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Ultrafast capturing in-flight objects with reprogrammable working speed ranges

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Abstract—**In-flight high-speed object capturing is crucial in nature to improve survival and adaptation to the environment, such as the predation of frogs, leopards, and eagles. Despite its ubiquitousness in nature, capturing fast-moving objects is extremely challenging in engineering implementations. In this paper, we report an ultrafast gripper based on tunable bistable structures. Different from current designs which are only suitable for objects with certain speed ranges once the grippers are fabricated, the working range of object speed of the proposed gripper could be reprogrammed by controlling the sensitivity of the structures. We present the design and fabrication of the proposed gripper in detail. A theoretical model is introduced to construct the energy landscape of the structures and the force response of the gripper when programmed to different states. The results show that in the original state, the gripper is capable of capturing a flying table tennis ball with a high speed of 15 m/s in only 6 ms. When the proposed gripper is controlled to the ultra-sensitive state, a flying ball with only 1 m/s could also be captured. This work broadens the frontiers of in-flight capturing design, and we envision broader promising applications.**

I. Introduction

In nature, the ability to capture in-flight high-speed objects is of importance for many plants and animals to improve their survival and occupy the certain ecological niche [1]. For instance, the frogs and chameleons can capture flies fleetly with their ultrafast tongues [2, 3]. In addition, the top predators in nature, like leopards and eagles, could capture their preys even if the preys try to escape with a high moving speed [4, 5].

To mimic the unparalleled ability of natural creatures to capture in-flight high-speed objects, researchers have tried their best to design ultrafast robotic grippers [6-8]. However, fast-flying objects capturing is always a challenging task in engineering implementations, restricted by the detection and response speed of grippers. Most of current works focus on the precise trajectory prediction of the fast-moving objects based on advanced algorithms or machine learning approaches, and then put the grippers or hands in the right place for fast grasping [9-15]. Nevertheless, these active detection-and-move methods always requires high computing costs, and these robots are usually very large in dimension (meter-sized) to accommodate the accessory sensing and actuation equipment. Restricted by the response speed of the robotic grippers, current designs are hard to cope with fast-flying objects when their moving speed exceeds 10 m/s.

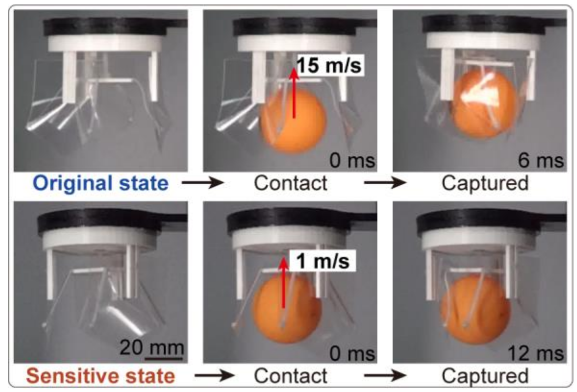

Figure 1. The working range of object speed for the proposed gripper.

Recently, more and more researchers turn back to the design of the robotic grippers. By proposing many novel mechanisms, sensors, and actuation methods, researchers hope that the grippers could handle more difficult grasping and manipulation tasks by taking advantages of the machine intelligence of the grippers themselves [7, 8]. In these designs, bistable structures which could shift between different stable states have attracted increasing attentions in constructing robotic grippers. When triggered by external physical stimulation, bistable structures could quickly release the stored strain energy when changing from one stable state to the other, which brings fast response and force amplification properties. Owing to their remarkable performances in fast response, power amplification, and self-lock ability [16, 17], bistable actuators have been widely applied in grippers and other applications [18-22]. However, capturing objects with a speed exceeding 10 m/s remains challenging. Furthermore, the speed range of the objects that current grippers could capture are inalterable once the grippers are fabricated, which limited their adaptation to different working scenarios [23-25].

