Design and Evaluation of a Low-Cost Tendon-Driven Soft Gripper Utilizing EPE Foam

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***Abstract*—Recent advances in soft robotic grippers have enabled versatile grasping capabilities, allowing robots to handle objects with uncertain geometries and varying stiffness. However, the widespread adoption of these technologies in educational and low-resource settings is often hindered by high costs, complex fabrication processes involving molding and casting, and the need for specialized pneumatic equipment. This study presents the design, fabrication, and evaluation of a low-cost, single degree-of-freedom tendon-driven soft gripper that innovatively incorporates commercially available expanded polyethylene foam nets as passive webbing components. Experimental evaluation across a diverse set of 43 household objects demonstrates a 53.5% success rate. The gripper demonstrated specific proficiency with cylindrical components and fruit-like geometries. These results suggest that foam nets can serve as functional, accessible webbing elements, lowering the barrier to entry for students and researchers exploring soft robotic systems.**

***Index Terms*—soft robotics, tendon-driven gripper, foam net, webbing**

I. Introduction

The integration of soft robotics into educational curricula offers transformative potential for teaching mechanical compliance, underactuation, and safe human-robot interaction. To maximize these educational benefits, hardware platforms must be accessible, affordable, and readily replicable. Low-cost systems enable high-ratio student-to-robot access, fostering deep hands-on engagement, while fabrication simplicity empowers students to maintain, modify, and iterate on designs without the fear of damaging prohibitively expensive equipment. These attributes (i.e., accessibility and scalability) are critical for democratizing robotics education and lowering the threshold for innovation in low-resource environments.

Despite the clear pedagogical advantages of accessible hardware, a significant gap exists between these ideal requirements and the soft robotic solutions currently available. State-of-the-art soft grippers typically offer high performance but rely on precision-molded silicone elastomers or complex pneumatic control infrastructures. The fabrication of such systems often necessitates specialized equipment, such as vacuum chambers and curing ovens, while their operation frequently requires tethered air supplies and valve arrays. These complexities create logistical and financial barriers that prevent the benefits of soft robotics, such as adaptability and safety, from being fully realized in standard classroom settings.

To bridge this gap, there is a compelling need for hardware that prioritizes accessibility without sacrificing core functionality. This study proposes a design paradigm centered on this objective: utilizing Expanded Polyethylene (EPE) foam nets, an ubiquitous agricultural packaging waste, as a functional structural element. By repurposing this widely available material as a passive webbing component, we aim to eliminate the complexities of molding and pneumatics. This approach seeks to provide a functional, safe, and extremely low-cost platform that retains the core mechanical characteristics of soft manipulation (pinching and enveloping), thereby making the educational benefits of soft robotics practically attainable.

This paper presents the design, fabrication, and evaluation of this tendon-driven soft gripper. We validate its utility through a rigorous pick-and-place experiment with 43 diverse objects, characterizing its performance boundaries. The results are analyzed not just in terms of grasp success, but as a case study in how accessible materials can serve as a foundation for effective robotics education.

II. Related Work

A. Multimodal Grasping in Soft Robotics

A substantial body of literature demonstrates the benefits of integrating pinching and enveloping behaviors within unified gripper architectures. The ability to switch grasp modes allows a robot to adapt to the specific affordances of the target object. Liu et al. [1] present a dual-mode two-finger pneumatic system capable of enveloping and pinching through differential chamber pressurization. Their design achieves grasp force adaptation by reconfiguring internal air pressure distribution, enabling manipulation of objects with diverse geometries. Similarly, Fang et al. [2] demonstrate that tendon-reinforced fingers can alternate between clamping (pinching) and enveloping through stiffness modulation, incorporating proprioceptive sensing for grasp state estimation. Jain et al. [3] further demonstrate that reconfiguring fingertip geometry enables manipulation of objects ranging from thin sheets to bulky items, achieving workspace expansion through variable finger configurations.

