Insect Tarsus-Inspired Compliant Robotic Gripper with Soft Adhesive Pads for Versatile and Stable Object Grasping

Sujet Phodapol[1], Atthanat Harnkhamen[1], Naris Asawalertsak[1], Stanislav N. Gorb[2]
Poramate Manoonpong[1,3,*], *Senior Member, IEEE*

***Abstract*—Grasping multiple object types (versatile object grasping) with a single gripper is always a challenging task in robotic manipulation. Different types of grippers, including rigid and soft, have been developed to try to achieve the task. However, each gripper type is still restricted to specific object types. In nature, many insects can be observed to use only one tarsus mechanism to cope with several tasks. They have a very high grasping capability with objects and can adhere to a variety of surface types. Inspired by insect tarsus, this paper proposes a novel underactuated, single cable-driven, compliant gripper design. The structure of the gripper is based on the hornet tarsus morphology with a proportional scale. An additional pulley-like structure is introduced to increase the generated grasping torque. To maintain the ability to automatically rebound back to the original position, a torsion spring is implemented at each joint. In order to stably grasp and hold objects, soft adhesive pads with an asymmetric sawtooth-like surface structure are attached at the tarsus segments. The performance of this insect tarsus-inspired gripper with the soft pads is evaluated by grasping 35 different objects of various sizes, shapes, and weights for comparison with industrial soft and rigid grippers. The proposed gripper shows a 100% success rate in grasping all objects, while the soft and rigid gripper success rates are 81.90% and 91.43% on average, respectively. We finally demonstrate the use of our gripper installed on a robot arm for pick-and-place and pouring tasks.**

Bio-inspired Gripper, Hybrid Soft-Rigid Gripper, Object Manipulation, Insect Tarsus, Hornets

I. INTRODUCTION

ONE of the challenges of object manipulation is the versatility to grasp and manipulate objects of multiple types and shapes. Over the years, various gripper types have been designed and developed. Conventional rigid grippers with rigid joints and fingers for industrial applications have been in operation for many decades [1], [2]. Typically, such grippers with two or three fingers are used for tasks requiring high precision and a strong gripping force. Despite being able to grasp several industrial objects, they are less flexible and have limitations when dealing with complex, soft/deformable, or brittle objects (e.g., grasping a plastic cup for a pouring task (Fig. 1)). Without sensor feedback, they might apply too much force, potentially squeezing or even damaging the cup, or use too little force, causing the object to slip.

To improve gripper flexibility and comply with the grasped object, tendon-driven or cable-driven grippers have been developed [4], [5], [6]. This type of gripper exploits passive compliance and underactuated mechanisms. The gripper typically requires a minimum of two actuators with an agonistic-antagonistic setup or two/three fingers to tightly grasp the

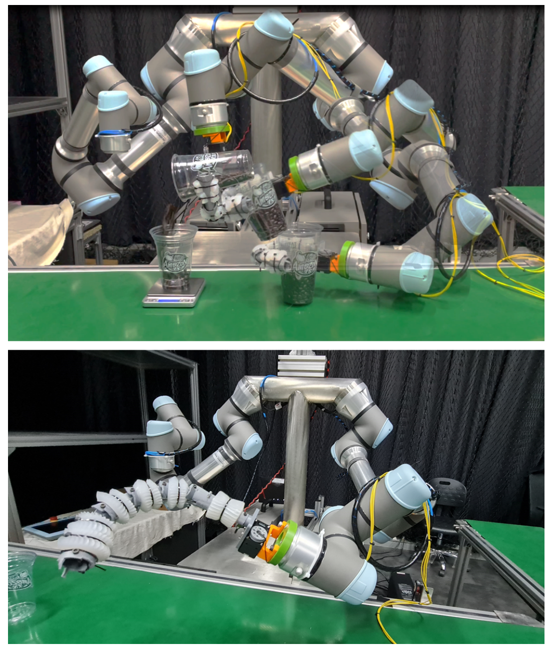

Fig. 1: Demonstration of a complex manipulation task (grasping a plastic cup and performing the pouring task) achieved by our proposed INSECT tarsus-inspirEd compliant Robotic gripper with soft adhesive pads (INSECTER) (top). The gripper is attached to a collaborative robot arm (UR5e) (bottom). The gripper can maintain a stable grip without crushing the cup or requiring sensory feedback. In contrast, this might be difficult to achieve using a pure rigid gripper; unless a special handler is attached to the cup or force/tactile sensing is used [3].

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[1]S.P., A.H., N.A., and P.M. are with the Bio-inspired Robotics and Neural Engineering Laboratory, School of Information Science and Technology, Vidyasirimedhi Institute of Science and Technology, Rayong, Thailand.

[2] S.N.G. is with Department of Functional Morphology and Biomechanics, Zoological Institute, Kiel University, Kiel, Germany.

[3]P.M. is also with the Embodied Artificial Intelligence and Neurorobotics Laboratory, SDU Biorobotics, the Mærsk Mc-Kinney Møller Institute, University of Southern Denmark, Odense, Denmark. (e-mail: poramate.m@vistec.ac.th)

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object from both sides at the same time [7], [8]. An advanced tendon-driven five-fingeredgripper, like shadow hand from the shadow robot[1], demonstrates a wide range of manipulation applications like the human hand. Despite its sophisticated manipulation capabilities, it has 20 active joints and four passive joints for 24 degrees of freedom (DOFs) in total, requiring sophisticated control methods [9].

