Bistable Spring Steel Grippers for Passive Grasping

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***Abstract*— Aerial grasping using flying robots necessitates gripper designs that can accommodate position/orientation errors to grasp different objects. This study investigates two bistable gripper designs that can automatically close upon contacting an object. Both grippers leverage pre-stressed spring steel bands (PSSB), with one having a single PSSB and the other having two PSSBs in a cross-shape. Both grippers can be opened with a single motor to drive a cable system routed through flexible joints on the bands. The same cable system, together with a friction adjustment mechanism, also ensures sequential closing of the gripper. We conduct experiments to evaluate and compare the gripping performance of both designs. On average, the single-band gripper can grasp within 0.14 s and open in 3 s, while the cross-shaped gripper takes 0.24 s and 4 s, respectively. Both designs can still grasp even when a cylinder makes off-center contact with the PSSB, up to a displacement of 50 mm. Further tests demonstrate both grippers can grasp cylinders with different diameters that approach the gripper with different orientations. Finally, we demonstrate both grippers can grasp real-world objects (e.g., water bottles, video game controllers, etc.). Our grippers, with their compact, lightweight design and passive grasping capabilities, hold the potential to advance aerial grasping for diverse applications.**

I. INTRODUCTION

Aerial grasping, the field that enables flying robots to pick up, manipulate, and execute specific tasks with various objects, has gained traction in recent years. This heightened interest is primarily attributed to the advantages it offers compared to the conventional ground-based counterparts. Their high accessibility and mobility make them suitable for diverse applications such as transportation, inspection and maintenance of structures, rapid deployment of emergency supplies in disaster response, precision agriculture, etc [1]–[4]. Successful aerial grasping emerges from good motion control together with proper gripper design. The gripper's design plays a major role in determining the success of the aerial grasping systems. If properly designed, the gripper can alleviate the requirement for precise motion control [5].

Many grippers have been recently designed for aerial grasping, but we only outline some key prior designs that inform and complement our contributions. Several research groups have developed passive grippers, often featuring two or three fingers. Notable examples include grippers leveraging pre-stored potential energy [6] and von Mises bistable mechanism [5], [7]. These grippers, while adept at perching,

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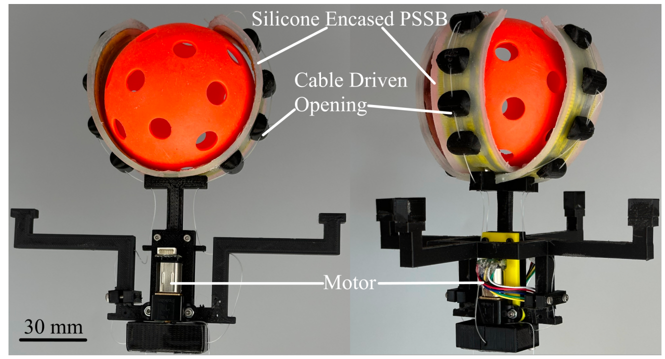

Fig. 1. Two bistable grippers with major design components shared by both. Left: Single-band gripper. Right: Cross-shaped gripper.

have limitations when grasping objects of different shapes. Other designs for passive grippers, such as the high-speed gripper [8], bistable claw gripper [9], bird-inspired robotic leg and claw gripper [10], utilize claw-like mechanisms to enable grasping. However, these claw-based designs can be quite complex and may encounter reliability issues. In contrast, some grippers adopt an active approach, such as servo motors or artificial tendons for controlling the gripper. Examples of these grippers include the hybrid manipulator/gripper [11], the soft fin-ray structure-based gripper [12], and the tendon actuated soft gripper [13]. The active energy consumption of these grippers poses a challenge since efficient energy utilization is critical in aerial applications. To address these issues, researchers have sought to simplify the gripper designs using pre-stressed bistable beams (PSSB) [14]–[16]. However, pneumatic systems are used for opening the grippers, which can lead to increased bulkiness and weight in the systems.