Collectively, these studies indicate that multimodal grasping significantly improves object retention and handling versatility. However, these high-performance approaches typically rely on engineered materials (custom-molded silicones, embedded sensors) and fabrication steps (multi-material casting, precision assembly) that may be inaccessible in low-resource settings.

B. Foam Materials and Webbing Structures

Polyethylene foams appear in prior work primarily as compliant padding or backing material rather than as active structural components. For instance, Jain et al. [3] incorporate open-cell polyethylene foam in their reconfigurable soft gripper to increase surface conformance, but the foam does not function as a webbing layer that spans between digits to provide geometric constraint.

Studies involving membrane-supported or webbed grippers usually employ more sophisticated materials. Cai et al. [4] develop a pneumatic webbed gripper using molded silicone sheets to provide structural support during enveloping, demonstrating effective grasping of agricultural products with irregular geometries. Zhang et al. [5] use a laminated composite jamming membrane to enable variable-stiffness envelopment, achieving controllable compliance through granular jamming mechanisms.

The literature therefore reveals a modest but distinct gap: no peer-reviewed study evaluates EPE fruit foam nets as structural webbing for soft grippers. Considering the foam net's porous geometry, inherent compliance, and widespread availability as packaging material, evaluating its suitability for tendon-driven grasping represents a meaningful contribution for educational and prototyping contexts where material accessibility is significant.

III. Design and Fabrication

A. Design Requirements and Concept

The gripper design was governed by four primary requirements:

1) **Actuation:** Single degree-of-freedom (DOF) actuation using available servo motors to minimize control complexity.
2) **Control:** Wireless remote operation via XBee modules implementing ZigBee protocol.
3) **Integration:** Mechanical compatibility with the UR3e robotic manipulator tool flange [7].
4) **Versatility:** Reliable grasping performance across multiple object categories (rigid, soft, fragile).

The physical realization of the design is shown in **Fig. 1**. It consists of three thermoplastic polyurethane (TPU) digits mounted symmetrically at 120° intervals around a central base. As seen in **Fig. 1(a)**, the EPE fruit foam net is integrated to span the interdigital spaces. This webbing deforms and stretches as the fingers converge **(Fig. 1(b))**, increasing the effective contact area during enveloping motions and preventing objects from slipping through the gaps. The internal mechanism **(Fig. 1(d))** utilizes a single servo to actuate all digits simultaneously.

B. Actuation Mechanism

The single-DOF actuation system employs a SG90 servo motor connected to brass wire tendon. This tendon is attached to a linear slider to actuate all three TPU digits.

The tendon mounting system ensures an equal force application to all three digits through a central linear slider mechanism housed within the palm. When the servo retracts the tendon, it produces synchronized bending of all digits. This bending occurs due to the asymmetric stiffness properties of the printed finger geometry. Conversely, tendon tension release allows the digits to return to their neutral (open) position solely through the elastic recovery of the TPU material; no antagonistic springs are required.

C. Digit Construction

The digits were fabricated via fused-filament 3D printing using TPU. This material was selected for its high tear strength and fatigue resistance. Each digit measures 140 mm in length with a 16 mm tapered cross-section at a distance of approximately 50 mm from the base.

To achieve the desired bending profile, the digits feature variable wall thicknesses as illustrated in the CAD cross-section in **Fig. 2(a)**. The rear (dorsal) surface is stiffened with a wall thickness of 2 mm, while the palmar surface is thinner at 0.8 mm. This structural asymmetry forces the finger to curl inward when the tendon is retracted. The physical print quality and internal fill can be seen in the cross-section slice in **Fig. 1(c)**.

A thin layer of rubber was applied to the palmar surface of each digit tip. This post-processing step is crucial for increasing the coefficient of friction. This enhancement significantly reduces the grip force required to lift low-friction objects like plastic bottles.