To reduce hardware and control complexities while being able to manipulate complex objects, soft manipulators/grippers inspired by nature have been introduced [10], [11]. Most of these grippers exploit the advantage of their morphology, soft material, and interaction with an object to simplify their control mechanisms. In other words, they can perform complex grasping motions without requiring complex control signals by offloading control computation to morphological computation [12]. For example, several soft grippers, based on an octopus tentacle, have been developed [13], [14], [15], [16], [17], [18]. They mimic the natural grasping motion of the tentacle to handle objects of various shapes and sizes. Another type of soft gripper is a continuum, helical soft fabric gripper, replicating the motion of helical gripping in nature (e.g., elephant trunk and snake) [19]. With a variable stiffness structure, this gripper can lift heavy objects and those of various shapes. In addition to purely soft or rigid grippers, there are also hybrid soft-rigid grippers [20], which demonstrate a better gripping force than soft grippers with vacuum and inflation pressure (pneumatic actuators). While all these purely soft or hybrid grippers show impressive grasping abilities, they need sophisticated fabrication. Additionally, soft grippers might exhibit material memory effects and low durability.

Alternatively, a jamming-based gripper containing granular material [21], [22] can be simply built[2]. It uses the principle of jamming granular material with multiple states (soft/deformable (unjammed) and rigid (jammed)) and their transitions for grasping a wide range of objects. All these states are controlled by vacuum and inflation pressure. The jamming-based gripper also utilizes friction, suction, and interlocking mechanisms to create a strong gripping force. However, the gripper can be destroyed or torn if it touches the sharp part of the grasped object unless a special material or complex structure design with string jamming is applied [23]. Since jamming-based and soft grippers require vacuum and inflation pressure, the use of an external air compressor and a vacuum pump is inevitable. As a result, the whole system (gripper with power source) is bulky and heavy, making it unsuitable for installation on a small mobile manipulator system (small mobile robot with a manipulator).

Due to existing gripper limitations described above, in this work, we propose an alternative INSECT tarsus-inspirEd compliant Robotic gripper with soft adhesive pads (INSECTER) (Figs. 1 and 2). Its underactuated structure is designed based on modular segments with mechanical stoppers, torsion springs, and a simple (single) cable-driven mechanism. The gripper uses only one single electric actuator, while its structure can be easily fabricated using a 3D printing machine. The use of the standard polylactic acid (PLA) filament material for printing the structure offers greater cut or sharp resistance and durability than purely soft silicone/rubber-based grippers. The compliance of the gripper helps to prevent impact damage and provides a safe gripper operation[3]. With the single cable-driven mechanism, we can easily control the gripper to perform a grasping motion akin to an insect tarsus (i.e., wrapping around the object) for handling various objects. The generated grasping by wrapping around an object [24] allows the gripper to handle object misplacement during grasping. By attaching soft adhesive pads to the gripper, we can increase the gripping force for stable object holding. With all its features, the gripper can versatilely deal with at least 35 different objects (tested here). While the insect-inspired tarsus structure has been utilized in other robotic applications, like robot foot development [25], to the best of our knowledge, applying it as a robotic gripper with the special features shown here has not previously been demonstrated. Thus, the contributions of this work can be summarized as follows:

- We propose an insect tarsus-inspired, underactuated, compliant gripper with its insect tarsus-like gripping (wrapping) technique. The novel gripper, based on cable-driven and pulley cable guiding mechanisms, integrated torsion springs, and soft adhesive pads, is easily operated by a single electric actuator. Our approach solves the problem of grasping closed-form, round-shaped, and large-sized objects which are difficult to be grasped by conventional soft and rigid grippers[4].
- We detail the mechanical design and provide an in-depth analysis of the gripper.
- We validate the performance of the gripper to handle various objects and compare it with conventional industrial soft and rigid grippers.
- We demonstrate the use of the gripper installed on a robot arm for pick-and-place as well as pouring tasks. We also show that the used grasping technique by wrapping around an object, inspired by the mono grasping motion (flexion) of an insect's tarsus, can facilitate a stable picking up of a container (e.g., a plastic coffee cup) for a pouring task[5].

II. INSECT TARSUS

In nature, insects use their functional segmented tarsus or tarsal chain (foot) as a versatile gripper to attach to different types of surfaces and grasp objects [26]. It consists of several flexibly interconnected segments (tarsomeres). The tarsal chain is mainly operated by a single muscle, which is situated in femur and tibia and connected with the claws through very long tendon (Fig. 2a). The tarsus bends from the claws toward the base when a pulling force is applied to the retractor tendon (Fig. 2c); thereby wrapping around an object. All elements of the tarsal kinematic chain have one active degree of freedom [27]. It has been previously demonstrated that

[1] https://www.shadowrobot.com/

[2] https://www.youtube.com/watch?v=3OjhoVuAQkQ&t=126s

[3] A demonstration video of the gripper function and its compliance can be seen at www.manoonpong.com/INSECTER/VideoS1.mp4.