In our recent work [17], we developed a passive bistable gripper utilizing a PSSB with adaptive control for aerial grasping. The gripper was opened with a single motor and a cable network, making the gripper lightweight. Nonetheless, this earlier design had some notable limitations. First, the gripper had reliability issues with consistent opening, as the cables from either side would snag and hinder proper opening. Second, the gripper did not close sequentially, meaning that the two sides of the PSSB would often hit each other when closing, preventing the required overlap for a strong grasp. In this study, we address these limitations by introducing two improved gripper designs, with one and two PSSBs respectively. Specifically, this study has the following two contributions:

- **Improved Gripper Design:** We have addressed the limitations in our previous work and achieved a more com-

pact and reliable gripper design. Both of our grippers implement a unique friction mechanism that enables the sequential closing of PSSB, creating overlapping PSSB ends that lead to stronger, more robust grasps. Moreover, the cables for opening the grippers are routed through flexible joints on the bands, which constricts their path to prevent snags for reliable opening.
- **Versatile Grasping:** Our passive bistable gripper designs, including a single-band and a cross-shaped configuration, provide a robust aerial grasping solution without requiring a precise alignment. It operates within a broad offset range from the gripper's center. Furthermore, the grippers can successfully grasp cylinders of different diameters at various orientations. This range of successful grasping enables our gripper can be applied to various real-world scenarios.

The rest of this paper is organized as follows. We will first describe the design of both grippers in section II. We then present the characterization and experimental results for them in section III before concluding the paper.

II. Gripper Design

In this section, the design of the two grippers is discussed in detail. Both designs use PSSB as fingers for grasping. A PSSB is an initially straight bistable beam that can curl rapidly to grasp an object. The first one uses a single PSSB, while the second one uses two PSSBs arranged in a cross-shape, as seen in Fig. 1.

The PSSB used in our gripper has a dimension of 210 mm $\times$ 27.5 mm $\times$ 0.5 mm. Each gripper features a 3D-printed base for mounting the PSSB and other components, along with a cable-driven mechanism for opening. The single-band and cross-shaped gripper weigh 54.7 g and 106.6 g, respectively. The designs for each gripper are discussed further in the following two sub-sections.

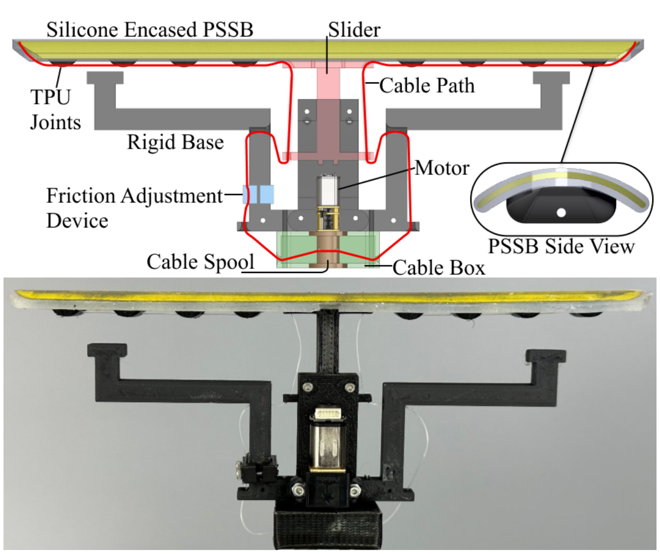

Fig. 2. Design for the single-band gripper. Top: illustration of the main components including the cable path (red). Bottom: the prototype.

A. Design for Single-band Gripper

For the single-band gripper, one PSSB is attached to the base by a free-floating linear slider, allowing the PSSB to retract. The PSSB is supported on both sides by two vertical beams that extend out from the base. When an object contacts the PSSB between these beams with a sufficient triggering force, the slider moves downwards, and the PSSB curls rapidly to grasp the object. Grasping can be initiated without any actuator due to the PSSB's bistable nature, reducing complexity and weight.

We enclose the PSSB with silicone (EcoFlex-30, Smooth-On) using the molding approach. The silicone can provide a flexible attachment for the flexible joints that can guide the cables to reliably open the gripper (Fig. 2) and provide shock absorption and protection for the PSSB, gripper, and the object being grasped. The silicone enclosure is 2.5 mm thick on the bottom side of the PSSB, and 1 mm on the top side. Silicone is molded using a fully enclosed mold where the PSSB is screwed into the mold to fix it, with a curved void of 2.5 mm below and a 1 mm spacing between the top of the PSSB and the curved top of the mold.

