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Structural Interlocking-Based Weaving Gripper for Enhanced Grasping Performance*

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Abstract— **Robotic grippers have been extensively developed to enable stable and efficient object manipulation across diverse applications. While soft grippers offer high adaptability and safety, their performance remains constrained by an inherent trade-off between flexibility and load-bearing capacity. This study was undertaken with the objective of addressing these challenges by proposing a compact weaving gripper that exploits structurally induced interlocking. Additionally, a prediction model is developed to predict and control grasping configurations. The proposed gripper is integrated with continuum robot, enabling operation in confined environments, and demonstrates applicability across diverse robotic platforms.**

I. INTRODUCTION

The operational capabilities of robotic systems are determined by gripper, which is the end-effector responsible for direct physical interaction with target objects [1]. Force transmission and contact stability during grasping operations govern task reliability and the range of feasible applications, making gripper design one of the most crucial components in robotic systems [2]. Conventional rigid grippers provide high load-bearing capacity and precise control, yet their inherent structural rigidity may result in object damage or grasp failure. Furthermore, rigid structures are primarily optimized for predefined objects and controlled environments, such that interactions with unknown objects in unstructured environments may result in grasp failure [3]. While these limitations can be mitigated through sensors and control systems [4-6], this leads to increased system cost and computational complexity In contrast, soft grippers achieve high adaptability and safety through material compliance, yet insufficient load-bearing capacity remains a persistent challenge [7]. A general trend observed across the literature is that gripper mass increases in tandem with increasing payload requirements, and supporting large absolute loads remains fundamentally difficult with existing soft gripper designs. Achieving both flexibility and high payload capacity simultaneously has thus been a central objective in gripper design.

In recent studies, weaving-based structural mechanisms have emerged as a promising approach to address this challenge [8]. Woven structures exhibit mechanical stability through inter-element interlacing and contact networks, enabling substantial load-bearing capacity without sacrificing compliance. Kang et al. demonstrated the feasibility of this approach, and subsequent studies have further investigated its applicability to gripper design.

In this study, a structural interlocking approach is introduced to overcome the current trade-off in soft grippers.

II. RESULTS

The weaving gripper consists of multiple closed-loop wires interlaced between two concentric components, an outer ring and an inner plate (Fig. 1). Gripping motion is generated by the relative rotation between these components, where the inner plate rotates while the outer ring remains stationary. Clockwise rotation increases wire interlacing to close the gripper, while counterclockwise rotation unwinds the loops to open it, all through a single rotational input that eliminates the need for additional actuators. Furthermore, the rotational shaft connecting the gripper to the motor can be extended to position the driving unit rearward, allowing the frontal structure to remain slim.

A prediction model is constructed to quantitatively characterize the shape variation of the gripper under rotational input and to systematically define the design parameters. The model treats each wire loop as a geometrically constrained flexible element, capturing the relationship between the rotation angle of the inner plate, the projected length of each loop segment, and the resulting aperture of the gripper.

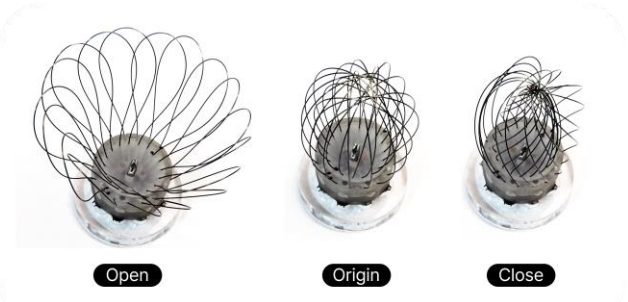

Figure 1. Overview of the proposed soft gripper.

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This enables quantification of the wire interlocking during the closing process and the wire expansion pattern during the opening process. By parameterizing these relationships, the model provides a principled basis for selecting parameters to achieve the target grasping force and aperture range.

To quantitatively analyze the payload capacity, the theoretical maximum payload L_{max} is first defined based on the tensile strength of the constituent wire material. The gripper structure comprises 18 wires, and under the assumption that the applied load is distributed uniformly across all wires, L_{max} is calculated to be 123.35 kg·f. Using this value as a reference baseline, two distinct failure modes were defined. The first, termed structural failure, refers to the condition in which the gripper loses its grasping state due to structural instability before the load reaches L_{max}. The second is termed material failure. This condition occurs when the load exceeds L_{max} and thereby surpasses the intrinsic tensile strength of the wires, resulting in plastic deformation or fracture. In this framework, L_{max} represents the material-level limit, whereas actual grasping performance may be constrained at lower loads by structural failure occurring prior to reaching this threshold.

This load-enhancement behavior is attributed to the progressive enhancement of weaving completeness with increasing rotation angle, which intensifies the degree of structural interlocking among the constituent wires. Consequently, the internal load transmission pathways become more diversified, distributing the applied load throughout the entire wire network rather than concentrating it on individual elements. Furthermore, the intensified interlocking increases contact friction between wires, constituting a distinct load-enhancement mechanism beyond simple force superposition.

To evaluate the actuation torque required for the opening and closing motion, a torque test is conducted across rotation angles. The results show that the required actuation torque remains below 0.02 N·m for all tested rotation angles. This value is notably low relative to the payload capacity of up to 170.19 kg·f, demonstrating that the weaving mechanism achieves high load-bearing performance without imposing a proportionally large actuation burden.

To assess grasping capability across diverse objects, experimental demonstrations are performed on objects of varying geometry and mechanical properties. The wire-based compliant structure enables stable grasping of flat, thin, and small-diameter objects, as well as simultaneous handling of multiple discrete objects. For irregularly shaped or compressible objects, stable grasping is achieved through compliant deformation. This versatility is attributed to the passive adaptability of the wire array, which conforms to object boundaries and generates distributed contact forces, without requiring object-specific customization or sensor-based control.

Furthermore, the proposed gripper is mounted at the distal end of a tendon-driven continuum robot, which is subsequently integrated onto a mobile robotic platform. The continuum robot enables the gripper to access narrow or curved spaces by bending toward the target object, overcoming the reach limitations of conventional rigid manipulators. This capability is particularly relevant in unstructured environments where direct linear access to target objects is not guaranteed. The mobile robot transports the entire assembly, enabling pick-and-place operations across different locations.

To validate system performance, several retrieval tasks were conducted in geometrically constrained environments. In the first task, a wooden ball located inside a spherical straight tunnel of 45 mm diameter was successfully retrieved. In the second task, a ring placed inside a hamster tunnel of 50 mm diameter was retrieved. This tunnel presents continuously varying curvature, such that accumulated pose errors during navigation may lead to wall interference or task failure. In both cases, the continuum robot conformed to the tunnel geometry and guided the gripper to the target object, which was then stably grasped and retrieved. These demonstrations confirm that the proposed gripper operates reliably in confined and curved spaces that are inaccessible to conventional rigid manipulators, and validate its applicability across diverse robotic systems and operational environments.

III. CONCLUSION

In this work, a weaving-wire gripper is developed that achieves grasping through the geometrical reconfiguration of closed-loop wires induced by a rotational input. The results demonstrate that structural interlocking constitutes an effective load-bearing mechanism capable of supporting large absolute loads without a proportional increase in gripper mass.

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