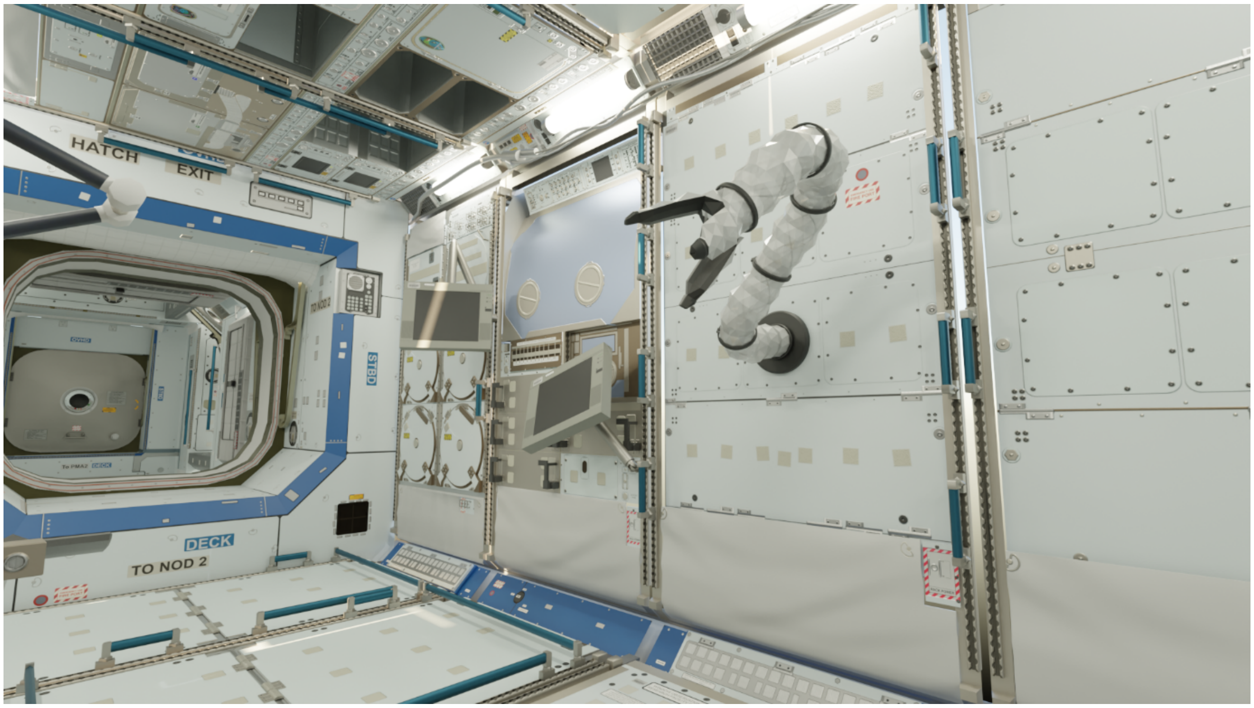

Figure 1: A render of a soft robotic manipulator onboard the ISS (ISS model credit NASA).

Introduction: The exploration of increasingly extreme and isolated environments in space necessitates innovative robotic solutions. Soft robotics offers a promising paradigm, addressing challenges posed by unstructured, high-risk conditions that expose limitations in current rigid robotic methods. A soft robot's ability to deform to its environment enables more compliant interaction with uncertainty, facilitating safer interactions with valuable assets, fundamental to ISRU. The resulting soft contact increases contact time, reducing force and softening interactions. For example, soft contact minimizes damage during grasping of fragile samples or allows for more stable manipulation in unstable environments.

Space resource exploration and extraction, interactions with plant matter (for increased yield), and human-robot interactions in space all benefit from these characteristics. In human-robot collaboration, inherent safety is paramount for future lunar and deep-space missions. One example of this is onboard pressurized space vessels, as shown in Figure 1. Furthermore, interactions with exotic terrain may benefit from novel locomotion methods unique to soft systems. Inspired by underwater invertebrates, soft locomotion leverages buoyancy, enabling movement in environments analogous to the reduced and microgravity of space.