To open the PSSB, a cable-driven system is utilized to pull each side of the PSSB open. The cables (fishing line) are routed through four 3D-printed flexible joints (thermoplastic polyurethane (TPU), 85A hardness) on the bottom of the gripper (Fig. 2). These joints are attached to the silicone on the bottom of the PSSB, approximately 12 mm apart, with a specialized silicone-TPU glue. A $1000:1$ geared DC motor with a magnetic encoder (#2373, Pololu) is used to wind the cable around a spool. The cable spool is enclosed in a box to ensure the cable does not get tangled during spooling and unspooling. The fishing line (illustrated by red in Fig. 2) is spooled to a set 'open' encoder position when the PSSB is fully flattened, then unspooled to its original position for rapid reuse. The line is routed from each end of the PSSB through the TPU joints, slider, and base, and to the cable box and spool. This routing allows for simultaneously extending the slider while opening the gripper, increasing opening reliability, and reducing complexity compared to our previous gripper design where two cables are used.

To achieve better grasping results around smaller objects (6 cm diameter or less), the two sides of a PSSB should ideally curl at different speeds so that they can overlap around the object to provide a high friction holding force. Without a proper design, the PSSB may curl at the same speed for both sides and hit each other, preventing the desired overlap. To address this problem, we add a friction adjustment mechanism to one side of the base that slows down the curling of one side of the PSSB by increasing friction on the cable (Fig. 2), which facilitates sequential closing (Fig. 5). The mechanism functions by clamping the cable between a 3D printed piece and the base with friction tape (GM631, 3M) attached to each.

B. Design for Cross-Shaped Gripper

The cross-shaped gripper integrates an additional perpendicular PSSB on top of the first (Fig. 3), with both bands connected to a free-floating dual-band slider for simultaneous activation. The rigid base is modified from the single-band base, with 2 additional vertical beams to activate the second PSSB. The additional beams sit 2 mm taller to accommodate different heights of the two PSSBs, and also aid in sequential closing by triggering the lower PSSB, followed by the upper. To open the second PSSB, a second fishing line (illustrated by blue in 3), equal in length to the single-band gripper, is used to flatten the band. The line runs from each end of the PSSB through the slider, base, and the dual cable box and spool, allowing for simultaneous spooling and unspooling of both cables without tangling. There are four TPU joints on each side of the second PSSB that are identical in form and function to the single-band design. During the opening process, only the first fishing line will make the slider mechanism move upwards. Only the cable path of the second PSSB is shown in Fig. 3A in blue, as the first cable path is identical to the single-band gripper path (red in Fig. 2). Video of the opening process for both grippers can be seen in the supplemental video.

To achieve sequential closing in the cross-shaped gripper, two friction adjustment mechanisms are added to the sides of the cross base with the cable path (red in Fig. 2) corresponding to the bottom PSSB in Fig 3A. The friction mechanisms slow the closing of the first (bottom) PSSB. For good grasping, one PSSB would close with overlap, then the next would overlap on top of those. No friction adjustment mechanism is required for the second PSSB since its cable path (blue in Fig. 3A) can enable the sequential closing for this band. This cable path behind the motor (left in Fig. 3A) has two additional guide holes in the base compared to the front (right) side cable path, providing the required friction for the right side of the PSSB to close first (Fig. 5).

