Woven-based Compliant Soft Gripper for Space Debris Removal Missions

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Abstract— **The rapid expansion of satellite networks in Low Earth Orbit (LEO) has intensified the risk of orbital collisions, making Active Debris Removal (ADR) a critical priority for space sustainability. This study introduces a compliant soft robotic gripper utilizing a dynamic weaving mechanism designed for the effective capture of uncooperative, free-floating objects. By adapting the principles of weaving interlocking, the proposed system achieves high stowage efficiency and a simplified deployment sequence through a single-actuator drive. A kirigami-inspired design is integrated to ensure the full reversibility of the grasping motion, allowing the structure to reliably encapsulate various targets without complex sensory feedback. Given the inherent mechanical stability and scalability of this woven architecture, the gripper provides a versatile and high-strength solution for the reliable execution of ADR missions. Notably, this gripper technology is scheduled for deployment in South Korea's upcoming ADR mission in 2027, marking a significant milestone in the practical application of soft robotics for orbital debris remediation.**

I. Introduction

The paradigm of space utilization has undergone a substantial shift with the advent of the New Space era [1]. In particular, the emergence of mega-constellations, such as SpaceX's Starlink and Amazon's Project Kuiper, which have dramatically intensified the spatial density of objects in Low Earth Orbit (LEO) [2]. According to recent reports from the European Space Agency, the number of operational satellites has more than tripled in the last five years, a trend that continues to accelerate as thousands of new units are deployed annually [3]. While these satellite networks enhance global connectivity, they also pose escalating challenges to orbital safety by significantly increasing the spatial density within popular orbital shells.

As the spatial density in LEO increases, the risk of orbital collisions rises proportionally, raising critical concerns regarding the Kessler Syndrome [4]. This phenomenon describes a self-sustaining cascade of fragmentations that could render specific orbital shells unusable for future missions. Current data suggests that even hypervelocity impacts from small debris can cause catastrophic failures in active spacecraft, further complicating the orbital environment [5]. These challenges necessitate a transition from passive mitigation measures to Active Debris Removal (ADR) strategies. ADR is now regarded as an essential mission for ensuring the long-term sustainability of space activities [6, 7]. To successfully execute these missions, however, advanced capture mechanisms are required to secure uncooperative, tumbling, or irregularly shaped targets without generating secondary debris. Conventional rigid docking systems often lack the adaptability required for such complex targets, highlighting the need for innovative solutions like soft grippers that can accommodate unpredictable geometries during the capture sequence [8].

To address these requirements, this study proposes a woven-based compliant soft robotic gripper [9] for the active removal of space debris. Aligned with South Korea's first ADR mission scheduled for 2027, this study focuses on providing a practical grasping interface designed to capture uncooperative space debris. By reconfiguring the fundamental principles of weaving, a flexible continuum structure was designed to instantaneously deploy and retract an enclosed workspace while maintaining high mechanical stability. Conceptually, weaving refers to the formation of a continuous surface from discrete elements, such as threads. The mechanical interlocking of weft and warp yarns, although composed of individual segments, provides structural integrity through continuous entanglement. The proposed gripper design leverages these core aspects of woven structures by utilizing multiple closed-loop strips to achieve a stable yet adaptable form.

A primary challenge in applying weaving principles to grasping mechanisms is ensuring the reversibility of the structure's opening and closing motions. To achieve this, a kirigami-inspired approach was integrated into the design. Kirigami enables the programming of continuum body motions and enhanced flexibility through strategic cuts in thin-film materials [10-12]. By applying this technique to the overall architecture, a dynamic weaving motion is generated, allowing the gripper to reliably encapsulate target objects. Due to the inherent mechanical stability induced by the woven geometry, the payload capacity of the material is fully utilized, effectively preventing grasping failures within the material's structural strength limits.

II. Woven-based Mechanism

The proposed gripper architecture utilizes the geometric interlocking of woven structures to achieve both flexibility and high load-bearing capacity. As shown in Figs. 1a and 1b, the design consists of multiple strips that function as warp and

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weft yarns, arranged to intersect along the z-axis with alternating vertical displacements. This specific configuration ensures that once the strips converge, they form a rigid, continuous surface through mutual mechanical constraint.

The woven gripper implements reversibility in its opening and closing states through relative rotational motion. In the schematic of the woven structure, horizontal strips represent the weft yarns while vertical strips correspond to the warp yarns. By sequentially connecting the ends of each strip to a dual-plate system, multiple closed loops are formed where the lines interlock with one another, as visualized in the Open state (Fig. 1c) and Closed state (Fig. 1d). This configuration significantly enhances the structural stiffness of the system during the grasping phase.

The fundamental driving mechanism behind this transition is illustrated in Fig. 1e using a single closed-loop strip. The shape transformation is driven by the relative rotation between the inner and outer parallel plates. By applying this logic to the overall architecture, the motor's rotational angle and velocity can precisely tune the grasping intensity and operational speed according to the dimensions of the target object.