In this work, we report the design and demonstration of an ultrafast gripper based on tunable bistable structures (Fig. 1). We first introduce the design of the gripper and explain the working principle in detail of how we can reprogram the

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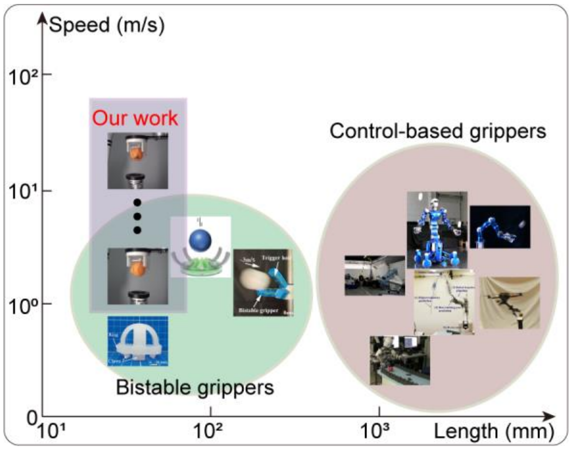

Figure 2. Comparison of the length scale and working range of object speed of our work versus those from the robotic grippers reported in literature [10-15, 23-25].

working range of object speed. To reveal the mechanics of the proposed gripper when adjusted to different states and construct its energy landscape, we provide a mathematical model based on bar-and-hinge discretization method [26]. Then, we prototype a gripper and experimentally characterize the required trigger energy when the gripper is adjusted to different states. After that, we conduct experiments to analyze the feasible speed range of the objects that the proposed gripper could capture in different states. The results of our work have also been compared to those reported in literature (Fig. 2). To validate the promising potentials of the proposed gripper, we also demonstrate its ability in selectively capturing objects with different speeds.

The main contributions of this work are:

- Compact design of an ultrafast gripper for in-flight capturing of objects with reprogrammable speed ranges;
- A bar-and-hinge method-based mathematical model to reveal the mechanics of the gripper when adjusted to different states;
- Characterization and demonstration of the proposed gripper in different working scenarios.

II. Design of the Ultrafast Gripper

In this section, we present the system overview of the proposed ultrafast gripper, and then introduce the principles of how the gripper could adjust its sensitivity to the speed of the flying objects so that it can reprogram the working range of object speed. After that, we describe the mathematic model in detail to reveal the mechanics of the proposed gripper.

A. System overview of the gripper

The basic framework and main components of the gripper is illustrated in Fig. 3. The gripper consists of three modules for different functions: three bistable origami plates to act as the "fingers" of the gripper, a control module to adjust the sensitivity of the gripper, and a 3D printed base as well as other ancillary parts to install the origami plates and control module.

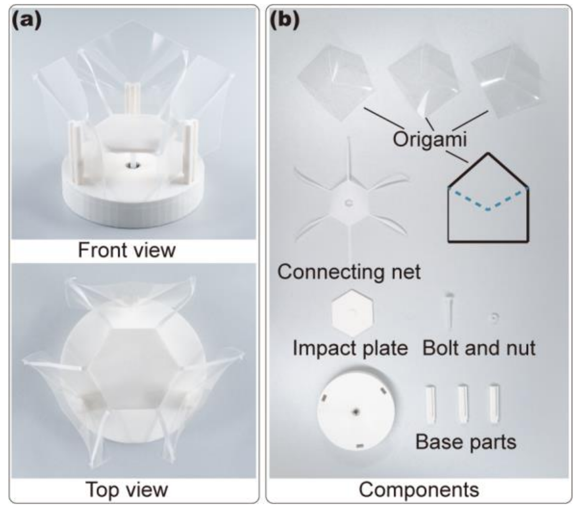

Figure 3. Schematic of the proposed ultrafast gripper. (a) Front view and top view of the prototyped gripper. (b) Components of the gripper.

The origami plates are fabricated by folding along the crease lines on pentagonal sheets as in Fig. 3(b). When the gripper is triggered, the bistable origami plates could transit from their open state (metastable state) to the closed state (stable state) in a short time to capture the flying objects and continuing trap it based on the intrinsic self-lock ability. The detailed working principle and force response of the bistable origami plate are given in the following sections.