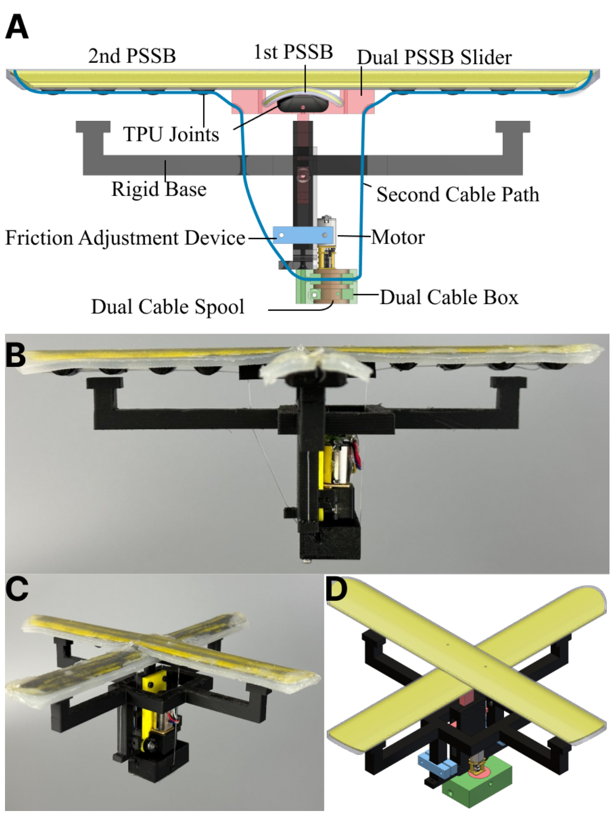

Fig. 3. Design for the Cross-Shaped Gripper. (A) A solid model that details the design and components of the cross-shaped gripper including the cable path (blue) for the second PSSB; (B) and (C) Front and Isometric views of the cross-shaped gripper; (D) Isometric rendering of the cross-shaped gripper where component colors match the solid model in A.

III. Characterization

With the two designed grippers, this section details the characterization of both grippers through four experiments. First, we characterize the triggering force at various offsets from the center of the gripper, where a lower force is desired for robust grasping without precise positional control and for potential future dynamic aerial grasping. Second, we quantify the activation time and sequential closing of both grippers. A quick activation time is preferred because it will decrease the instances of failed grasping, while sequential closing is desired to create an overlap of the PSSB around an object for a stronger grasp. Third, we test grasping performance on cylinders with various diameters and varying pitch and offset angles, which are important to quantify grasping performance in different scenarios. Finally, we demonstrate both grippers' grasping ability for various real-world objects. The experimental methods and results are detailed in each of the following subsections.

A. Triggering Force

We first determine the triggering force of both grippers at offset distances of 0, 10, 20, 30, 40, and 50 mm from the center of the PSSB. 50 mm is the max offset distance used because, after this, both grippers fail to activate as the offset location approaches the outside beam. An adjustable 3D-printed base secures the gripper in the lower jaw of a test stand (ESM303, Mark-10), while triggering force is measured with a force gauge (M5-2, Mark-10) holding an 8 cm cylinder just above the gripper. The cylinder is lowered at 40 mm/min until the gripper is activated. For the cross-shaped gripper, the offset distance used is along the bottom PSSB. The experiment is repeated five times for each offset distance. The results are plotted in Fig. 4, where the average triggering force for the single-band gripper starts at 4.67 N for 0 mm of offset and gradually increases to 9.48 N for 50 mm. While the cross-shaped gripper gradually increases from an average triggering force of 6.22 N at 0 mm offset to 12.11 N at 50 mm offset.

The cross-shaped gripper has a triggering force only slightly larger than that of the single-band gripper. This might be due to the different stack heights of the two PSSBs and different beam heights that cause the sequential triggering. Although the measured triggering force is a bit large for grasping, we can potentially reduce this in our future work by applying pretension to the PSSB using springs, as done in our previous work [17], using a smaller PSSB, or actively tuning the triggering force by attaching artificial muscles (e.g., twisted-and-coiled actuators [18]) onto the PSSB.