[4] www.manoonpong.com/INSECTER/VideoS3.mp4

[5] www.manoonpong.com/INSECTER/VideoS5.mp4

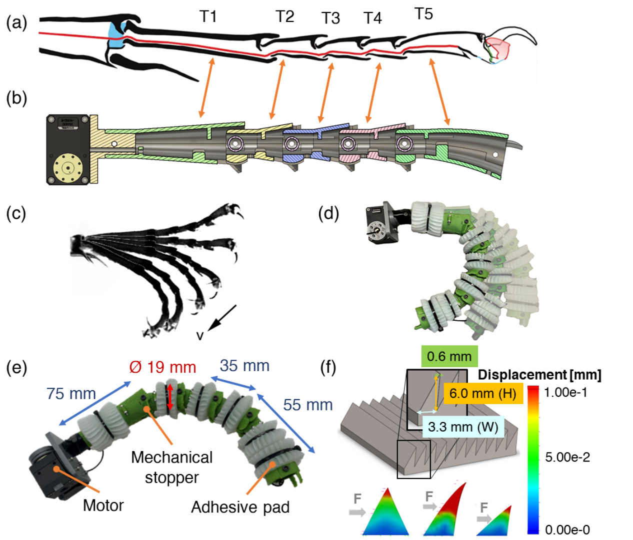


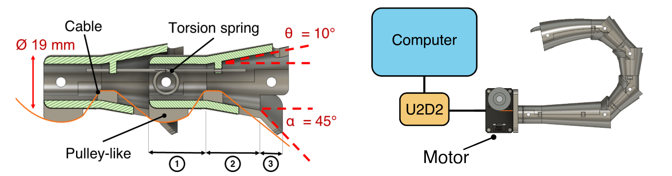
Fig. 2: (a) and (b) The cross section of a real insect leg with five segments and a tendon-driven mechanism (reproduced from [30] with permission, Copyright 2004, Elsevier) and the gripper (INSECTER) with five similar segments and a cable (tendon)-driven mechanism. (c) and (d) The mono grasping motion (flexion) of the insect tarsus (reproduced from [30] with permission, Copyright 2004, Elsevier) and the gripper. (e) The dimensions and important features of the gripper. It consists of five 3D-printed PLA segments with integrated torsion springs, mechanical stoppers, soft (silicone) adhesive pads, and one Dynamixel actuator. The total weight of the gripper is 162 g. (f) The soft pad with an asymmetric sawtooth-like surface structure (used here) and finite element analysis (FEA). The measured displacement (bending) gradients of different structure designs (i.e., symmetric sawtooth structure (SS, left), asymmetric sawtooth structure with a high height(H)-to-width(W) ratio of approximately 1.8 (ASH used here, middle), and asymmetric sawtooth structure with a low height(H)-to-width(W) ratio of approximately 0.9 (ASL, right)) are compared under an applied force (F) of 0.1 N. The regions with relatively significant displacement are indicated in red and yellow. As can be observed, the asymmetric profile with the high ratio shows higher deformation (displacement) than the other profiles; therefore, it is appropriate for use in gaining high contact area-mediated friction for stable grasping. Note that further FEA analysis of other structures (e.g., half-circle, square) can be seen in [31].

tarsal chain rigidity, measured with the force tester, increases, when the retractor muscle tendon was tightened [28]. Inspired by this, we have preliminarily investigated and translated the segmented tarsus for a robot gripper [29]. This study significantly extends our previous investigation in terms of design iteration, in-depth analysis, system validation, and use case demonstrations.

III. Insect Tarsus-Inspired Gripper Design

A. Mechanical Design and Control

This section describes in detail the gripper's mechanical design. Here, the structure of our gripper (INSECTER), after the hornet (*Vespa crabro*) [30], is shown in Fig. 2. The hornet tarsus consists of five hollow segments (T1–T5). Additionally, there are two claws at the end of the last segment (T5) and an adhesive organ called arolium. According to the hornet tarsus, the INSECTER gripper also has a total of five segments of varying lengths. The size of each segment is proportionally scaled from the tarsus structure, joined together by a revolute joint. For the sake of simplicity, the claw mechanism and function are omitted in this design. As shown in Fig.3a, the underactuated gripper is driven by a single cable, functioning as a tendon in the real insect tarsus.



(a) Cross section of the gripper (b) System overview

Fig. 3: The gripper mechanism. The cable/tendon for driving the gripper is shown in orange. It goes through all the segments via the pulley-like parts (curvature). The mechanical stoppers prevent excessive gripper hyperflexion, while the torsion spring in each joint passively returns the gripper to its default position. Each segment consists of ① a base, ② main body, and ③ mechanical stopper. In order to operate the gripper, the current/torque control signal from the computer is manually given through the U2D2 interface.

The gripper structure includes pulley-like parts. These are used to increase the radius of the pivot, resulting in more torque with the same pulling force and thus increasing the gripping force. The cable is pulled by an actuator, as shown in Fig. 3b. The actuator is interfaced with a desktop computer through a communication converter (U2D2). The required torque for the actuator can be estimated from the tension of the cable (T or pulling force). From the INSECTER free body diagram (FBD, Fig. 4), the required cable tension is calculated as follows:

$$T = (r_2 \times F_g)/r_1, \quad (1)$$
$$F_g = F_h/\mu, \quad (2)$$

where F_h is the maximum-designed holding force, which should be greater than the load or grasped object weight (i.e., 20 N). μ is the friction coefficient between the soft adhesive pad and grasped object (e.g., plastic cylinder), which is approximately 2.103. F_g is the gripping force (or normal force), which is approximately 9.5 N. Based on our design, r_1 and r_2 are 12.5 mm and 27.5 mm, respectively (Fig. 4). According to the analysis, we use a Dynamixel servo motor (XM430-w350-r) as our actuator which can provide enough torque to generate the cable tension T of approximately 21 N.

