GTac-Gripper: A Reconfigurable Under-Actuated Four-Fingered Robotic Gripper With Tactile Sensing

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***Abstract*—Humans can use different grasping poses and forces for everyday objects of different shapes and sizes. Grasping and manipulating everyday objects have been longstanding challenges in robotics. Performing multiple grasping configurations is difficult for robotic end-effectors with limited degrees of freedom (DOF). Integrating tactile sensing into robotic grippers will facilitate grasping and manipulating a wider range of objects. In this letter, we present a robotic gripper with a reconfigurable mechanism and tactile sensors (GTac) integrated into the fingers and palm. Each finger consists of two phalanges with a 2 DOF underactuated design and a metacarpophalangeal (MCP) joint. Our gripper with four adaptive fingers can perform 5 grasping configurations and obtain 228 tactile feedback signals (normal and shear forces) at 150 Hz. Our results show that the gripper can grasp various everyday objects and achieve in-hand manipulation including translation and rotation with closed-loop control. In the YCB benchmark assessment, the gripper achieved a score of 93% (round objects), 0% (flat objects), 78% (tools), 90% (articulated objects), and 65% in total This research provides a new hardware design and could be beneficial to various robotic applications in the domestic and industrial fields.**

***Index Terms*—Grippers and other end-effectors, force and tactile sensing, multifingered hands.**

I. Introduction

DEXTERITY of our hands allows us to perform a variety of grasping poses to grasp various everyday objects of different shapes and sizes [1]. Bringing dexterity to the robotic end-effectors will allow for feasible grasping with a wider range of objects [2], [3]. During the physical interactions of grasping and manipulation, tactile afferents in our hands provide information, such contact forces, to estimate whether the grasp is failing and ensure the safety of objects [1]. Robots with tactile sensing feedback will be able to grasp and manipulate objects autonomously and safely [4], [5]. Human hands are commonly the natural inspiration for robotics design. However, it is challenging to design a robotic end-effector with comparable dexterity, tactile sensing capabilities, and the integration compactness to human hands [1], [3], [6].

With increasing research interest in gripper design, the grasping and manipulation capabilities of robots have been found to be drastically improved by multi-fingered design [7]–[11]. The underactuated finger design has been widely adopted in many multi-fingered grippers [9], [12], [13] by actuating multiple finger joints using a single actuator, where the number of actuators and controller complexity can be greatly reduced. Some studies [7], [12], [14] have been focusing on reconfigurable mechanisms with multi-fingered design and realized that the reconfigurable gripper pose could increase the dexterity of grippers to interact with objects of various shapes and sizes, such as grasping and in-hand manipulation (translation and rotation).

Moreover, tactile sensing capabilities have been playing an important role in robotic grasping and manipulation [1], [15] and many tactile sensors have been developed for robotics [13], [16]. Li *et al.* [5] have reviewed different types of robot applications with tactile sensing feedback and indicated that coverage and shear force sensing are essential characteristics of tactile sensors for robotics. Some studies have integrated tactile sensors into robots to control the end-effectors for grasping or manipulation [13], [17], [18] and demonstrated that tactile feedback could facilitate grasping and manipulating a wide range of objects, including fragile objects and irregularly shaped objects.

According to the promising previous works, Lu *et al.* [12] developed a three-fingered underactuated reconfigurable gripper and achieved various objects' grasping and manipulation. However, the coupled finger motion introduced limitation in performing grasping configurations and the lack of tactile sensing resulted in labor-intensive open-loop control for grasping and manipulation. Kim *et al.* [7] developed a gripper consisting of three adaptive fingers using a belt, linkages, and reconfigurable bases and performed remarkable transition between precise pinching, compliant grasping, and in-hand manipulation. However, two different types of contact surface and the movable palm would introduce difficulty in the integration of tactile sensors in terms of coverage. Dollar *et al.* [13] designed an adaptive gripper with four underactuated fingers and the grasping compliance was improved due to the tactile sensors integrated in the fingers. Although only one motor was required because of the promising underactuated design, the grasping configurations that the gripper can perform for differently shaped objects were

