A Rigid-Soft End-Effector Mechanism for Microgravity Free-Flying Manipulation

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***Abstract*—Compliant robotic mechanisms offer a novel approach to grasping complex geometries through contact-rich manipulation. In extreme uncertain environments such as space, a contact-rich compliant grasp could offer a mechanism for robust manipulation under conditions such as microgravity. This article presents the design and fabrication of an rigid-soft end-effector mechanism prototype for conforming manipulation. The end-effector is a prototype of the three-finger underactuated tendon-driven gripper with rigid claw-shaped joints and inflatable compliant fabricated padding surrounding the grasping region. These pads can be pneumatically inflated to conform around an object within the gripper's claw-like grasp. This rigid-soft mechanism could allow for increased surface area and contact-rich manipulation with less reliance on actuating the gripper's motors. This article presents the design, mechanism, and material selection of the gripper. This prototype could be attached to an intra-vehicular free-flying robot like Astrobee to perform a variety of free-flying manipulation tasks in space.**

***Index Terms*—Rigid-soft mechanism, gripper prototype, microgravity manipulation, uncertain environments, free-flying robots**

I. Introduction

Manipulation in uncertain extreme environments, such as space, could open new opportunities for robotic exploration and operation [1]–[3]. As operations in on-orbit space stations increase, novel mechanisms for grasping in microgravity could enable the automation of tasks such as logistics management and habitat maintenance leveraging free-flying robots [4]–[7]. Free-flying robots have been operating on the International Space Station (ISS) since 2006, and have been filling in gaps in robotic capabilities through perception, locomotion, and manipulation [8]–[10]. The Astrobee free-flying robot is one such example. Astrobee has been used for intra-vehicular activities (IVA), such as perching onto ISS handrails, anchoring onto walls using gecko-adhesion grip, and ISS cargo transfer bag (CTB) transport [11]–[14]. As new on-orbit habitats are flown to low-Earth Orbit (LEO), lunar orbit, and beyond, these free-flyer-enabled robotic manipulation capabilities will become ever more integral to on-orbit operations [15].

Examples of such free-flying manipulation capabilities could include grasping a screwdriver for a subsystem maintenance task, such as screwing a bolt into an ISS payload. The lack of gravity on station would increase uncertainty in manipulation tasks with regards to surface area contact, robust grasp on the object, and control [16], [17]. This level of complexity for future space stations would require novel mechanisms to ensure robustness with limited power supply, temperature concerns, and crew safety constraints [18], [19].

Soft robotic manipulation mechanisms have been identified as a promising alternative to traditional designs for on-orbit missions [20]. The compliant materials would allow for pnuematic inflation and flexible surface area contact-rich grasp, two key attributes needed for manipulation in future space stations [21]. This article presents the design, mechanism, materials selection, and simulation of a novel rigid-soft gripper mechanism for use on a free-flying robot like Astrobee in an on-orbit space station. This article also outlines preliminary testing of the gripper at the Granite Lab at NASA Ames Research Center, as seen in Fig. 1.

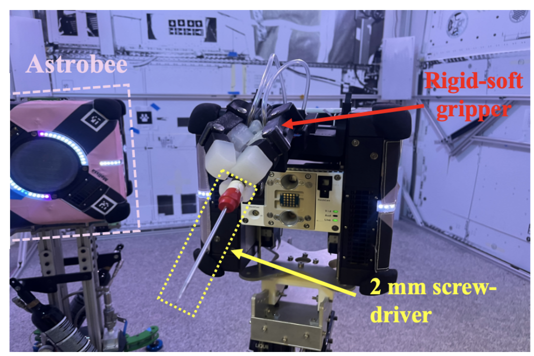

Fig. 1. Rigid-soft gripper prototype attached to Astrobee grasping a screwdriver in the NASA Ames Granite Lab.