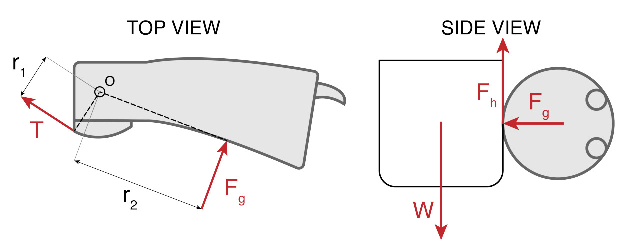


Fig. 4: The free body diagram describing the interaction force between the gripper and grasped object. F_h is the holding force. F_g is the gripping force. T is the cable tension of the gripper. r_1 and r_2 are the radius of the pivot and the estimated distance between the contact point and pivot.

A simple current (torque) control method is implemented on the computer to actuate the grasping motion of the gripper. The control method has the advantage of being able to stop and prevent the gripper from breaking the grasped object. The signal is set to 1.0 to activate it, as shown in Fig. 5. As a result, the cable is pulled, and the gripper flexes or bends, demonstrating its grasping motion (Fig. 2d). On the other hand, the gripper can automatically and passively rebound back to release the object by setting the control signal to 0.0. This automatic rebounding back to release the object or return to its original position is achieved by the installation of a torsion spring in each joint of the gripper. The spring stiffness varies at different joints (the closer to the base, the stiffer the spring). This is because, in the horizontal posture, the joint closer to the actuator/base is subjected to more gravitational force because it must also bear the load/weight of distal joints. Through our empirical investigation, the spring constants are set to 3.28, 3.12, 2.86, 2.34, and 2.09 Nmm/deg from the base (T1) to tip (T5), respectively.

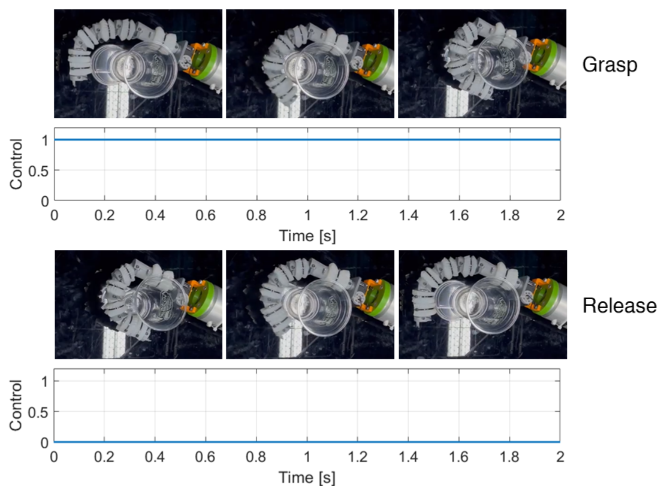


Fig. 5: Insect tarsus-inspired gripper actuated by a single and simple control signal. Setting the signal to 1.0 (on) causes the gripper to grasp the object, while setting the signal to 0.0 (off) causes the gripper to release the object and passively rebound back to its original position due to the torsion springs

The minimum grasping radius of the gripper is constrained by the mechanical stoppers. The stoppers also act as a safety mechanism to prevent the hyperflexion (over-grasping) and self-collision of the gripper, even when it is overdriven (Figs. 6a and 6b). In this setup, the gripper is not controlled to stop during the object grasping mode, but instead it is controlled by a constant current control signal (Fig. 5) to grasp all objects with the same maximum gripping force of approximately 9.5 N. The force is also redistributed through all the joints and segments of the gripper as such the peak force of the first contact will not be that dangerous. The maximum gripping force is designed to provide a secure grip while preventing damage to a (plastic deformable) object (like a plastic cup). This amount of gripping force, however, may cause damage to a fragile or soft object, if it cannot withstand the force. The basic setup of the gripper allows it to grasp or wrap around an object and hold it with mechanical interlocking [32]. However, due to its rigid structure, the grasped object might slip due to discrete contact points. To increase the contact points (area) and ensure stable object grasping, soft adhesive pads with an asymmetric sawtooth-like surface structure are attached to all segments of the gripper. For simplicity, the position of each pad is placed in the middle of each segment. The soft pads are made of silicone rubber (Ecoflex 00-30, Smooth-On, Macungie, PA, USA) (see Fig. 2f). The soft pad design with an asymmetric sawtooth-like surface structure is based on our previous work [31]. There, we investigated different surface structure designs (half-circle, square, symmetric sawtooth, and asymmetric sawtooth profiles) and showed that the asymmetric sawtooth-like surface structure with a high height-to-width ratio (ASH, Fig. 2f) can effectively deform to create large real adhesive contact area with the substrate (or here object surface). Without soft pads or with typical flat soft pads, the INSECTER gripper surface in contact with the object will be less (as shown in Fig. 6). As a proof of concept, we use large sized pads for simplicity of installation and to guarantee that there is sufficient surface area in contact with the object. We will, however, optimize the pad size in the future work.

