SOFT ROBOTICS FOR SPACE APPLICATIONS: EMBRACING FLEXIBILITY FOR EXTREME ENVIRONMENTS. W. Foster-Hall[1], D. J. Harvey[1] and R. Akmeliawati[1], [1]william.foster-hall@adelaide.edu.au, School of Electrical and Mechanical Engineering, The University of Adelaide, SA 5005, Australia.

Figure 1: A soft robot exploring an asteroid.

Introduction: To enhance the development of a sustained human presence in space, successful and collaborative human-robot partnerships are essential. We propose that robotic partners with an emphasis on inherent safety may prove instrumental to this goal. Soft robotic design presents promising solutions in the areas of human-robot interaction, operation in unknown environments and novel locomotion methods.

A soft robotic structure can perform safe interactions with high values assets. In a space environment these interactions are plentiful; interactions with human operators, plant life and objects of scientific or archaeological significance. A soft robot's ability to deform or comply to its environment enables these systems to more gracefully deal with uncertainty compared to their rigid counterparts.

This abstract presents practical work towards soft robotic systems that operate in extreme environments present in space. We present a soft robotic design methodology that favors structural morphology over material selection and validation of a soft robotic limb operating in cryogenic conditions.

Environmental Challenges: A soft robotic system depends on the ability to deform to external influences, known as compliance. Soft robots encounter unique challenges where extreme environmental conditions in space can limit the available compliance. This prevents traditional soft robotics constructed from elastomers or resins being used [1]. Harsh environmental conditions such as cryogenic and super-heated temperatures, as well as radiation, all have significant effects on traditional elastomeric materials that soft robots have typically been composed from.

Design Philosophy: Our soft robotic design philosophy prioritizes structural morphology over material selection to achieve compliance with traditionally non-soft materials. This approach overcomes the limitations of traditional soft materials in space environments, such as reductions to flexibility in extreme temperatures and radiation degradation.

We construct metallic robotic prototypes as these materials are already well understood in the context of space environments and can be easily substituted with their space grade counterparts. Furthermore, we embrace a modular philosophy, creating single elements then characterizing and validating their responses to environmental conditions. We construct chains of modules to form limbs and legs for legged robots and arms for manipulator-based systems. A family of soft robotic locomotion platforms was developed using this approach [2]. An example of these systems in a rendered environment can be seen in Figure 1.

Testing Methodologies: Evaluating the performance of robotics in their intended environment is critical. As such evaluation and validation are at the center of our design philosophy. Due to the lack of in-situ testing availability we rely heavily on the use of piecewise environmental testing, and holistic simulations. Simulation for soft systems is challenging compared to their rigid counterparts. Complex non-linear deformations are a mainstay of soft robotic motion, similarly interactions between multiple deformable materials can be complex to understand and model. Using a piecewise approach, we can capture information from real world environmental testing for sets of conditions and use simulation techniques to model cross-coupling behaviors.

Temperature ranges of target environments are replicated using heated furnaces and liquid nitrogen for hot and cold environments respectively. Analogue terrains are constructed in our Extra-Terrestrial Environmental Simulation Lab (Exterres) where locomotion evaluations can be performed in both sand and LHS-1E lunar simulant, shown in Figure 2.

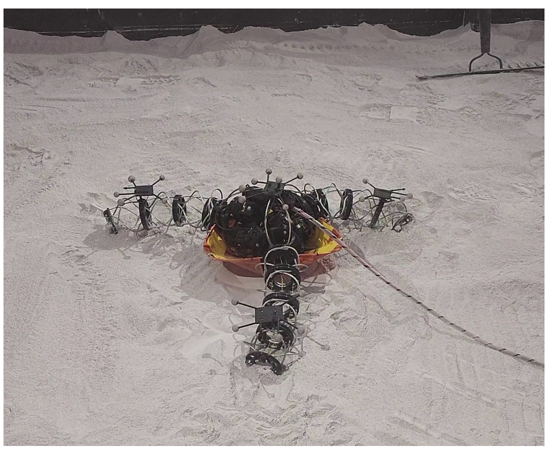

Figure 2: A soft robot locomotion platform in LHS-1E lunar simulant.

Validation: Evaluation of the structural modules in cryogenic and ambient conditions has been conducted. Liquid nitrogen is used to simulate an environment approaching minimum temperatures experienced on the lunar surface [3]. A scaled soft robotic arm, constructed from modules described above, is submerged in liquid nitrogen, and allowed to reach thermal equilibrium with temperature measuring -196°C. The limb is then actuated from an external cable-tendon system and the velocity and range of motion is recorded from a camera tracking system. Our findings indicate that the modules retain their flexibility, and show the scaled soft robotic limb operate successfully in both ambient and cryogenic environments.

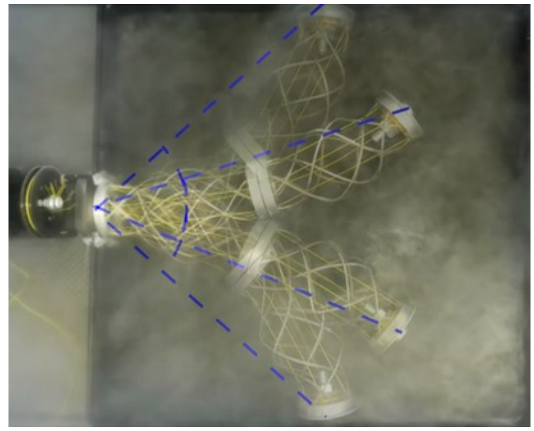

Figure 3: A soft robotic limb operating while submerged in liquid nitrogen. The range of motion is highlighted in blue.

Conclusions: Soft robotics presents a promising solution for inherent safety in collaborative domains present in space environments. Experimental trials have validated that our soft robotic structures maintain flexibility and operation at cryogenic temperatures, an important step for soft robotics for extreme environments.

References: [1] Y. Zhang, P. Li, J. Quan, L. Li, G. Zhang, and D. Zhou, "Progress, challenges, and prospects of soft robotics for space applications," Advanced Intelligent Systems, vol. 5, no. 3, p. 2200071, 2023. [2] W. Foster-Hall, D. J. Harvey, and R. Akmeliawati, "Soft Robotics for Space Applications: Towards a Family of Locomotion Platforms" 7th IEEE-RAS International Conference on Soft Robotics (ROBOSOFT 2024). (2024). [3] J.-P. Williams, et al. (2019). Seasonal polar temperatures on the Moon. Journal of Geophysical Research: Planets, 124, 2505–2521. https://doi.org/10.1029/2019JE006028