A Soft Robotics Concept for Assistance in Space

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I. INTRODUCTION

In the confined environment of a space station, efficient utilization of available space is crucial. Traditional rigid robots, while effective in certain applications, can become obstacles themselves, limiting their utility in such restricted spaces. This paper proposes a novel solution: a soft robot capable of adapting its form to the task. Our hypothesis is that a soft robot, which can morph its shape as needed, will provide significant advantages in maneuvering within the tight quarters of a space station. The inherent flexibility and adaptability of soft robots enable them to navigate around obstacles and operate without becoming obstructions themselves. This paper explores the design and applications of a soft robot for intra-vehicular use, focusing on cargo handling within space stations. We aim to highlight how soft robots can revolutionize space station operations, as shown in Fig. 1.

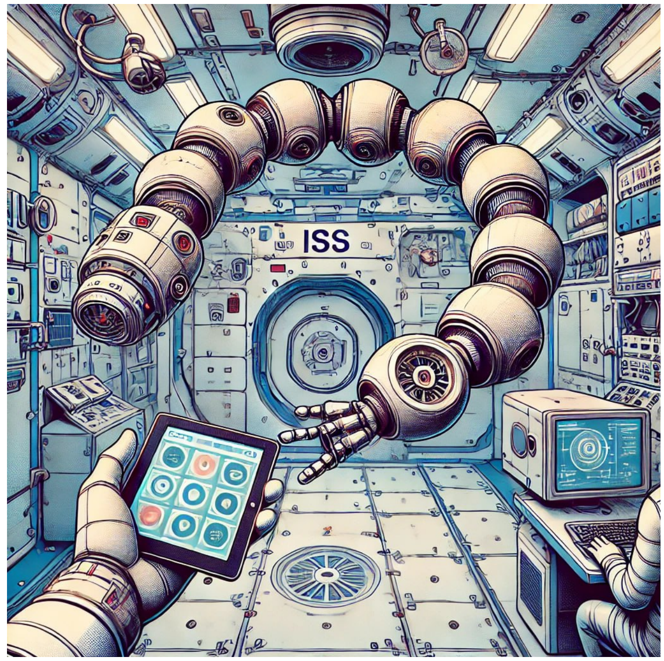

Fig. 1: Simulation of a soft robot inside a space station, generated using ChatGPT-4o.

II. RELATED WORK

In the past several designs of soft robots have been proposed. Soft robots offer enhanced dexterity, adaptability, and robustness compared to rigid counterparts, crucial for space applications. In accordance to [1], soft robots can be categorized into continuum soft robots and articulated soft robots. We describe a design concept for continuum soft robots. Examples of soft robots in this category include an earthworm-like robot that creates peristaltic motion with a continuously deformable exterior [2], a textile origami soft robot imitating the non-wavy movement of snakes [3], and a worm-like soft robot with a multi-movement mode enabled by pneumatic actuators [4].

Several distinct design concepts for soft robots have been proposed. A comprehensive review of the current state of the art in the design and optimization of soft robots provides a broad overview of design variables and respective example solutions, but it does not address considerations regarding space applications [5]. One design framework introduces environment-specific behavior for fluid-actuated soft robots, but it is unsuitable for microgravity environments due to the different behavior of fluids in such conditions [6]. In another study, the use of pneumatic and magnetic actuation and biocompatible materials is proposed, but these cannot be used on space stations due to limitations of materials suitable for use in space [7]. There is one dedicated study that analyzes the advantages and constraints of soft robots for application in space [8]. However, this study does not take space environment conditions into account.

III. DESIGN CRITERIA FOR SOFT-ROBOTS IN SPACE

While the literature on design considerations has laid the groundwork for soft robots, there is no approach available with an application in microgravity in mind. This section derives a design concept for a soft robot based on space station tasks and microgravity's impact on material, geometry, actuation, and docking interfaces.

A. *Tasks on the ISS*

Table I highlights the comparison between tasks performed by astronauts on a space station and the potential for these tasks to be executed by either rigid or soft robots. Cleaning tasks refer to the cleaning of different assets such as filters, hand rails, and communication interfaces. Organizing tasks refer to the organization of the entire space station, including personal belongings. The main advantage of a soft robot compared to rigid robots is their ability to access tight spaces, potentially even ventilation systems, which makes it the robot of choice for inspection and repair. The ability of soft robots to adapt to the curvature of Cargo Transfer Bags (CTBs) make them an optimal choice for the cargo handling considering the limited accessibility of the transport vessels.

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Task	Astronaut	Rigid Robot	Soft Robot
Cleaning	●	●	●
Organizing	●	●	●
Experimentation	●	◐	◑
Inspections	●	◐	●
Repairing	●	◐	◑
Cargo transport	●	◐	●

TABLE I: Tasks performed by an astronaut and tasks for a soft robot, ●: capable, ◐: partially capable, ◑: capable.