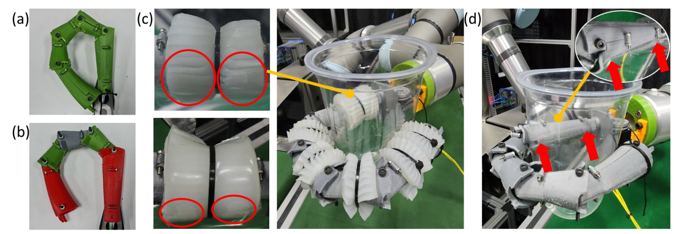
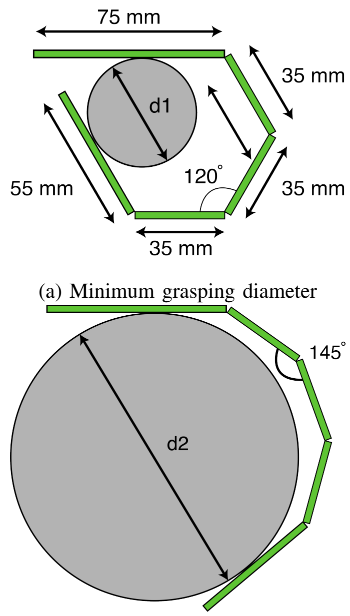


Fig. 6: (a) The gripper without a mechanical stopper. (b) The gripper with a mechanical stopper at each segment for avoiding a self-collision. (c), (d) A comparison of the real contact area of the gripper with our sawtooth-structured soft pads (right and top left in (c)), with standard flat soft pads (bottom left in (c)), or without soft pads (d) while grasping a plastic glass with the same gripping force. Based on visual analysis, the gripper without soft pads can build only a few contact points with the object (see arrows in (d)) while the gripper with soft pads results in contact area. When compared to flat soft pads, our sawtooth-structured pads have nearly double the contact area, resulting in higher adhesion-mediated friction for stable object grasping [33].

B. Grasping Object Size Analysis

In this section, we analyze the grasping object size of the gripper. As previously mentioned, the gripper consists of five segments, each with three main parts: base, main body, and mechanical stopper. The base of each segment, where the torsion spring is mounted, has a diameter of 19 mm (Fig.3a). The main body of each segment extends from the base at an angle of 10 degrees. The length of the segment is scaled proportionally based on the morphology of the real insect tarsus[6], such that the lengths of all segments (from the base to the tip) are 75, 35, 35, 35, and 55 mm, respectively (Fig. 7). The last part is the mechanical stopper, extending from the main body at an angle of 45 degrees. The soft adhesive pad (described above), having a thickness of 1 cm, is attached at each segment of the gripper. With the adhesive pads, the maximum grasping object diameter is 120 mm, while the minimum diameter is limited to 40 mm by the mechanical stoppers (Fig. 7).

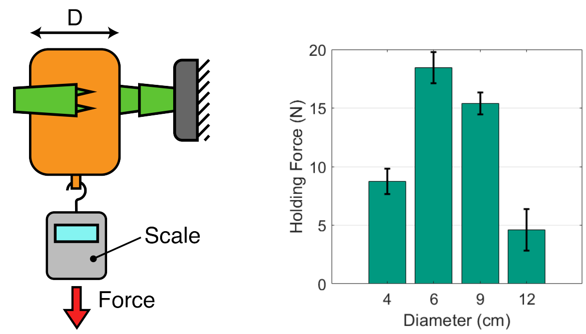
[6]Compared to the insect tarsus, the INSECTER gripper size is scaled up with a factor of 30. This factor is designed according to the desired minimum and maximum grasped object sizes/diameters.



(a) Minimum grasping diameter

(b) Maximum grasping diameter

Fig. 7: This simplified structure shows the minimum and maximum grasping diameters, namely 40 mm (d1) and 120 mm (d2), respectively. It should be noted that the gripper can stably hold objects of varying sizes within the range due to contact area-mediated friction from the adhesive pads. The pads are not drawn here but can be seen in Fig. 5.



(a) Experimental setup (side view) (b) Holding force

Fig. 8: The experimental setup for measuring the holding (vertical pulling) force while grasping different cylinders with diameters (D). Firstly, the object is manually provided to the gripper, and the current control subsequently activated the gripper to tightly grasp the object. The object is then pulled downward. The maximum holding (vertical pulling) force is then measured until it slipped. The average maximum holding (vertical pulling) forces according to the different object sizes and their standard deviations are based on five runs for each cylinder.

IV. EXPERIMENTS AND RESULTS

We conducted four main experiments to evaluate the performance of the gripper. The first experiment investigated the holding/gripping force of the gripper. In the second investigation, the gripper's ability to handle object misplacement was examined. The third experiment tested the versatility of the gripper to grasp 35 different objects for comparison with conventional industrial soft and rigid grippers. Finally, the applications of the gripper in pick-and-place as well as pouring tasks were demonstrated. In all experiments, the gripper was installed on a collaborative robot arm (UR5e, Fig. 1).