Traditional soft robotic systems face challenges in space, where extreme environmental conditions can cause embrittlement and performance degradation due to material composition, limiting flexibility. Our design methodology prioritizes morphology over material selection, enabling the use of space-compatible materials in place of traditional flexible materials that cannot withstand these conditions. Thermal ranges and cycling are critical considerations, as traditional elastomer properties are limited by temperature, with low temperatures increasing stiffness and high temperatures introducing plastic behavior [2]. Similarly, radiation degrades polymer materials, increasing the chance of mechanical failure [3].

Monolithic and fixed morphology robotics encounter similar issues; modular robotics have been proposed as one such solution to address challenges associated with ISRU [1]. Building on the combination of modular and soft systems, we have developed a modular design methodology for soft systems applicable to a range of different ISRU and space applications.

Design and Prototype Development: We present a summary of our research into soft robotics for space applications, outlining our design methodology and demonstrating prototype soft robotic systems performing simulated scenarios in analogue space conditions.

We have developed:

- Soft robotic platforms for locomotion in lunar and asteroid analogue environments.
- A configurable metallic soft manipulator for diverse space environments: a 1-meter tall system with modular end effectors, integrated force/position/velocity sensing, and an aluminized mylar multi-layer insulation (MLI) skin, shown in Figure 2.
    - Modules include: a gripper with integrated camera and sensing suite, a microspine array for manipulation and locomotion across porous surfaces (e.g., asteroids), and an inspection head with camera and light source.
- A series of scaled metallic soft robotic manipulators for experimentation whilst submerged in liquid nitrogen and in a temperature vacuum chamber.

Figure 2: A soft robotic manipulator designed for extreme space conditions.

Cryogenic Manipulation Experiments: We demonstrate prototype soft robotic systems performing successful precision manipulation and movement in mission analogues for satellite grappling and servicing, and resource examination and extraction, in cryogenic environments (-196°C). A scaled soft robotic manipulator was placed in a 300mm square liquid nitrogen (LN2) bath, along with multiple chess pieces. An operator successfully captured these pieces from various positions demonstrating the systems flexibility and controllability whilst under cryogenic conditions. This task of precise positioning, manipulation, and capture has relevance to space resource utilization. The LN2 bath environment emulates the extreme cryogenic temperatures of celestial bodies such as Europa and permanently shadowed regions (PSRs) on the Moon, as well as asteroids with limited solar visibility. Limitations of this analogue environment include the absence of vacuum and increased drag.

Discussion and Conclusion: Our work demonstrates the potential of soft robotic systems to significantly advance space resource utilization. The successful cryogenic manipulation experiments validate the manipulator's robustness, precision, and controllability in conditions relevant to resource extraction in permanently shadowed regions and on icy bodies. The modular end effectors and morphology-driven design offer a versatile and adaptable solution for a variety of in-situ resource utilization (ISRU) tasks, including sample acquisition, equipment maintenance, and resource processing. This technology enables safer, more robust, and efficient missions, addressing key challenges in future space exploration and resource exploitation efforts.

Our work highlights the transformative potential of soft robotic systems in overcoming current and future challenges in space exploration, enabling safer, more robust and efficient missions.

References: [1] A. S. Howe, B. H. Wilcox, H. Nayar, R. P. Mueller and J. M. Schuler, "Maintenance-optimized Modular Robotic Concepts for Planetary Surface ISRU Excavators," 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1-15, doi: 10.1109/AERO47225.2020.9172688. [2] Robbins, R.F., Weitzel, D.H. and Herring, R.N., 1962. The application and behavior of elastomers at cryogenic temperatures. In Advances in Cryogenic Engineering: Proceedings of the Cryogenic Engineering Conference, Michigan August 15–17, 1961 (pp. 343-352). Springer US. [3] Kerlin, E.E. and Smith, E.T., 1963. Measured Effects of the Various Combinations of Nuclear Radiation, Vacuum, and Cryotemperatures on Engineering Materials (No. NASA-CR-50020).