B. *Design Concept*

To develop a design concept, the following design variables for a space station environment have to be covered: actuation, geometry, material and maintenance.

1) Geometry: The geometry considerations are based on Table I to specifically enable the soft robot to assist in conducting experiments and repairing tasks, performing inspections and cargo handling. We suggest a soft robot design that allows the robot to function as a gripper by itself, depending on the shape it forms. Most critically, cargo handling was identified as a significant challenge for robots on future uncrewed space stations [9], where CTBs need to be transferred from a visiting space craft into the cargo bay. CTBs come in various sizes to accommodate diverse hardware, effectively utilizing available volume and mass across different vessels [10]. A "1.0 CTB" is approximately the size of 50 cm x 42 cm x 25 cm [11]. Thus, the soft robot should be at least 120 cm long and have three links to enclose three sides of the CTB.

2) Actuaction: Actuators play a crucial role in shaping, exerting force, and directing movement in soft robots. For use inside a space station, it is not advisable to use Dielectric Elastomer Actuators (DEAs) due to their reliance on high external voltages [5]. Magnetically responsive materials should be avoided because of the potential magnetic interference with sensitive electronic systems [5]. Similarly, Soft Pneumatic Bending Actuators (SPBAs) are unsuitable as they require fluid control, which behaves unpredictably in microgravity [5]. Instead, we propose utilizing a cable-driven actuation system as presented in [12]. Cable-driven actuators function by controlling the movement of the soft body through the retraction of cables integrated into the structure and secured at specific points. This technique does not interfere with the equipment of the space station and it is not sensitive to microgravity.

3) Material: To select the appropriate material, the following factors have to be considered:

Microgravity Adaptation: The material must maintain its mechanical integrity and functionality in a microgravity environment.

Thermal Stability: The material must withstand the temperature fluctuations typical in space which can vary from 121 °C to -157 °C outside and 19 °C to 27 °C inside. Since we limit our soft robot design to be applicable only inside the ISS, we do not expect thermal stability as a characteristic for our material.

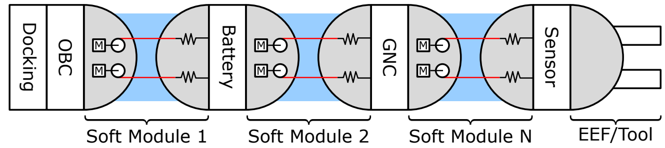

Fig. 2: Modular Soft-Robotics-Concept.

Radiation Resistance: High-energy particles can ionize atoms in the material, leading to the formation of free radicals, which can break chemical bonds and degrade the material's properties.

Based on these factors, it is recommended to use an ultra-low-outgassing silicone to minimize contamination, as it has been approved for microgravity environments and demonstrates radiation resistance [13]. Another desirable factor is the capability of the surface to act antibacterial considering the interaction of the robot with humans and experiments for both the rigid parts of the housing [14], as well as the soft housing components [15]. However, the suitability for these materials in space remains an open research question. As for the tendons, steel and Vectran suffer from increased wear for small radii such that Dyneema or Zylon fiber where identified as most suitable for application under space conditions for their resistance to radiation even in vacuum [16].

4) Maintenance: Easy maintenance is crucial for space robots, as it is evident from the complete hardware failure of Robonaut 2 during an upgrade on the ISS [17]. To enhance maintainability and upgradability, we propose a modular soft robotics concept [18], as shown in Fig. 2. Our concept builds on standardized soft actuation modules comprising two half-spheres connected by a cable-driven actuation system (red) covered by a soft silicone hull (blue). These modules can be mechanically linked, allowing for energy and data transfer. Additional components, such as an Onboard Computer (OBC), a Guidance, Navigation and Control module (GNC), batteries, and various sensors, can be connected in-between. The two ends can accommodate a docking interface or different tools and End Effectors (EEFs).

IV. CONCLUSION AND OUTLOOK

With a crewed mission time of 30 days only, the operation of the lunar gateway sets critical demands for the use of intra-vehicular robots [19]. Initial investigations into tasks performed by astronauts indicate that soft robots offer significant advantages, particularly in managing housekeeping duties. Furthermore, soft robots excel in tasks requiring access to hard-to-reach areas. Based on our initial assessments of geometry, actuation, materials, and maintenance, it is evident that the requisite technologies for developing space-grade soft robots are available and ready for exploitation.

Our next steps include the design and implementation of a ground demonstrator to verify our design approach. Eventually, we aim for deployment of our soft robot on the ISS in order to demonstrate the technology readiness for future application on the lunar gateway.

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ChatGPT-4o was used to polish wording and generate figures where indicated.

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