A. *Experiment 1: Gripping Force vs. Object Size*

In the first experiment, four plastic cylinders with diameters of 4, 6, 9, and 12 cm were used to estimate the gripping force of the gripper. The minimum and maximum sizes were based on the analysis shown in Fig. 7. The gripper was positioned horizontally and held the object. Each object was slowly pulled downward using the force gauge model JEDTO HF-500 until it slipped off (Fig. 8a). Using the force gauge, we could measure the maximum holding force which is the maximum load the gripper can hold. The results are shown in Fig. 8b. As can be observed, the 6 cm-diameter cylinder has the highest maximum holding force (approximately 18.45 N), and the 12 cm-diameter cylinder the lowest (approximately 4.61 N). Based on the average maximum holding forces, the cylinders measuring 4, 6, 9, and 12 cm in diameter exhibit average maximum gripping forces of approximately 4.16, 8.77, 7.31, and 2.19 N, respectively (see Eq. 2 for the gripping force calculation). According to the results, the best object size for the gripper is around 6 cm in diameter.

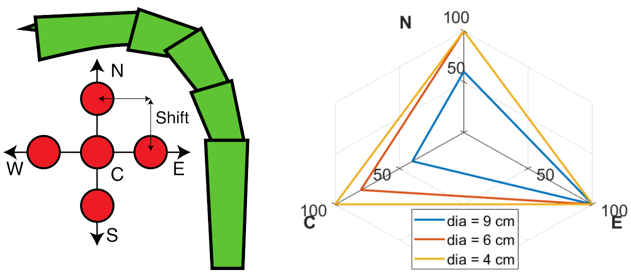
B. *Experiment 2: Tolerance*

The maximum deviation or tolerance of an object was examined from a grasping center point to demonstrate that this gripper design has the advantage of being able to handle the tolerance. We set the experiment by defining the center (C) point of the object with respect to the gripper, and the object shifted in four different directions: north (N), east (E), west (W), and south (S) as shown in Fig. 9a. The same four cylindrical objects measuring 4, 6, 9, and 12 cm in diameter used in the previous experiment were also employed here. The shifted distance was inversely proportional to the object's diameter (i.e., the large one can only be shifted a small distance and vice versa). We ran the experiment five times in each direction. If the gripper could grasp and lift the object placed on a conveyor belt by itself, we considered that a success. The results are shown in Fig. 9b. It can be observed that our gripper can handle the deviation in three directions: C, N, and E. The gripper can also handle more shifts or deviations for a small object (i.e., 4 cm), resulting in a high success rate (100%). A video of the experiment can be viewed at www.manoonpong.com/INSECTER/VideoS2.mp4.

C. *Experiment 3: Versatile Object Manipulation*

The performance of versatile object manipulation was validated and demonstrated by testing the gripper with 35 objects of different sizes, weights, and geometries (Fig. 10). We also compared it with the conventional commercial/industrial soft and rigid[7] grippers, each of which is driven by a single actuator comparable to our gripper. For the experiment, each object was manually provided to a gripper. If a gripper can grasp and hold the object in the air, it was considered a success. The experiment was repeated three times for each object and gripper.

[7]The soft gripper is the four-finger centric SoftGripper from SoftGripping driven by a single pressure source (actuator) for opening and closing the fingers and the rigid gripper is the two-finger parallel gripper (2F-85) from ROBOTIQ driven by a single actuator for opening and closing the fingers.



(a) Experimental setup (top view) (b) Grasping success rate

Fig. 9: The experimental setup for measuring tolerance when each object deviates from the center point (C). Each object is placed on a conveyor belt and shifted to the north (N), west (W), east (E), and south (S) locations. The shifted distance is defined by the distance from the center. It can be observed that the smaller the object, the higher the success rate. In this experiment, the gripper fails to grasp and lift the largest object (12 cm) placed on the N, W, and S locations. Although it can grasp the object in the E location with an 80% success rate, it fails to lift the 12 cm-diameter object up. The shifted distances are set within graspable areas as follows. The 12 cm, 9 cm, 6 cm, 4 cm-diameter objects are shifted by 1 cm, 1.33 cm, 2 cm, and 3 cm from the C location to the N, W, E, and S locations, respectively. Note that the shifted distance is determined by the maximum object diameter among all/tested object diameters (e.g., 12/6 = 2 cm for the 6 cm-diameter object).

Fig. 10: A variety of objects for evaluating the grasping ability of our insect tarsus-inspired gripper and comparing it with the soft and rigid grippers. The names of the objects that match the specified numbers can be seen in Table I.