D. Foam-Net Webbing

The EPE fruit foam net was selected due to its commercial availability and compliant cellular structure. The foam net exhibits an open-cell diamond lattice geometry with approximate dimensions of 140 mm $\times$ 140 mm and a wall thickness of 5 mm.

Sections were cut to match the interdigital spacing. Attachment was achieved manually using cable ties through the foam cell walls and TPU digits. The foam net is not engineered

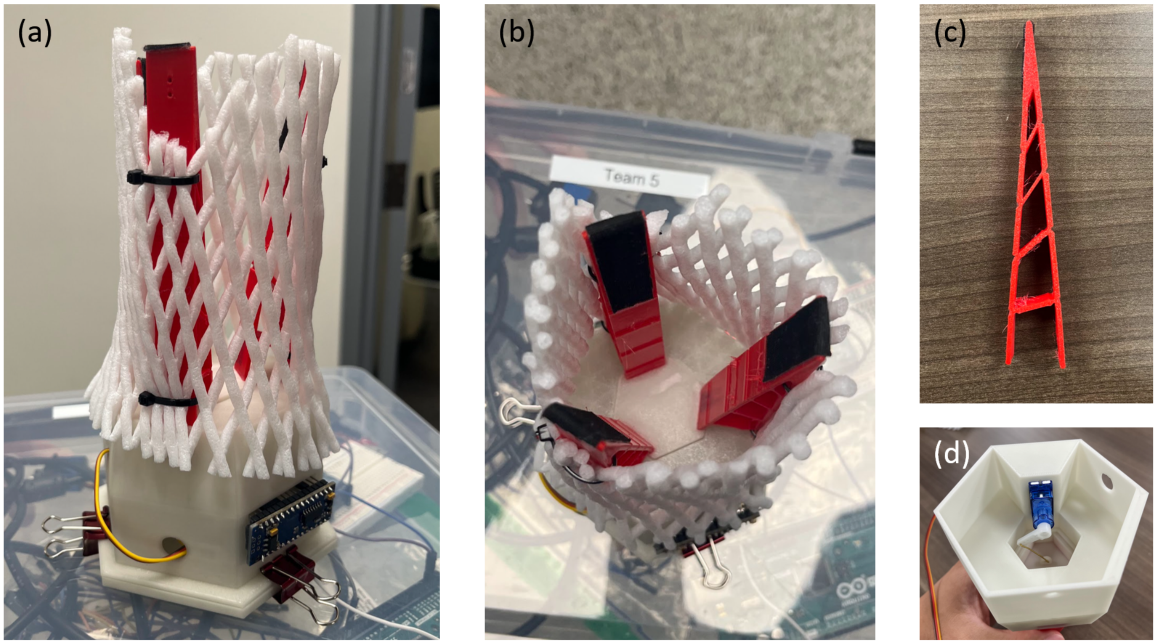

Fig. 1: Fabricated prototype of the soft gripper. (a) Complete assembly with EPE foam net webbing acting as a passive constraint. (b) Top view showing the symmetric arrangement of the three digits. (c) Physical cross-section of the 3D-printed TPU digit showing the internal structure. (d) Internal view of the base housing containing the servo motor and tendon linkage.

for high tensile structural loads. However, its function here is geometric rather than structural: under tendon-induced tension, the net deforms to "cage" the object.

E. Wireless Communication System

Remote operation was implemented using XBee Series 2 modules configured in ZigBee API mode [6]. The system architecture is divided into two parts: the Base Station and the Gripper Controller.

The Base Station wiring is shown in **Fig. 3**. It consists of an XBee module connected to an Arduino Mega 2560, which interfaces with a laptop computer. A Python-based graphical user interface runs on the PC to send high-level commands.

The Gripper Controller wiring is illustrated in **Fig. 4**. The gripper-mounted XBee module receives the position commands and transmits them to an Arduino Nano. This microcontroller then generates the appropriate PWM signals to drive the servo motor, executing commands such as Open, Close, or Pinch.