II. Related Works

Soft robotic grippers that use pneumatic actuation have been developed to conform to complex geometries on Earth [20], [22]. Their compliant materials allow for adaptive deformation and non-traditional designs compared to rigid grippers [23]. However, fully soft grippers have limitations in the necessary air volume required and complexity to control their dynamics [24]. Furthermore, underactuated tendon-driven grippers, such as anthropomorphic end-effectors, achieve robust and adaptive grasping with reduced actuation [25], [26]. These grippers use passive elastic joints and a single-motor tendon to create human-like manipulation trajectories. While effective on Earth,

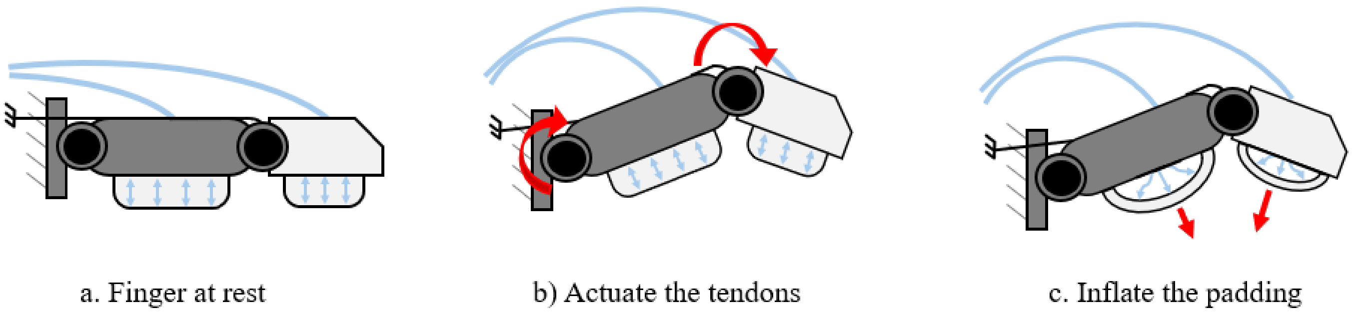

Fig. 2. States for the rigid-soft mechanism. a) the finger at rest with no inflation, b) actuation by pulling on the tendon, c) inflate the padding pneumatically.

their multi-finger complexity and reliance on rigid phalange geometry make them challenging to integrate within the free-flying robots given tight payloads, power constraints, and microgravity effects [27], [28]. Hybrid manipulation mechanisms that combine rigid components with soft actuation have also been proposed to increase manipulation performance without sacrificing compliance [29].

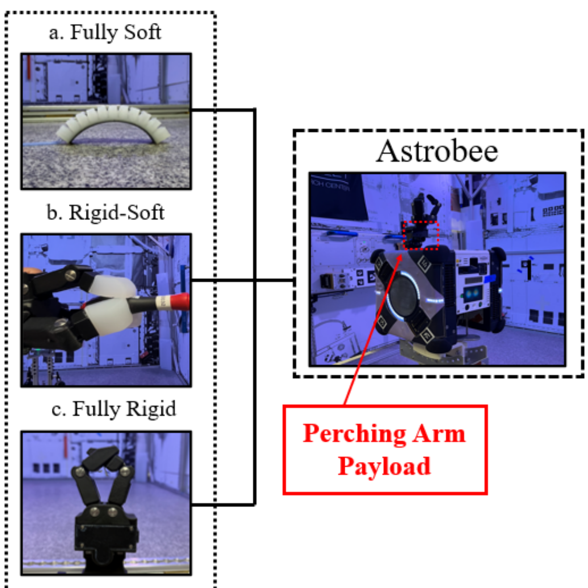

Fig. 3. Systems diagram showcasing the different gripper types: fully soft, rigid-soft, and fully rigid and how they integrate with Astrobee's perching arm payload.

Grippers used for microgravity manipulation including those previously flown on Astrobee and Robonaut, rely primarily on rigid linkages and parallel-jaw mechanisms with limited ability to conform to objects beyond basic geometries [28], [30], [31]. While sufficient for tools performing ”pick and place” and perching tasks, these hardware designs lack in contact-rich grasp with complex geometry items or soft-bodied objects such as ISS CTBs [5], [14]. A design that offers a compact, underactuated gripper capable of dynamically conforming around a complex geometry using inflatable materials could enable more robotic manipulation in space.

This article's gripper takes a hybrid rigid-soft approach by introducing a rigid-claw design with inflatable soft pads for pneumatic inflation. As seen in Fig. 3, the rigid-soft is a different approach to gripper designs from full soft and rigid designs. This design minimizes actuation effort while increasing surface contact area and adaptability. It is stowable to a payload of small volumes, compliant, and could be integrated directly into Astrobee's arm, offering a low-power and low-complexity robotic solution to fully rigid or soft grippers.