The control module is made of a laser-cut connecting net to connect the module to the origami plates, a 3D printed impact plate to prepare for the contact of the flying objects, and a bolt-nut component to adjust the sensitivity of the proposed gripper. In the next section, we will introduce in detail the working principles on the sensitivity adjustment.

Of note, in this work, we use PET sheets to construct the origami plates, PLA materials to 3D print the impact plate and base, TPU-fabric membrane to fabricate the connecting net with a laser-cut machine, and a nylon bolt-nut to adjust the position of the impact plate. Based on the design principle introduced in this paper, we believe that other reasonable materials, dimensions, and configuration could also work.

B. Mathematical modeling of the gripper

Constructing the thorough energy landscape of the bistable actuator and capturing their kinematic and mechanic properties during transitions among different states have always been of importance to reveal the underlying fast-response principles of bistable structures. Here we present a mathematical model of the ultrafast bistable gripper based on bar-and-hinge discretization method [26-28].

First, we provide a parameterized description of the proposed gripper to investigate the relationship between the height of the impact plate and the shape of the three origami plates when the gripper is in its different states. As illustrated in Fig. 4, we can obtain that

$$D_{op} = \sqrt{L_{net}^2 - H_{net}^2 - W_0^2} \quad (1)$$

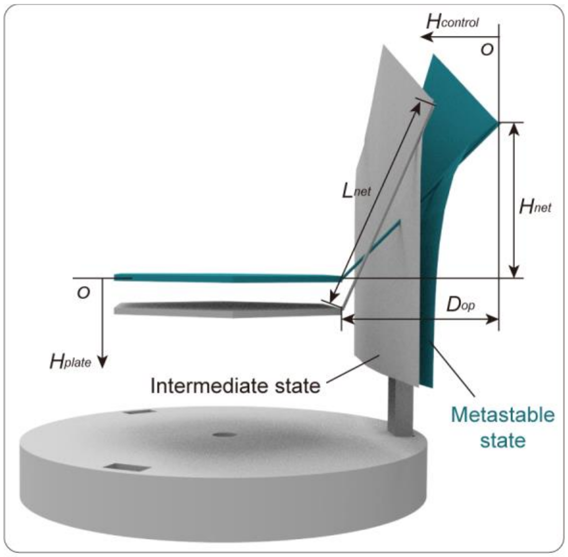

Figure 4. Parameterized description of the proposed gripper with only one origami plate is shown to study the relationship between the controlled height of the impact plate and the shape of the origami plate.

where D_{op} denotes the distance of the distal point of the origami plate to the proximal point of the impact plate which is also related to the parameter $H_{control}$ as depicted in Fig. 4, L_{net} is the length of the cable on the connecting net between the origami plate and the impact plate, H_{net} and W_0 are the height and width of the cable (W_0 is not shown on the figure for simplification), respectively. H_{net} is related to the height of the impact plate H_{plate}.

When adjusting the gripper to different states, we tune the height of the impact plate H_{plate} by turning the nut as in Fig. 3(b). When H_{plate} changes, the origami plates deform accordingly induced by the pulling forces of the connecting net. Hence, the whole strain energy stored in the origami plates changes and the gripper get to its different states with reprogrammable energy barriers before it is triggered (we define it as trigger energy in this paper) by external flying objects.

To determine how the trigger energy of the gripper varies when the gripper is adjusted to different states, we need to construct the energy landscape of the origami plates during deformation. In this model, we discretize the origami plate into a bar-and-hinge frame as illustrated in Fig. 5. To thoroughly capture the kinematic and mechanics of the origami plate, the discretized frame is compose of three types of elements: (1) folding hinges along the creases to capture the crease opening and folding during deformation; (2) bending hinges in the non-rigid panel to describe the out-of-plane bending motion between discretized triangles; (3) truss bars that form the triangles to calculate the stretching and shearing of the panel.

