Toward Inflatable Soft Robotic Arms for Space Debris Capture: A Preliminary Study

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***Abstract*—This paper presents research on the design and development of an inflatable soft robotic arm system intended for capturing non-cooperative space debris. Drawing on concepts from ground-based inflatable actuator technologies, the project investigates how these principles might be adapted to the context of Active Debris Removal (ADR) missions. Design considerations, early fabrication, and preliminary testing are discussed. If successful, this approach could contribute to motor-free robotics in space, eliminating the need for radiation-hardened motors and complex electronics—offering a transformative step toward simpler, scalable systems. This work combines simulation and physical prototyping to begin assessing the feasibility and performance of inflatable soft robotic arms in orbital scenarios, with the aim of informing the development of future prototypes for active debris removal.**

I. Introduction

Space debris poses a critical threat to active and future satellite missions. Over 30,000 trackable objects remain in orbit, with millions of smaller fragments undetectable to current systems yet still capable of catastrophic impact. Active Debris Removal (ADR) technologies have become essential to mitigate these risks and preserve the usability of Low Earth Orbit (LEO) [1].

Space debris mitigation strategies can broadly be classified into two categories: passive and active methods [2]. Passive methods focus on reducing the risk of debris creation by equipping spacecraft with end-of-life disposal technologies, such as drag sails. In contrast, ADR involves deploying a second spacecraft to physically engage, capture, and remove existing debris—particularly in high-risk regions like LEO and geostationary orbit (GEO). These active systems are essential to prevent further collisions and the exponential growth of debris through fragmentation.

ADR techniques also differ based on the nature of the target. Cooperative targets include objects designed with docking features or communication systems, which simplify removal. Non-cooperative targets, such as defunct satellites and rocket bodies, present greater challenges due to their tumbling motion, irregular shapes, or lack of rendezvous aids [3]. This paper focuses specifically on robotic systems intended for capturing non-cooperative debris.

While rigid robotic systems have been deployed in orbital servicing missions, their complexity, fragility, and high-cost limit their broader adoption. In contrast, soft robotic systems — particularly inflatable architectures — offer compliant, lightweight alternatives that can absorb impact energy and reduce the chance of fragment generation. Their deployability and potential reusability make them highly attractive for multi-target ADR scenarios [4].

Inflatable soft robots have already demonstrated promise in a variety of terrestrial applications, including confined-space navigation, wearable assistance, and disaster response [5], [6]. However, their potential in orbital settings remains largely unexplored.

Despite advances in soft robotics, few systems have been explicitly designed for orbital debris capture. Zhang et al. reviewed the potential of soft robots in space, identifying major technical challenges such as temperature extremes, radiation exposure, and vacuum-induced material degradation [4]. Addressing these challenges may require designs that incorporate passive adaptability, reliable deployment mechanisms, and resilience to environmental stressors—characteristics that inflatable, fabric-based structures could potentially offer in ADR scenarios.

This paper investigates the potential of inflatable fabric-based robotic arms for ADR. A prototype design is introduced alongside the motivations behind its development. The current stage of this work focuses primarily on the conceptual design, early prototyping, and identification of simulation strategies for future validation.

The remainder of the paper reviews relevant literature on inflatable soft robotics and their potential for orbital applications (Section II), presents the design and initial testing of the proposed prototype (Section III), outlines key research questions and simulation strategies (Section IV), and concludes with directions for future work (Section V).

II. Related Work

The development of inflatable soft robotic systems draws on a wide range of research spanning material architectures, actuation methods, modelling frameworks, and experimental validation methods. This section reviews key advances grouped into three categories: (A) inflatable arm architectures and actuation strategies, (B) modelling and control tools, and (C) developments related to space applications.

A. Inflatable Robotic Arm Architectures

Efforts to develop inflatable arms for soft robotics have explored a variety of actuation mechanisms and structural layouts, often emphasising simplicity, compliance, and low weight. A common goal across these works is to reduce mechanical complexity while enabling safe interaction with humans or fragile environments. Approaches include eversion-based actuators, modular chamber designs, and antagonistic pneumatic systems using TPU-coated fabrics [5], [7]–[9].

One strategy relies on eversion-based actuation, where the robot inverts its body like a sock turning inside out. These systems rely on non-stretchable fabric and internal pressure modulation to achieve linear extension and adjustable stiffness [5]. While limited in degrees of freedom, such robots demonstrate effective morphing and model-based control. Follow-up studies introduced observer-based feedback schemes to improve pose estimation and performance [10].

More recent work has focused on simplified, modular designs. Some systems segment inflatable arms into bidirectional chambers for low-cost planar bending [8], while others use coupled inflatable tubes in configurable topologies to prioritise scalability and durability over repeated actuation cycles [9]. These architectures enable distributed motion control but typically lack autonomy and are not designed with the constraints of space environments in mind.