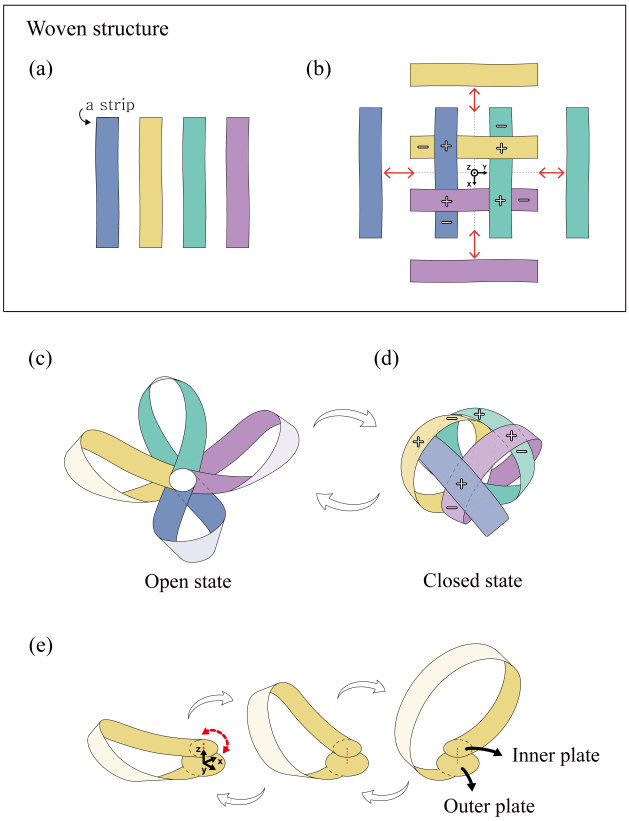

Figure 1. Operational principle of the woven-based soft gripper. (a, b) Schematic of the woven structure, where discrete strips interlace with alternating vertical displacements along the z-axis (+ and -). (c, d) Transformation of the proposed multi-loop architectural gripper between the deployed open state and the interlocked closed state. (e) Reversibility of a single closed-loop strip, which forms the fundamental component of the gripper, achieved through the relative rotation of parallel inner and outer plates.

III. Experimental Validation and Applications

The proposed woven-based architecture offers significant scalability, allowing the gripper's dimensions to be tailored for various target sizes—ranging from small debris fragments to large decommissioned satellites—by simply adjusting the strip geometry. Furthermore, to ensure mission success in unpredictable orbital environments, the gripper operates through a predefined sequence of state transitions: Stowed, Ready-to-Capture, Initial Constraint, and Final Capture.

A. High-Payload and Multi-Scale Experiments

The scalability and structural integrity of the proposed woven architecture were verified through experiments across three distinct scales (Fig. 2). Based on the strip geometry of the medium-scale prototype (G_m), we developed a millimeter-scale version (G_s, 0.2x) and a large-scale version (G_l, 4x).

The gripper's precision was first validated at the smallest scale. As shown in Figs. 2a–d, the small-scale gripper (G_s) showcased high-precision grasping by reliably lifting millimeter-scale objects, including a 0.5 kg·f weight, a 1-cent coin, an M10 bolt, and M6 nuts. These results demonstrate that the woven structure maintains its functional effectiveness even when miniaturized.

Following the precision tests, the load-bearing capacity was evaluated using the medium and large models. The medium-scale gripper (G_m) successfully captured a total payload of 90 kg·f, composed of three 30 kg·f dumbbells, confirming the exceptional structural strength arising from the interlocking woven strips (Fig. 2e). Furthermore, the large-scale gripper (G_l) proved its versatility by handling large-volume targets, such as a 12 kg·f water pack, a 60 kg·f dumbbell, and a 5 kg·f box (Figs. 2f–h).

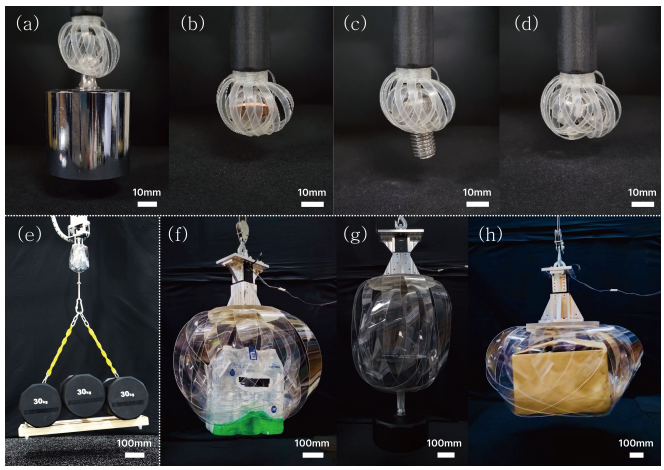

Figure 2. Multi-scale validation and high-payload tests of the woven gripper. (a–d) Millimeter-scale gripper (G_s): Grasping small and diverse objects including a 0.5 kg·f weight, 1 cent coin, M10 bolt, and 4 M6 nuts. (e) High-payload test with medium-scale gripper (G_m): Grasping and lifting three 30 kg·f dumbbells (total 90 kg·f). (f–h) Meter-scale gripper (G_l): Capturing large-volume targets such as a 6-pack of 2L water bottles (12 kg·f), a 60 kg·f dumbbell, and a 5 kg·f box.