IV. Experimental Evaluation

A. Testing Protocol and Object Set

To rigorously evaluate the gripper's versatility, a comprehensive set of 43 household and laboratory objects was assembled. This dataset aims to identify specific failure modes related to object geometry.

The objects were tested in a systematic pick-and-place task:

1) **Grasp:** The gripper closes on the object.
2) **Lift:** The object is lifted vertically by 3 cm.
3) **Hold:** The object must be retained for 1 second.

A trial was recorded as a success only if the object remained stable throughout the entire procedure. Any slip, rotation resulting in drop, or failure to initially grasp was recorded as a Failure.

B. Object Categorization and Definitions

To analyze performance trends, the 43 objects were classified into five distinct categories based on their physical and geometric properties. The full set of objects is visualized in **Fig. 5**. We provide explicit technical interpretations for these categories:

- **Fruit-like Objects:** Natural objects characterized by single continuous curvature and elliptical or spherical mass distribution (e.g., Apple, Lemon, Banana).
- **Deformable/Irregular:** Objects composed of compressible internal materials (fiber, foam) with non-uniform boundaries (e.g., Stuffed dolls).
- **Component-type Parts:** Small-scale engineering elements featuring functional geometries (e.g., Screws, Gears, Tape rolls, Caps).
- **Cylindrical:** Rigid objects with a constant circular cross-section along a primary axis (e.g., Cups, Bottles, Cans).
- **Prismatic/Box:** Rigid objects defined by planar faces and sharp corners, such as cubes or rectangular prisms.

C. Quantitative Results

Of the 43 tested objects, the gripper successfully manipulated 23, yielding an overall success rate of **53.5%**. Table I summarizes the distribution of objects and success rates per category.

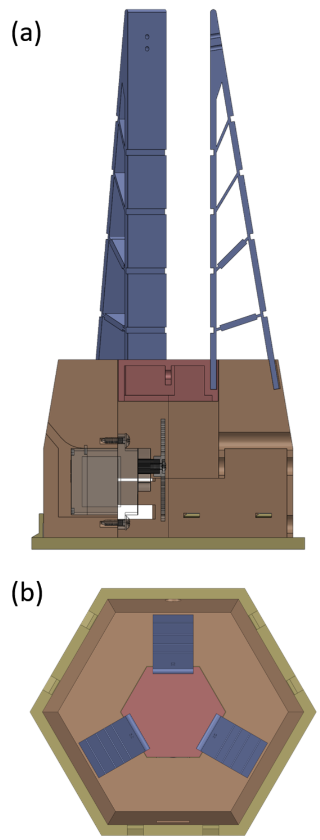

Fig. 2: CAD model of the gripper mechanism. (a) Cross-sectional side view detailing the internal tendon routing channel and the variable wall thickness design. (b) Top view of the base hub and digit mounting interface.

TABLE I: Grasp Success Rates by Object Morphology

Category	**Total Objects**	**Successes**	**Success Rate**
Cylindrical	11	6	54.5%
Prismatic (Box/Cube)	10	3	30.0%
Deformable/Irregular	7	3	42.9%
Fruit-like	5	3	60.0%
Component-type	10	6	60.0%
Hybrid/Other	–	*2*	–
Total	**43**	**23**	**53.5%**

D. Qualitative Analysis of Success Cases

The gripper demonstrated distinct proficiency in specific categories. As indicated by the highlighted items in **Fig. 5**, notable successes include:

- **Fruit-like Objects (60% Success):** The Green Apple, Red Apple, and Lemon Toy were grasped securely. The natural curvature of these objects matched the bending profile of the digits, and the foam webbing provided a high-friction "hammock" effect that prevented the fruits from rolling out.
- **Deformable Objects:** The White Doll and the Red/Yellow/Green Doll were successfully manipulated. The low stiffness of the objects allowed the digits to compress the target, creating a form-closure grasp that compensated for the lack of independent finger control.
- **Component-type Parts (60% Success):** Surprisingly, the gripper performed well with small, complex geometries. Successful items included the Black Tape, Blue Ping-pong Ball, White Cylindrical Tape, Screws, and the Small Green Gear. The foam net proved critical here.
- **Cylindrical Objects:** Standard items like the Paper Cup and various Caps were reliable. The "White Cylindrical

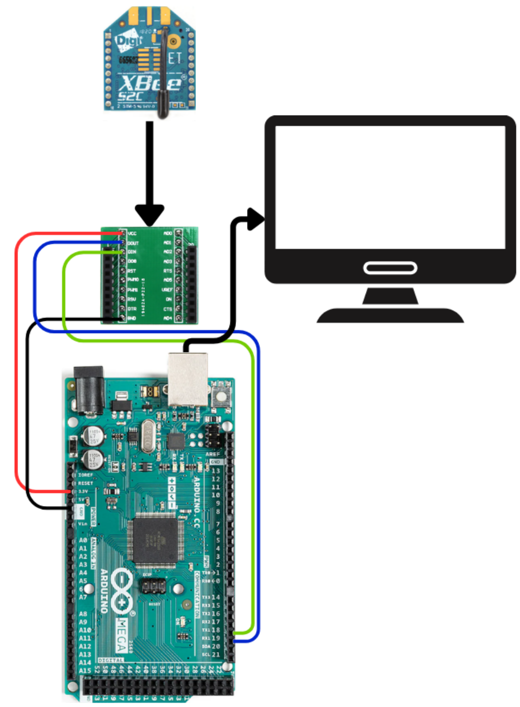

Fig. 3: Wiring diagram for the Base Station (Transmitter). The PC interfaces with an Arduino Mega, which transmits control commands via the connected XBee module.

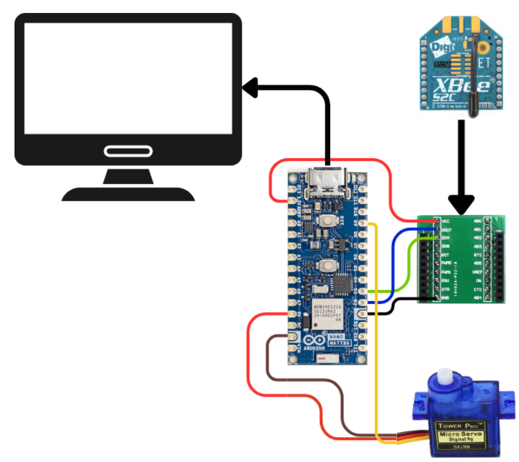

Fig. 4: Wiring diagram for the Gripper (Receiver). An Arduino Nano receives commands via XBee and generates PWM signals to control the servo motor.

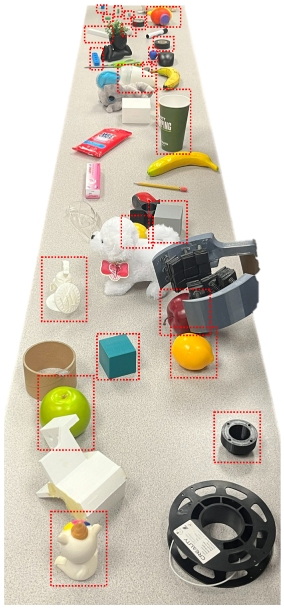

Fig. 5: The complete set of 43 household and laboratory objects used for experimental validation. Objects marked with red dotted boxes indicate those that were successfully grasped and retained by the gripper.

Object" and "Blue Long Hollow Object" were also successes, indicating that as long as the object allowed the fingers to wrap around a central axis, the grasp was stable.

E. Failure Mode Analysis

The quantitative data reveals a significant drop in performance for prismatic objects (30% success rate). Only 3 out of 10 box-like objects were successfully grasped.