III. Mechanism

The gripper grasps an object using a pneumatic mechanism with custom inflatable pads that can be inflated at the distal, proximal, and palm joints. When inflated, these pads conform to irregular surface geometries, distributing contact forces more uniformly and enabling stable, contact-rich manipulation of geometries like a screwdriver. Fig 2 highlights the high-level mechanism of the gripper in three different states showing the actuation and pressure changes inside the inflatable padding. The inflatable padding at each joint is created using a custom design casting mold for fabricating using conformant material.

These molds are 3-D printed using computer aided design (CAD) to match the shape of the gripper's interior fingers and allow the pads to fit inside the grasp. Once cured, the pads are cured into the gripper's fingers and connected with a pneumatic system pipes for inflation. The complete gripper payload is designed to fit into a standard 1U Astrobee payload ($10 \times 10 \times 10$ cm). The gripper has a 1-Degree-of-Freedom (DOF) motion and is driven by a single motor using tendon actuation at the wrist joint of the Astrobee perching arm. Torsional springs are installed at each pivot joint for assisting in passive finger closure. The gripper is tested at NASA Ames' Granite Lab while attached to Astrobee to demonstrate stable grasping and adaptability to irregular objects in a 3-DOF microgravity environment on the granite table. Fig. 1 shows the rigid-soft gripper attached to Astrobee holding a screwdriver free-flying on the granite table in the Granite Lab at NASA Ames.

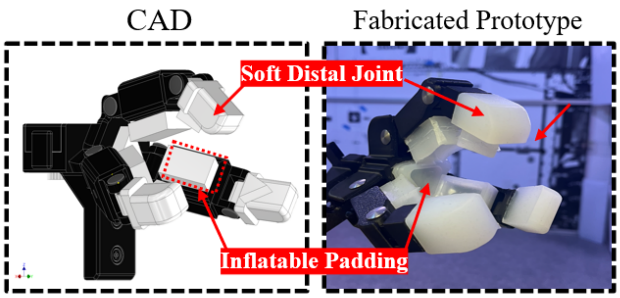

Fig. 4. Fabricated rigid-soft gripper prototype next to its CAD model with labeled soft joints and inflatable padding areas.

IV. Material Selection

Soft robotics uses a variety of elastomers that could be suitable for space applications given its robustness and actuation capabilities [21], [32]. A survey of this material and other commonly used components in soft robotics highlights the potential of siloxane gels, silicone elastomers (Ecoflex 00-30), fluoroelastomers (Viton FKM), thermoplastic polyurethanes (TPU), and reinforced polyetheretherketones (PEEK) in particular. A summary of the main characteristics of these five materials that make them viable for pad fabrication can be seen in Table I.

Although other materials could serve as viable selections, based on the air tightness, flexibility, durability, and wide use in traditional soft robotics, Ecoflex 00-30 is the conforming material used for this prototype. Ecoflex 00-30 is poured into the custom made inflatable pad molding and allowed to cure into the proper shape for each joint. For future prototypes, especially flight hardware, other material such as TPU-fabric may be more optimal but require more advanced fabrication.

TABLE I
Materials for conforming inflatable pads

Material	*E (MPa)*	*SR*	Details
Siloxane Gel	0.01	Low	Ultra-soft with a decrease in durability in a vacuum
Ecoflex 00-30	**0.125**	**Med**	**High flexibility, but needing a low-outgassing grade**
Viton FKM	7.0	High	Chemically resistant due to space seals
TPU-Fabric	5–20	High	State-of-the-art for inflatable aerospace structures
Reinf. PEEK	60–100	High	Strong and space radiation-tolerant

[a]E: Elastic modulus. [b]SR: Space readiness *(Low/Med/High)*.

V. Conclusion & Future Work

The rigid-soft gripper prototype including the custom inflatable pads and rigid joints have been fabricated and assembled into a working prototype. The inflatable mechanism has been tested at NASA Ames' Granite Lab testing facility with the ground-Astrobee testing units. This article presents the design, mechanism, and materials of a rigid-soft gripper prototype for a free-flying robot. Equipped into Astrobee, this gripper would allow for contact-rich grasp at reduced actuation required. For future work, we intend to develop a more high fidelity and passive mechanism and equip the gripper with force sensors for feedback. This feedback will allow for more design optimizations and performance studies with other objects of interest, like CTBs.

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