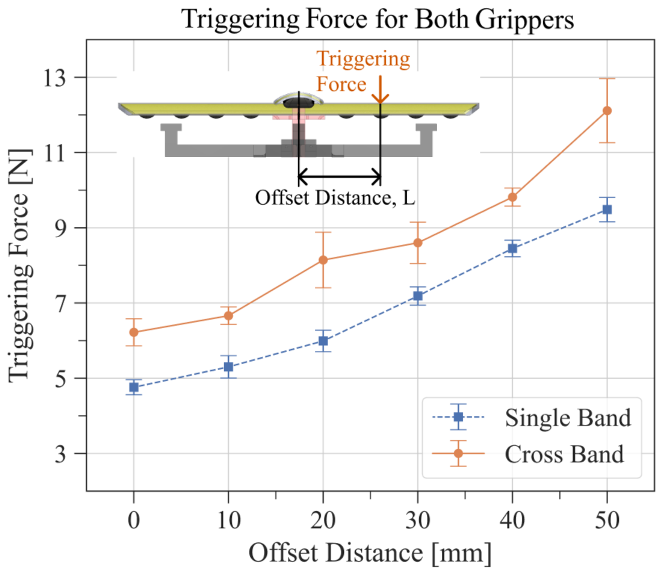

Fig. 4. The triggering force with respect to offset distances varying from 0 to 50 mm with a step size of 10 mm for both grippers with the average triggering force and variance between maximum and minimum shown for 5 tests.

B. Activation and Sequential Closing

A quick gripper activation is desired to decrease the chances of a failed grasp due to the relative motion between the gripper and the object. We test the activation time using a thin rod with a 15 mm $\times$ 10 mm flat piece attached to its end to activate the PSSBs. The thin rod is used to avoid interference with the closing process of the PSSBs and make the closing process clearer on camera.

For both grippers, the flat end of the rod is placed on the center of the PSSB, aligned with the center of the slider, and pressed down to trigger the gripper. The activation sequence is captured using a high-speed camera at 240 frames per second (fps). The activation time is the time from the PSSB first moving ($t = 0$) to stopping after fully curling, and is accurate to $\pm$.005 s. Each test is repeated three times, with average times represented in Fig. 5. The single-band gripper closed on average in 0.14 s, with the cross-shaped gripper taking slightly longer (0.24 s) due to the delay for PSSB overlap. Both grippers' average activation times allow for quickly securing a grasp around an object as desired. The grippers can also open in 3 s for the single-band gripper, and 4 s for the cross-shaped gripper, enabling rapid reuse.

The recorded video is also used to show the sequential closing capabilities of both grippers, which allow for high-friction overlapping. For the single-band gripper, the right side of the PSSB will close first, in 0.10 s, followed by the left 0.04 s later at 0.14 s (Fig. 5A). The left side of the PSSB will overlap the right every time the gripper is activated over five tests. For the cross-shaped gripper, the second PSSB on top will close first, with the right side (front right in Fig. 5B) in 0.07 s, and the left (back left in Fig. 5B) overlapping it at 0.14 s. The first PSSB at the bottom will close after the second PSSB and overlap it, with the right (back right in Fig. 5B) at 0.17 s, and the left side (front left in Fig. 5B) overlapping it at 0.24 s. The high-speed footage of the sequential closing can be seen in the supplemental video.

C. Grasping Success Rate with Different Parameters

To determine the grasping abilities and parameters of both grippers, two experiments were conducted using cylinders with different diameters (4, 6, 8, 10, and 12 cm). The experiments are similar and aim to test the effect of different orientations of the cylinders on grasping success. First, we test the effect of offset angle (α) on grasping success. We then determine the effect of pitch angle (θ) on grasping success for the same cylinders.

The offset angle α is the horizontal angle from the axial centerline of the PSSB to the centerline of the cylinder upon impact (Fig. 6A). The gripper is secured with the various offset angles labeled below it such that the center of the gripper is lined up over the origin of the angles. The cylinder is placed in the center of the band and rotated until the desired offset angle is reached. The cylinder is then pushed down using a guide until the gripper is activated. The gripper is then lifted upwards out of the vice and held. We consider the grasp successful if it can maintain the grasp around the object for 10 s without falling off. Representative images of successful and failed grasp can be seen in Fig. 6D. For both grippers, this test is repeated five times for each cylinder diameter for each offset angle. For the single-band gripper, offset angles of $0° - 90°$ with a step size of $15°$ are tested. Since the gripper is symmetrical in both directions, this range of offset angles covers all possible angles. For the cross-shaped gripper, offset angles of $0° - 45°$ with a step size of $7.5°$ are tested. This range also covers all possible angles from $0° - 360°$ due to symmetry. The results can be seen in the first figure of Fig. 6B. The single-band gripper has the highest range of grasping success rate for the widest range of cylinder diameters at $\alpha = 90°$, with the success rate decreasing as α goes towards $15°$. The cross-shaped gripper had the greatest grasping success rate for the widest range of diameters at $\alpha = 22.5°$, with the success gradually decreasing as α goes towards $0°$ or $45°$. The grasping success rate is the highest at $\alpha = 22.5°$ because one band can wrap around the cylinder, while the second acts as support. The cross-shaped gripper has a more consistent range of successful grasping than the single-band gripper, being able to securely grasp for any offset angle for diameters less than 6 cm, while the single-band gripper performs better with larger cylinders.