Failure Mode 1: Corner Slip on Rigid Faces. For objects like the "Black Block Set" or large rectangular boxes, the gripper failed to establish a secure contact. The digits, bending in a circular arc, often made point contact with the flat face of a box. Without the ability to conform to the sharp 90-degree corners, the digits would slide off, and the webbing tension was insufficient to pull the object into the palm.

Failure Mode 2: Ejection of Tapered Objects. Certain conical objects or specific caps failed because the squeezing force of the digits, combined with the slippery surface of the plastic, converted the clamping force into a vertical ejection force, shooting the object out of the grasp before the lift occurred.

Failure Mode 3: Webbing Transparency. Extremely small components, such as the “Very Small Green Gear,” frequently failed to be grasped because their dimensions were below the effective gripping range of the gripper.

V. Discussion

A. Performance Assessment and Trade-offs

The overall success rate of 53.5% (23/43 objects) provides a realistic view of the capabilities of this low-cost system. While lower than high-end industrial grippers, this performance is significant for an educational prototype constructed from packaging waste.

The data highlights a clear geometric dependency. The gripper excels at "organic" shapes (Fruits, 60%) and "Circular" geometries (Cylindrical 54.5%, Components 60%). This confirms the hypothesis that the EPE webbing is most effective when wrapping around a curved surface, where it can distribute tension evenly. Conversely, the poor performance on Prismatic objects (30%) highlights a limitation of the single-DOF tendon design. The lack of independent joint control prevents the fingers from executing a parallel pinch, which is necessary for stable grasping of cubes and boxes.

B. The Role of Webbing in Component Handling

A key finding is the high success rate with "Component-type" objects (Screws, Gears, Tape). Typically, soft grippers struggle with small, dense items. In this design, the EPE foam acted not just as a stabilizer, but as a trap. Cylinder shaped objects were essentially entangled in the webbing structure. This suggests that for educational robotics tasks involving sorting mixed waste or parts, the foam net offers a unique advantage over simple rigid fingers.

C. Material Durability and Hysteresis

Although functional, the EPE foam net can exhibit significant hysteresis. When grasping large and irregular shaped objects, the netting may undergo plastic stretching and may not immediately return to a taut state. This so-called “bagging” effect implies that if a large grasp is followed by a small-object grasp (e.g., Apples), the webbing can remain too loose to provide adequate support. In a classroom setting, this behavior can serve as an effective demonstration of material hysteresis and the trade-offs associated with non-Hookean materials.

D. Educational Value

Despite the 46.5% failure rate, the educational value remains high. The clear distinction between success (Curved/Soft) and failure (Flat/Rigid) provides an excellent platform for students to learn about:

- **Mechanical Affordance:** Understanding how gripper geometry dictates graspable object sets.
- **Friction vs. Form Closure:** Analyzing why the "White Doll" (Form Closure) succeeded while the "Black Block" (Friction) failed.
- **System Integration:** The successful integration of XBee wireless control and UR3e mounting proved that students can build systems compatible with industrial standards using low-cost components.

VI. Conclusion

This study presented the design and extensive evaluation of a soft gripper utilizing EPE foam-net webbing. Testing across 43 diverse objects revealed a 53.5% success rate, with strong performance in manipulating fruit-like, deformable, and small component-type objects. The system struggled with rigid prismatic shapes, identifying a clear area for future mechanical improvement.

The results confirm that while EPE foam nets cannot replace engineered silicone membranes for high-precision industrial tasks, they offer a functional, accessible, and educationally rich alternative for introductory robotics. The ability to grasp delicate items like raw eggs and small items like screws with a single mechanism validates the multimodal potential of this low-cost approach. Future studies may investigate optimized tendon routing strategies to enhance parallel grasping performance for prismatic objects, as well as the potential of hybrid webbing materials for hysteresis reduction.

Acknowledgment

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