During the deformation, the strain energy variation of the origami plate is induced by the three types of elements. Quantitative descriptions could be given as:

$$\begin{gathered}\Pi = E_{folding} + E_{bending} + E_{bar} - E_{external} \\ E_{folding} = \sum_{i=1}^{P} \frac{1}{2} k_f (\varphi_i - \varphi_0)^2 \\ E_{bending} = \sum_{j=1}^{M} \frac{1}{2} k_b \theta_j^2 \\ E_{bar} = \sum_{q=1}^{N} \frac{1}{2} k_s \delta^2 \end{gathered} \tag{2}$$

where Π denotes the total strain energy stored in the gripper; the folding energy $E_{folding}$ denotes the strain energy stored in the folding creases which is a function of the folding stiffness

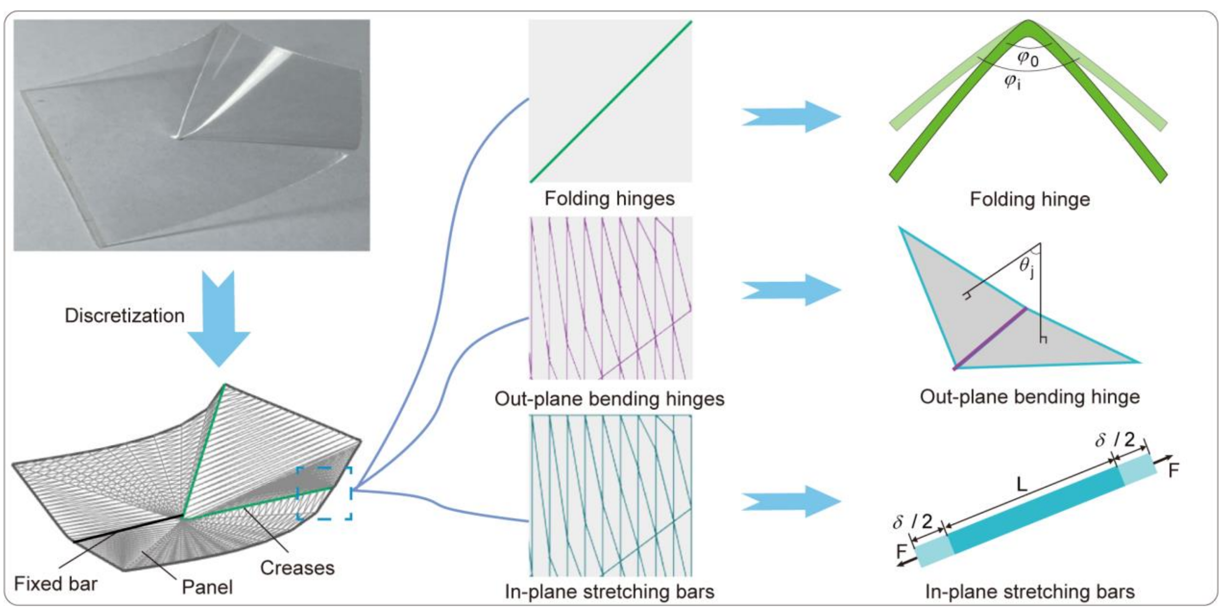

Figure 5. Schematic of the proposed bar-and-hinge method-based triangulated discretization model of the origami plate in which the deformation of the origami plate is split into three main parts: folding hinges along the folded creases, bending hinges in the panel between the triangles, and stretching bars that form the triangles.

k_f and the variation of the dihedral angle φ_i of the triangular panels on both sides of the crease compared to its initial value φ_0; the bending energy $E_{bending}$ indicates the deformation of the bending hinges between the truss bars, which can be described by the bending stiffness k_b and the dihedral angle of the triangular panels on both sides of the bending hinges θ_j; the bar energy E_{bar} represents the stored energy due to the stretching and shearing of the truss bars, related to the bar stiffness k_s and bar elongation δ; the energy $E_{external}$ means the energy variation caused by the external impact of the flying objects; P, M, N indicate the amounts of the folding hinges, bending hinges, and in-plane bars, respectively.