No.	Object	Weight (g)	Size (cm)	%Success INSECTER	%Success Soft gripper	%Success Hard gripper
1	Min diameter object	55.5	4	100.00%	100.00%	100.00%
2	Small spray	77	4.5 (2.2*)	100.00%	100.00%	100.00%*
3	Glasses case	68	4.6	100.00%	100.00%	100.00%
4	Blue spray	244	4.8 (2.6*)	100.00%	100.00%*	100.00%
5	Remote control	104	5.2	100.00%	100.00%	100.00%
6	Blue glass	10.7	5.8 (6.1*)	100.00%	100.00%*	100.00%
7	Joystick	183	6	100.00%	100.00%	100.00%
8	Light bulb	162	6	100.00%	100.00%	100.00%
9	Small ball	4.2	6	100.00%	100.00%	100.00%
10	0.5 litre water bottle	250	6.1 (5.7*)	100.00%	100.00%*	100.00%
11	Bag of snacks	56	6.2	100.00%	100.00%	100.00%
12	VitaminC bottle	230	6.4 (4.1*)	100.00%	100.00%*	100.00%
13	Stainless bottle	294	6.7 (4.2*)	100.00%	100.00%*	100.00%
14	Shampoo bottle	80	6.8	100.00%	100.00%	100.00%
15	Octagonal tape core	23.8	7.3	100.00%	100.00%	100.00%
16	NAMO doll	263.6	7.4 (6.8*)	100.00%	100.00%*	100.00%
17	Paper bag	26	7.5	100.00%	100.00%	100.00%
18	Big ball	7.6	7.5	100.00%	100.00%	100.00%
19	Tennis ball	59	7.8	100.00%	100.00%	100.00%
20	Light bulb box	27	7.8 (6.7*)	100.00%	100.00%*	100.00%
21	Scotch tape	50	8.7	100.00%	100.00%	100.00%
22	Plastic tumbler	15	9.5 (8.4*)	100.00%	100.00%*	100.00%
23	1.5 litre water bottle	234	9.6 (7.9*)	100.00%	100.00%*	100.00%
24	Plastic cup	15	9.8 (0.4*)	100.00%	100.00%*	100.00%
25	Yellow tape	48.3	10.1	100.00%	100.00%	100.00%
26	Big spray	254	11.3	100.00%	100.00%	100.00%
27	Max diameter object	195.4	12 (0.5*)	100.00%	100.00%*	100.00%*
28	Aluco cubic	107	7.1 (5.5*)	100.00%	66.66%*	100.00%
29	Dynamixel box	68.5	9.5, 5.8	100.00%	66.66%	100.00%
30	Detergent bottle	505	8.8	100.00%	0.00%	100.00%
31	Cookie box	164	10.4 (1.6*, 0.5*)	100.00%	33.33%*	100.00%*
32	Plastic ball	175	9.9	100.00%	0.00%	0.00%
33	Stainless tumbler	311	10	100.00%	0.00%	100.00%
34	Circular candy jar	369	10.3	100.00%	0.00%	0.00%
35	Cartoon candy jar	623	11.4	100.00%	0.00%	0.00%
	Average percentage			**100.00%**	**81.90%**	**91.43%**

Size (cm): The width of the grasped object

TABLE I: The performance of each gripper on grasping various types of objects. The grippers shown on top are the INSECTER, soft, and rigid grippers from left to right, respectively. The object pictures can be seen in Fig. 10. The INSECTER can effectively grasp all objects from the side, while the soft and rigid grippers can only grasp certain objects from the side and others (marked with an asterisk) from the top. Note that, some objects (no. 2, 4, 6, 10, 12, 13, 16, 20, 22, 23, 24, 27, 28, 31) have different parts with different widths that the soft and rigid grippers can successfully grasp.

The results are shown in Table. I. As can be observed, our gripper can successfully grasp and hold all objects (100% success rate), while the soft and rigid grippers, on the other hand, are unable to handle all objects and exhibit average success rates of 81.90% and 91.43%, respectively. Since our gripper uses a grasping technique by wrapping around an object from the side, it can effectively deal with closed-form, round-shaped, and large-sized objects (see object numbers 32, 34, and 35 in Fig. 10) which can hardly be grasped by the conventional soft and rigid grippers. A video of the experiment can be viewed at www.manoonpong.com/INSECTER/VideoS3.mp4.

D. Experiment 4: Use Case Demonstrations

The final experiment demonstrates two use cases of our gripper in pick-and-place as well as pouring tasks. For the pick-and-place task, we preprogrammed the robot arm equipped with the gripper to move to the spot where the object is to be picked up. The gripper is then activated to grasp the object, after which the arm transfers the object to the placing spot, and the gripper releases it. We performed the task with 16 different objects. The results of this can be seen in Fig. 11. The gripper can successfully pick and place the objects, as shown in a video of the experiment at www.manoonpong.com/INSECTER/VideoS4.mp4.

For the second task, the robot arm was preprogrammed to move and pick up a plastic cup filled with granular media (like coffee beans or granular polystyrene foam). The gripper is then activated to grasp the cup, and the arm performs the pouring action while the gripper stably holds the cup. Finally, the arm places the cup, and it is released by the gripper. The results in Fig. 11 show that the gripper can stably grasp the cup and pour coffee beans into the other cup. A video of the experiment can be viewed at www.manoonpong.com/INSECTER/VideoS5.mp4. We also tested the pouring task