The pitch angle θ is the vertical angle from the axial centerline of the PSSB to the centerline of the cylinder upon impact (bottom of Fig. 6A). The grippers are again secured and rested against a vertical board with the pitch angles labeled such that the center of the PSSB is lined up with the origin of the pitch angles on the board. The cylinder is placed on top of the PSSB and rotated upwards until it reaches the desired pitch angle, then pushed down using a guide until the gripper activates. The grasping success is defined similarly. For each gripper, this test is repeated for each cylinder diameter and pitch angle. We test a θ range

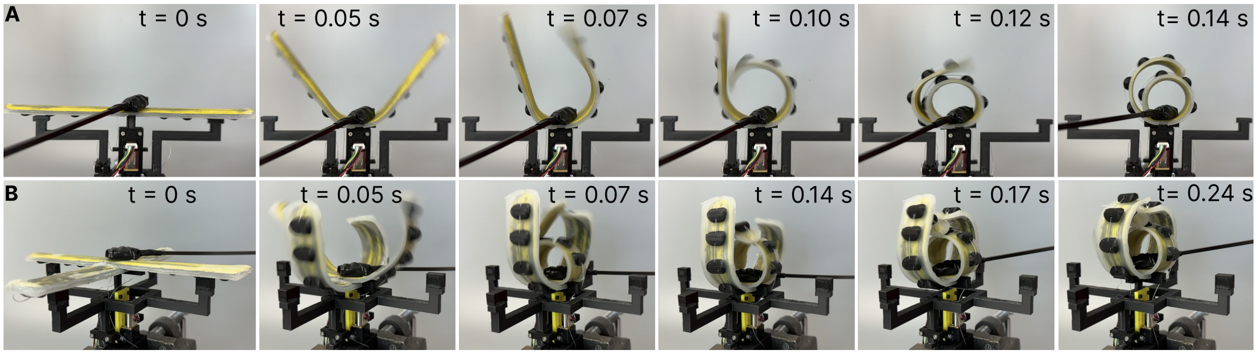

Fig. 5. The sequential closing of both grippers. (A) Sequential closing of the single-band gripper; (B) Sequential closing of the cross-shaped gripper.