B. ADR Mission Operation

The proposed soft gripper offers a high-potential solution for the active capture of noncooperative, free-floating space objects on orbit. Exploiting the structural scalability, ADR missions can adopt a deployable gripper, which requires resource efficiency and deployment reliability. The operational sequence is categorized into four discrete states: Stowed, Ready-to-Capture, Initial Constraint, and Final Capture, all driven by a single rotary actuator (Fig. 3).

During the launch and early orbit phase (LEOP), the gripper remains in the Stowed state to maximize volume efficiency (Fig. 3c). The structural reliability of this configuration was validated through launch environment vibration tests, ensuring the compliant woven structure can withstand mechanical stresses. In the rendezvous phase, the system transitions to the Ready-to-Capture state (Fig. 3b). Upon contact, the actuator drives the strips to converge, achieving an Initial Constraint to perform caging the free-floating object (Fig. 3d). A critical advantage of this mechanism is its full reversibility, allowing the gripper to be re-deployed for a re-attempt if the initial capture is not achieved. This combined approach of envelope exploration and environmental validation highlights the gripper's potential for reliable ADR maneuvers.

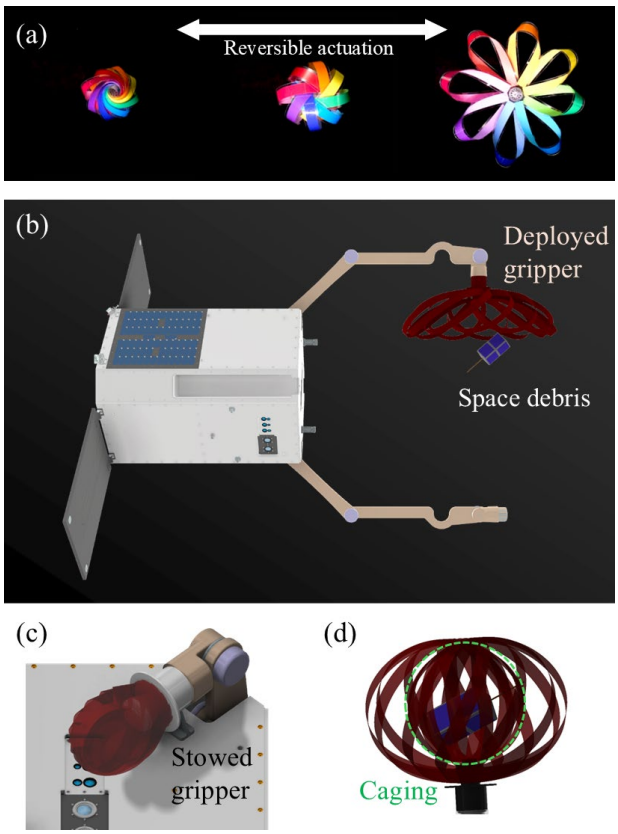

Figure 3. Concept of Operations of the woven-based soft gripper for space debris removal missions. (a) Capability of reversible actuation. The gripper can employ both compactly stowed size and widely deployed span. (b) The gripper can be attached and operated as an end-effector. (c) The stowed gripper can be stored on the spacecraft structures. (d) The gripper performs capture tasks via caging (or encapsulating) motion.

IV. Conclusion

The development of the woven-based compliant soft gripper represents a significant advancement in capture mechanisms for ADR. Beyond providing a simple mechanical solution, this research establishes a new design paradigm where the structural complexity of weaving and the geometric adaptability of kirigami are synergistically integrated. This architecture effectively overcomes the trade-off between high-load capacity and lightweight storability, which has been a long-standing challenge for conventional rigid docking systems in orbital environments.

Furthermore, the multi-scale scalability demonstrated in this study suggests that the weaving mechanism can be customized for a wide spectrum of space missions, from the capture of small-scale fragments to the docking of massive decommissioned satellites. Future extensions of this work will explore the specialized space-grade polymers to enhance the gripper's performance under extreme thermal cycles and vacuum conditions. By providing a reliable, sensor-less, and reversible grasping method, this technology is expected to serve as a foundational tool for ensuring the long-term sustainability of the LEO environment.

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