The stiffness of the three types of elements could be further described as

$$k_f = \frac{L_f}{L^*}\frac{Et^3}{12(1-v^2)}$$
$$k_b = \frac{Et^3}{6}\frac{L^2}{A_1 + A_2} \tag{3}$$
$$k_s = \begin{cases} \left(\frac{h^2}{2w^2} + \frac{5}{4}\right)\frac{EA_{tri}t}{L^2}, Diagonal\ bars \\ \frac{EA_{tri}t}{L^2}, \quad Non-diagonal\ bars \end{cases}$$

where the detailed explanations of each parameters could be found in our previous work [26].

Combining the Equations (2) and (3), we can obtain the relationship between the strain energy of the bistable origami plate and its structural parameters when triggered by external forces. To quantitatively analyze the force response and energy variation of the origami plate, we propose a multi-loading bar-and-hinge simulating program [26-28].

Figure 6 shows the calculation results. As illustrated in Fig. 6(a), we apply pushing forces F_p on the distal points of the creases and calculate the force-displacement response as the origami plate transits from the metastable state to its stable state. The results in Fig. 6(b) depict that the pushing force increases gradually at the beginning as the origami plate is in the intermediate states between the metastable state and the critical state. Meanwhile, the total strain energy accumulates in this process. Once the origami plate turns to its critical state,

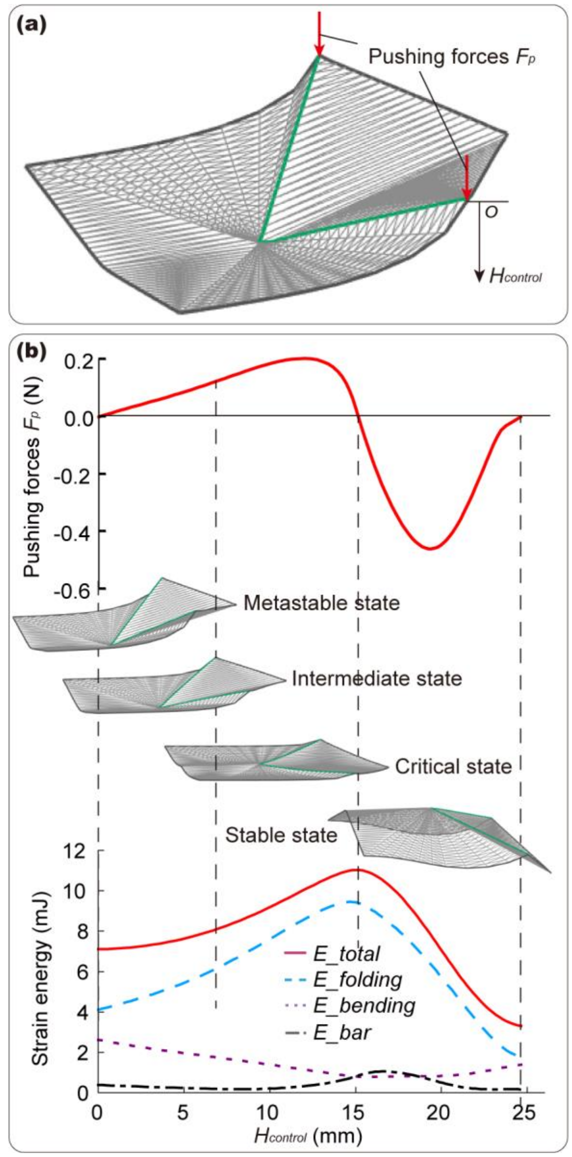

Figure 6. Force-displacement analysis and strain energy landscape construction of the origami plate when transits from its metastable state to the stable state. (a) Parameterized description of the external trigger force and the corresponding displacement. (b) Force response and energy landscape of the bistable origami plate during the transition.