B. Modelling and Control of Inflatable Systems

The modelling and control of soft inflatable systems remain major challenges, particularly for tasks requiring precision, adaptability, or operation in uncertain environments. As inflatable robots are governed by nonlinear material properties and internal pressure dynamics, their behaviour can be difficult to predict and control without specialised simulation tools.

Comparative studies have explored control strategies for inflatable systems using different modelling paradigms. One notable example is a fully inflatable humanoid platform implemented this architecture and subsequently served as a testbed for comparing control strategies based on pseudo-rigid-body (PRB) models and continuum formulations [7], [11]. PRB models approximate soft systems using rigid segments and torsional springs, whereas continuum models represent curvature as a continuous function of pressure and elasticity. These comparisons highlighted trade-offs in model accuracy, responsiveness, and computational efficiency.

Several modelling approaches have been proposed to approximate the behaviour of soft robotic arms. Finite element analysis (FEA) offers high accuracy but can be computationally intensive for dynamic simulations. More tractable alternatives include beam-based models, modal approximations, and piecewise constant curvature assumptions, each with trade-offs in fidelity, speed, and generalisability [12], [13]. Although most of these methods were originally developed for continuum robots, their principles can be extended to simulate inflatable arms, particularly those with hinge-like geometries or modular segments.

To support early-stage design and testing, open-source simulation frameworks such as SOFA (Simulation Open Framework Architecture) provide a modular environment for simulating soft bodies [14]. These tools allow users to define pressure-driven actuation, textile or elastomeric materials, and environmental interactions—making them suitable for prototyping inflatable systems under variable conditions.

In parallel, control-oriented models have been explored to improve the responsiveness and predictability of inflatable actuators. Variable-stiffness structures, for example, have been modelled using pressure dynamics and geometric constraints, enabling more accurate control without relying on rigid joints [5]. Observer-based methods have also been used to estimate internal state variables in systems where direct sensing is limited [10].

C. Toward Space Applications

Despite advances in modelling and control, the application of these strategies to inflatable robots in space environments remains limited. Orbital conditions introduce unique factors—such as microgravity, extreme temperatures, radiation exposure, and interaction with rotating targets—that require novel design and simulation approaches tailored to deployment in such settings [4].

While inflatable soft robots have shown potential in terrestrial settings, very few systems have been developed with the specific demands of orbital debris removal in mind. Among the exceptions is a recent robotic arm design that integrates inflatable links with traditional electric motors to reduce launch mass and volume while preserving conventional control architectures [15].

This hybrid system achieves joint-level actuation using embedded motors housed within inflatable structural elements. Experimental evaluation demonstrated the ability to support payloads of up to 2 kg in terrestrial gravity conditions at 30 kPa inflation pressure, and generate torques up to 21.8 Nm at 50 kPa. In addition, the deployable structure occupies only 20% of its deployed volume, making the system well-suited for compact stowage during launch.

However, despite these advances, the system retains mechanical complexity through its use of motors and rigid-body control. In contrast, the system presented in this paper explores a fully inflatable alternative, where both the structure and the actuation mechanism are realised using pneumatic pressure alone. This design choice eliminates the need for motors or rigid links, resulting in a system with lower mechanical complexity and potentially higher resilience to impact or misalignment. It also introduces new challenges in modelling and control, particularly for tasks involving interaction with non-cooperative targets in uncertain orbital environments.

To the best of our knowledge, no existing platform combines inflatable fabric actuators, origami-inspired hinge geometries, and pressure-based deformation for autonomous orbital debris capture. The proposed system contributes to this emerging area by integrating design, control, and simulation strategies tailored for scalable ADR missions.

III. Prototype Design and Preliminary Studies

The current prototype consists of a TPU-coated ripstop nylon sleeve, thermally sealed to create three independently actuated segments. Each segment is separated by diamond-shaped hinges that encourage bending in desired directions, inspired by the Aeromorph patterning method [16]. The hinge geometry and segment length were designed based on scaling studies from previous debris capture missions, such as CleanSpace One [17], while actuation pressure ranges were chosen based on previous lab testing of similar fabric-based actuators [18].

As shown in Fig. 1, the current configuration uses two arms fabricated to create a claw-like structure designed to envelop debris rather than grasp it rigidly. Actuation is achieved using an SMC ITV electro-pneumatic regulator and an Arduino control loop. The setup enables precise control of internal pressure, allowing segment-wise bending based on applied input.