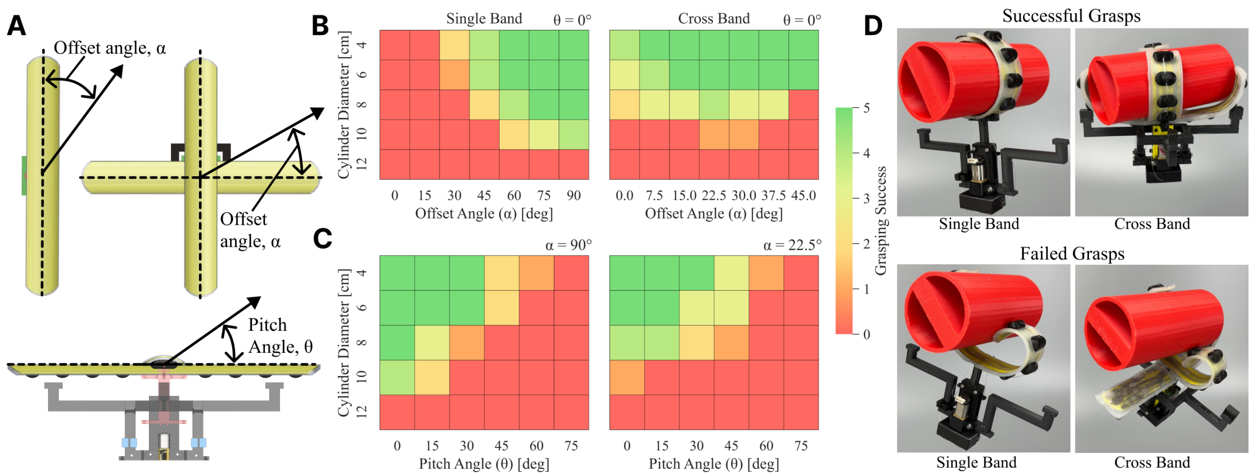

Fig. 6. Experimental results for evaluating grasping success rate with different parameters. (A) Illustration of the offset angle α, and pitch angle θ; (B) Grasping success rate for both grippers out of five attempts for varying diameters vs. offset angle (for $\theta = 0$) where the first graph is for the single-band gripper and the second is the cross-shaped gripper; (C) Grasping success rate for both grippers out of five attempts for varying diameters vs. pitch angle for $\alpha = 90$ and $\alpha = 22.5$ for the single-band gripper and the cross-shaped gripper, respectively. (D) Representative images of successful and failed grasping conditions for both grippers.

of $0° - 75°$. For the pitch angle test, we utilize the best offset angle for each gripper as determined from the previous experiment (90° for single-band, 22.5° for cross-shaped). The results can be seen in Fig. 6C. Both grippers performed similarly in this experiment, performing best at $\theta = 0°$ (no pitch angle), with the grasping success rate decreasing as θ increased. The cross-shaped gripper performed slightly better at angles above 30°, while the single-band had more successful grasping for angles less than 30°.

D. Grasping real-world objects

We finally demonstrate the grasping ability of both grippers with many real-world objects, such as plastic water bottles, video game controllers, sunscreen bottles, screwdrivers, school glue, wiffle balls, and a 5-pound kettlebell. For these demonstrations, we first secure the gripper in an inverted position and then manually feed various objects to activate the gripper by hand. The objects are then left hanging in the grippers, with more than 30 s without falling being considered a successful grasp. The grippers are then tested for both vertical and horizontal grasping, where the PSSB is oriented facing sideways, and downwards respectively. The results can be seen in Fig. 7. The results show the ability of both grippers to grasp a wide variety of real-world objects with different weights and geometry. For horizontal grasping, the single-band gripper can grasp various objects successfully. It does, however, struggle with larger, heavier objects like the water bottle and video game controller (Fig. 7A). While the cross-shaped gripper can successfully grasp the same objects as the single-band gripper, it performs much better when holding larger, heavier objects like the game controller and water bottle (Fig. 7B). The cross-shaped gripper also excels in vertical grasping, being able to hold a full water bottle, sunscreen bottle, and game controller, while the single-band gripper fails to grasp these objects. The vertical grasping results for both grippers are shown in Fig. 7C.

IV. CONCLUSIONS

In this paper, we present two passive bistable gripper designs (single-band and cross-shaped) that can automatically initiate grasping upon contact with an object using bistable spring steel beams. Both grippers can close rapidly (less than 0.24 s) and sequentially using a friction adjustment mechanism to allow for overlapping PSSB ends. Both grippers can successfully grasp for a wide range of varying conditions, including cylinder diameters ($2 - 10$ cm for both), offset angles ($30° - 90°$ for the single-band, $0° - 45°$ for the

Fig. 7. Object grasping performance for both grippers in the horizontal axis where: (A) Horizontal grasping for the single-band gripper for (left to right) a video game controller, half-full plastic water bottle, full sunscreen bottle, wiffle ball, screwdriver, and 5 pound kettlebell. (B) Horizontal grasping for the cross-shaped gripper for the same objects as the single-band gripper; (C) Vertical grasping for both grippers with (left to right) a game controller, a full plastic water bottle, and a full sunscreen bottle.

cross-shaped), and pitch angles ($0° - 30°$ for single-band, $0° - 45°$ for cross-shaped). Both grippers can grasp a wide range of real-world objects, including plastic water bottles, video game controllers, etc. The cross-shaped gripper excels in vertical grasping of objects compared to the single-band gripper. We expect our gripper can potentially enable better aerial grasping when they are attached to a flying robot, which may not require precise position/orientation control during the grasping process.

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