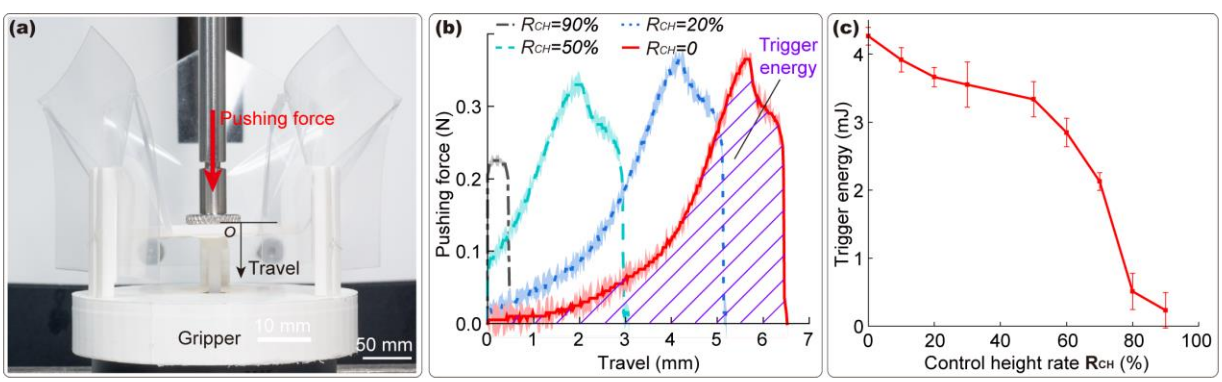

Figure 7. Quasi-static experimental analysis of the force response and trigger energy variation of the proposed gripper when adjusted to different states. (a) The test platform. (b) Experimental results of the pushing forces and the related travels for the tests on the gripper in different states. (c) Required trigger energy of the gripper for different control height rate.

the pushing force decreases rapidly to be negative, and the total strain energy stored in the origami plate reaches its maximum value. In this state, the origami plate is quite unstable, and any tiny physical stimulation could trigger it to the stable state and release large amounts of energy in a short time according to our previous work [26]. Hence, by adjusting the nut in the control module as introduced above, we can reprogram the sensitivity of the proposed gripper so that it can capture flying objects with different speed ranges.

III. Characterization and Demonstration

In this section, we experimentally characterize the performances of the proposed gripper, including the force response, adjustable sensitivity range, and object speed ranges that the gripper can capture when reprogrammed to different states. Furthermore, we demonstrated the gripper in selective capturing to show the potential in real-life applications.

A. Quasi-static characterization of the gripper

To observe the force response and trigger energy adjustment range of the proposed gripper more intuitively, we prototyped a gripper and conducted quasi-static experiments.

The test platform is given in Fig. 7(a). We first reprogram the state of the gripper by tuning the height of the impact plate and then press down the plate slowly with a load cell. Meanwhile, the pushing force and travel were recorded.

To describe the different states quantitatively, we define a control height rate R_{CH} as

$$R_{CH} = \frac{H_{CH}}{H_{stroke}} \tag{4}$$

where H_{stroke} means the whole height variation of the impact plate when the origami plate transits from its metastable state to its critical state, H_{CH} denotes the controlled height variation of the impact plate during the reprogramming process where we pull down the impact plate by turning the bolt-nut system. To sum up, $R_{CH} = 0$ means that we do not adjust the gripper and it is in its original state with the largest trigger energy. As the parameter R_{CH} gets higher, the trigger energy decreases and the gripper becomes more sensitive to external stimulation. When $R_{CH} = 100\%$, the gripper gets to its critical state and could close itself automatically.