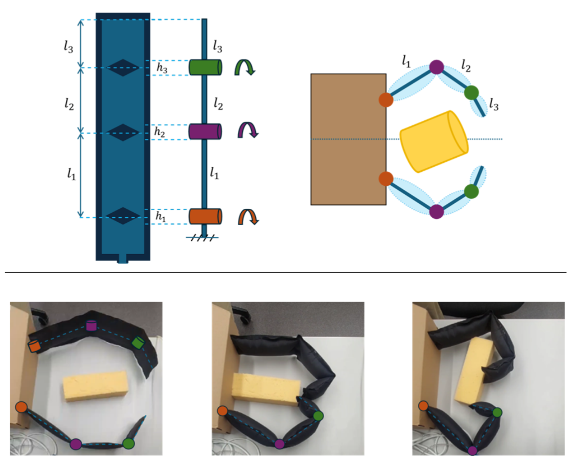

Fig. 1. Top: Conceptual design and actuation layout of the inflatable soft robotic arm using modular, diamond-sealed TPU segments. Ground-based demonstration of two actuated arms enveloping a lightweight target using coordinated inflation.

Preliminary tests showed consistent actuation and initial contact with lightweight target objects in ground-based experiments. The heat-sealed construction appeared to prevent noticeable leakage and maintained structural integrity during a limited number of inflation cycles.

IV. Research Questions and Simulation Roadmap

This work is guided by the following research questions, some of which are only partially addressed in this preliminary study. Questions related to design feasibility and the formulation of simulation strategies are explored, while issues such as scalability and long-term control remain directions for future work:

- **Q1: Can an inflatable arm with tunable stiffness reliably capture space debris?**
  This question explores the feasibility of using embedded pressure sensing and feedback control to achieve tunable stiffness during interaction. Such capability could support safer and more adaptive grasping of irregular, non-cooperative targets. While not yet implemented, this functionality is considered in the conceptual design of the current prototype.
- **Q2: How can simulations model soft arms in orbital conditions?**
  Simulating soft robotic systems is a growing area of research that involves complex interactions between structural deformation, pressure dynamics, and contact with external environments. Key topics of interest include computational efficiency, material fidelity, and the integration of actuation models for accurate motion prediction.
  This project proposes a hybrid simulation approach. Analytical beam models allow for rapid design iteration in early stages, while the SOFA framework enables detailed simulation of material deformation, pressure distribution, and interaction forces. These tools are intended to complement one another across different phases of the design process, as illustrated in the simulation setup shown in Fig. 2.
  In addition, the use of TMTDyn is being explored for future work. TMTDyn is a MATLAB-based simulation library for modelling hybrid rigid–continuum systems using discretised, lumped-parameter dynamics. It supports reduced-order modelling and symbolic equation generation, making it particularly suitable for soft robots where computational efficiency is critical. Compared to frameworks like SOFA, which prioritise material-level fidelity, TMTDyn enables multibody simulations and controller-friendly modelling pipelines. Its integration with symbolic dynamics and dynamic control makes it a promising candidate for later-stage evaluation of the system's orbital behaviour [19].

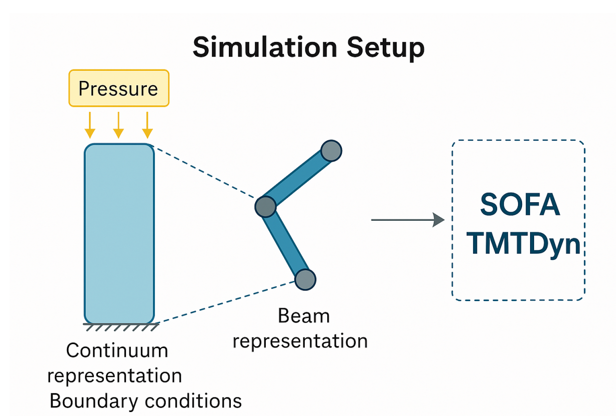

Fig. 2. Conceptual simulation setup illustrating the continuum and beam-based representations used to model inflatable soft arms under internal pressure and boundary conditions. Both SOFA and TMTDyn are considered for simulating deformation and dynamics.

- **Q3: What architectural adjustments are needed for scalability?**
  Future design iterations will investigate origami-inspired structures and spiral or webbed linkages between seg-

ments. These adaptations aim to increase surface coverage and passive adaptability across a wider range of debris profiles. This question is beyond the scope of the current prototype and is reserved for future exploration.

V. Conclusion and Future Work

This paper outlined the early development of an inflatable soft robotic arm for space debris capture. A lab-scale prototype was constructed using heat-sealed TPU-coated fabric and tested under ground-based conditions. Initial experiments demonstrated reliable actuation and deformation, providing a foundation for further refinement and evaluation.

Planned directions for future work include:

- Implementing antagonistic actuation schemes to enable bidirectional control and tunable stiffness.
- Conducting simulation studies to evaluate hinge layout, inflation dynamics, and deformation using high-fidelity tools such as SOFA [14].
- Investigating the use of reduced-order models, including potential integration with TMTDyn [19], to support dynamic analysis and controller development.
- Exploring origami-based and spiral-joint geometries to enhance compliance, adaptability, and compact stowage.
- Assessing tendon-driven actuation as a complementary approach to improve precision while maintaining flexibility.

This research contributes to the development of soft robotic solutions that are scalable, reusable, and well-suited for active debris removal missions in orbital environments.

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