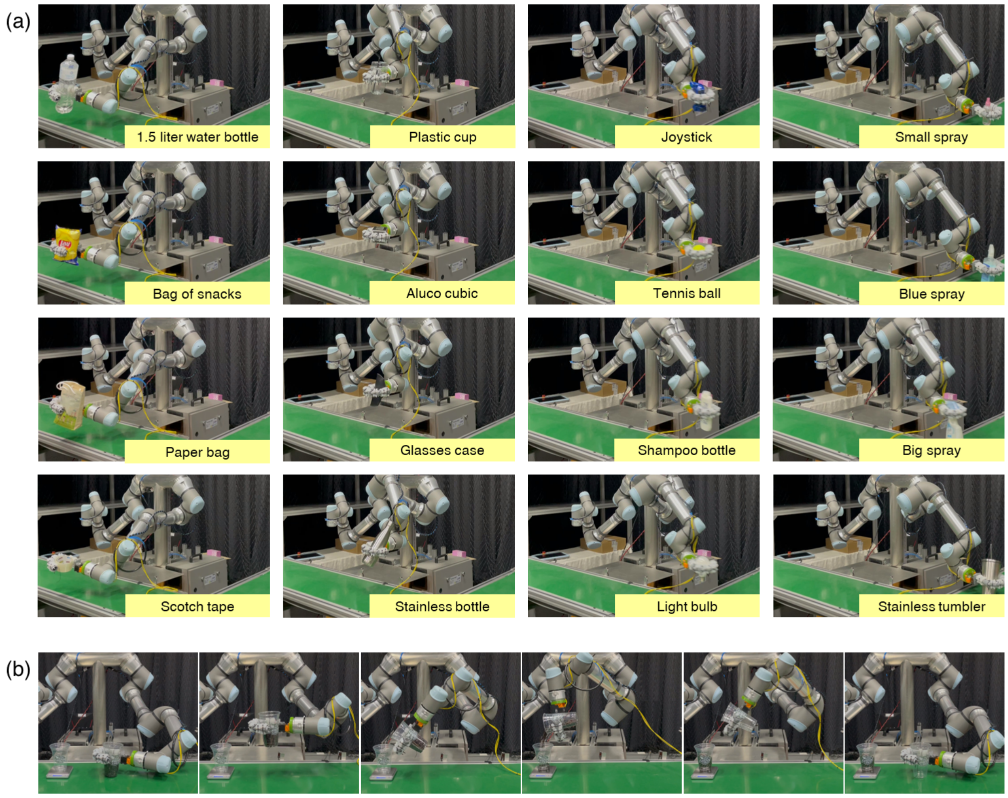


Fig. 11: Demonstrations on the use of the gripper for pick-and-place as well as pouring tasks. Each snapshot in (a) shows the robot arm and gripper behaviors at a certain period during the pick-and-place task for a specific object. During the test, the robot continuously and successfully picks and places a total of 16 objects. The snapshots in (b) depict the sequence of grasping a plastic cup and pouring coffee beans from the cup into the other cup (from left to right).

with the soft and rigid grippers. A video of the test can be seen at www.manoonpong.com/INSECTER/VideoS5.mp4. The result shows that the soft gripper fails to grasp the cup from the side, while the rigid gripper can damage or distort the cup if it applies too much force. Grasping the cup from the top is a possible option for the soft and rigid grippers. However, there is a danger that the grippers' tips will become submerged in the media (or beverage) in the cup.

V. DISCUSSION AND CONCLUSION

In this paper, we present an insect tarsus-inspired, underactuated, segmented gripper consisting of five segments. All these segments are driven by a single actuator through a single cable to grasp a variety of objects. Its grasping function is accomplished by wrapping around the object, introducing mechanical interlocking [32] to lock the object by the gripper segments. The gripper is made of compliant, soft, and rigid components. The rigid parts act as its exoskeleton with embodied compliance (realized by passive joints with torsion springs). Its soft parts consist of soft adhesive pads with an asymmetric sawtooth-like surface structure attaching to the (tarsus) exoskeleton. With the material softness and surface structure, the pads can well deform and create contact area-mediated friction (adhesion-mediated friction [33]) with the grasped object[8]. The contributions of the contact area-mediated friction and mechanical interlocking lead to stable object grasping of the gripper. Our hybrid compliant, soft, rigid gripper can passively adapt to various object shapes/sizes and safely grasp them without breaking due to its soft pads, passive compliant (spring) joints, and mechanical stoppers, while its rigid structure makes it stiffer and easier to control than soft grippers [13], [14], [15]. Since the entire gripper system is light (less than 200 g), it can be applied to a mobile manipulator system with a small robot arm (e.g., OpenMANIPULATOR-X[9], Kinava, UR3e) for mobile manipulation in delivery service tasks.

Through the findings of our experiments, we show that our gripper is capable of handling a range of items as well as object position misalignment in certain locations. Although our gripper outperforms the conventional soft and rigid grippers[10], it still has limitations. It is longer than the soft and rigid grippers. Thus, it should be practically operated in a large/open working space. Our gripper, in contrast to a soft gripper, would not be able to stably grasp, place, and release particular objects if not positioned correctly (see www.manoonpong.com/INSECTER/VideoS4.mp4). Due to the grasping radius and mechanical stoppers of our gripper, it can grasp objects of certain diameters (from 40 mm to 120 mm for object grasping and less than 120 mm for stable object grasping and lifting). The minimum size of an object that can be grasped

[8]Note that the soft structured pads with adhesion-mediated friction of our insect tarsus-inspired gripper can be considered as soft tarsal attachment pads (euplantulae) in stick insects which also generate adhesion-mediated friction for stable substrate gripping [34].

[9]https://www.youtube.com/watch?v=Qhvk5cnX2hM

[10]It is important to note that using other types of grippers [4], [5], [6], [17], [18], [19] to compare with ours could lead to different results.

is limited because of the mechanical stoppers that set a safe working limit for the gripper and prevent the object from being destroyed. As a consequence, our gripper cannot grasp a small object with a grasped width or diameter less than 40 mm. In the future, we will investigate the gripper design in various sizes to determine whether it can be scaled down to fit in a small working space or scaled up to handle larger/heavier objects (scalability). However, when the dimension is scaled up, the size is restricted by the cable tension (T) and gripping force (F_g) required (see Eqs. 1 and 2), which determine the actuator torque and size as well as the cable transmission system. Additionally, we will also investigate soft and expandable/controllable pads [35] for gripping force enhancement.

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