The results in Fig. 7(b) illustrate that as R_{CH} increases, the maximum pushing force descents and the travel of the impact plate decreases gradually. By calculating the area formed by the force curve and the travel line, we can obtain the trigger energy that the load cell exerts on the gripper before the gripper reaches its critical state and then close itself rapidly because of the bistability of the origami plates. The results in Fig. 7(c) show that the trigger energy could be reduced from 4.3 mJ when the gripper is in its original state with $R_{CH} = 0$ to merely 0.2 mJ for the sensitive state with $R_{CH} = 90\%$.

B. Working range of object speed of the gripper

To obtain how the reprogrammable trigger energy could contribute to the adjustable working range of object speed, we prepared a test platform as in Fig. 8(a). As illustrated, the proposed gripper was mounted on a robotic arm for better position modulation and control, a launcher was installed beneath the gripper to control the speed of a table tennis ball. The launcher controls the ball speed with the help of a steel spring. By tuning the initial compression height of the spring before releasing, we can adjust the speed of the table tennis

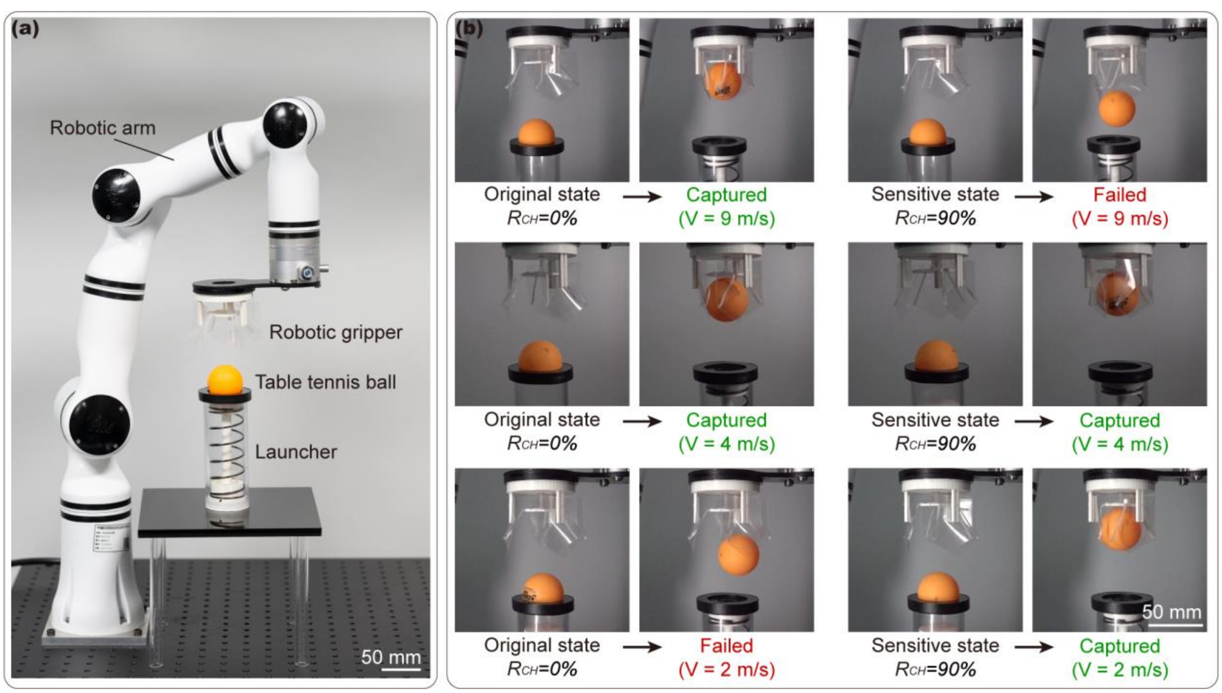

Figure 8. Demonstration of the proposed gripper in selective capturing of in-flight objects with different speeds. (a) The platform consists of a robotic arm, a prototyped robotic gripper, a table tennis ball, and a device to launch the ball. (b) Snapshots of the selective capturing demonstration to validate that the proposed gripper could capture in-flight objects with different speeds by reprogramming its sensitivity.

ball roughly. In the experiments in this paper, the ball speed was obtained carefully by calculating the video frames and related displacements (the videos were in high frame rate).

We first reprogram the proposed gripper to different states with $R_{CH} = 0$, 50%, and 90%, respectively. Then, we shot the table tennis ball to the gripper with different speed to test if the ball could be captured and obtained the working range of object speed for the gripper in different states.

The results are given in Table I. As described, the gripper could catch a flying table tennis ball with a high speed of 15 m/s, which is much higher than that from the work reported in literature [23-25]. However, the table tennis ball slower than 3 m/s could not be captured by the gripper because the impact energy didn't break the trigger energy barrier in this state.

TABLE I. REPROGRAMMABLE WORKING RANGE OF OBJECT SPEED OF THE PROPOSED GRIPPER

Control height rate R_{CH}	**Working range of object speed**	
	Lower limit of velocity (m/s)	***Upper limit of velocity (m/s)***
0	3	15
50%	1.9	11.7
90%	1	8.4

When we reprogrammed the gripper to its sensitive state with $R_{CH} = 90\%$, the maximum working object speed decreased to 8.4 m/s because that in this state, the trigger energy was adjusted to be quite small and the gripper is very sensitive to external stimulation. If the ball moves too fast, much more impact energy could not be absorbed by the gripper, and the ball escaped rapidly. However, the lower speed limit in this sensitive state decreased significantly to merely 1 m/s. It is because that the trigger energy in the sensitive state is much smaller that a flying ball with a low speed could also break the trigger energy barrier and be captured by the gripper.

By reprogramming the state of the proposed gripper, the working range of object speed of the gripper could be further enlarged. In this case, the overall speed range is 1 to 15 m/s as illustrated in Fig. 1 and the supplementary video.

C. Demonstration in speed-based selective capturing

Based on the platform as described in Fig. 8(a), we also demonstrated the proposed gripper in object speed-based selective in-flight capturing. The results are given in Fig. 8(b).

As illustrated, we conducted three groups of experiments in which the ball speed was 9, 4, and 2 m/s, respectively. In each experiment group, the gripper was in its original state with $R_{CH} = 0$, and sensitive state with $R_{CH} = 90\%$, respectively. Then, the gripper tried to capture the table tennis ball with different speed. The results in Fig. 8(b) show that for a high-speed table tennis ball (9 m/s), the gripper in its original state could capture it easily, while the gripper in the sensitive state failed. For a ball with a medium speed (4 m/s), the gripper in both states succeeded to capture the ball. For a relatively slow-speed ball (2 m/s), only the gripper in the sensitive state captured the ball, and the original state failed.

The results validated that by simply reprogramming the states of the proposed gripper, we could realize object speed-based selective capturing. This might found potential application in our real life in the future.

IV. CONCLUSION

In this paper, we present a compact design of an ultrafast bistable gripper with programmable working range of object speed for in-flight capturing. We introduced the structural design, working principle, theoretical model, experimental characterization and demonstration of the proposed gripper to investigate the design comprehensively. The results show that the trigger energy of the gripper could be reduced from 4.3 mJ to merely 0.2 mJ by reprogramming the sensitive state before capturing. Besides, the working range of object speed for in-flight capturing of the proposed gripper could be significantly enlarged by adjusting the trigger energy. In total, the gripper could capture a table tennis ball with a speed range from 1 to 15 m/s, which exceeds the ranges of most grippers reported in literature. Furthermore, we experimentally validated that the proposed gripper could realize an object speed-based selective in-flight capturing by adjusting the gripper to different states with varied trigger energy.

This work could broaden the design space of ultrafast grippers and inspire more functional designs based on the own machine intelligence of the mechanisms. In the future, we will expand the ultrafast gripper design and investigate its applicability for different structural configuration, dimensions, and materials. In addition, the integration with agile carriers and advanced control algorithms will be studied to realize more elaborate and practical applications.

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