Manuscript received February 24, 2022; accepted May 31, 2022. Date of publication June 10, 2022; date of current version June 20, 2022. This letter was recommended for publication by Associate Editor S. Sundaram and Editor H. Liu upon evaluation of the reviewers' comments. This work was supported by the Agency for Science, Technology and Research, Singapore, through the National Robotics Program, with A*star Science and Engineering Research Council (SERC) under Grant 192 25 00054. *(Corresponding author: Haoyong Yu.)*

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This letter has supplementary downloadable material available at https://doi.org/10.1109/LRA.2022.3181370 and https://rooboot.github.io/GTac_/gtac_gripper.html, provided by the authors.

Digital Object Identifier 10.1109/LRA.2022.3181370

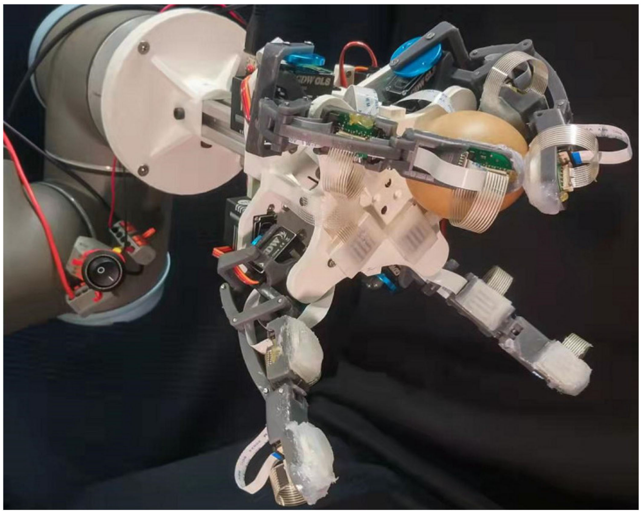

Fig. 1. The GTac-Gripper with four adaptive fingers, reconfigurable mechanism, and tactile sensors integrated into the fingers and palm.

limited. Morgan *et al.* [8] proposed a novel control method for object in-hand translation and rotation using a four-fingered reconfigurable gripper. The closed-loop controller relied on the external vision feedback to track the pose of the object and execute structured motion steps accordingly. However, for such contact-rich tasks, tactile feedback can bring more flexibility and safety to facilitate the in-hand manipulation task. Therefore, it is still crucial and challenging to develop a reconfigurable multi-fingered gripper with integrated tactile sensing capabilities.

Built upon the promising previous works, we propose a gripper system, called GTac-Gripper, which has four reconfigurable fingers and GTac tactile sensors [19] on each finger phalanx and the palm (Fig. 1). The GTac-Gripper can obtain 228 tactile feedback signals, including arrayed normal forces and gross shear forces. Our results showed that the GTac-Gripper could perform 5 configurations by grasping taxonomy definition [20] for grasping different everyday objects of various shapes and sizes. The GTac-Gripper achieved the object grasping and in-hand translation with closed-loop control which was facilitated by the tactile sensing capabilities for adapting to objects of different shapes and sizes. The GTac-Gripper also achieved object in-hand rotation relying on the closed-loop grasping. According to the YCB benchmark assessment results, the GTac-Gripper achieved a score of 93% (round objects), 0% (flat objects), 78% (tools), 90% (articulated objects) and 65% in total.

II. Methods

A. Gripper Design

1) 2-DOF Linkage-Driven Underactuated Finger: We adopted a 2 DOF linkage-driven underactuated design for the finger with two phalanges. The underactuated mechanism was constructed by stacking the 4-bar mechanism with the parallelogram mechanism (Fig. 2(a)). The actuation link l_1 was connected to a servo motor. With the 1-DOF parallelogram mechanism, the rotation of the active link AB was transmitted to the motion of the link O_1C, which actuates the 2-DOF underactuated four-bar linkage O_1CDO_2.

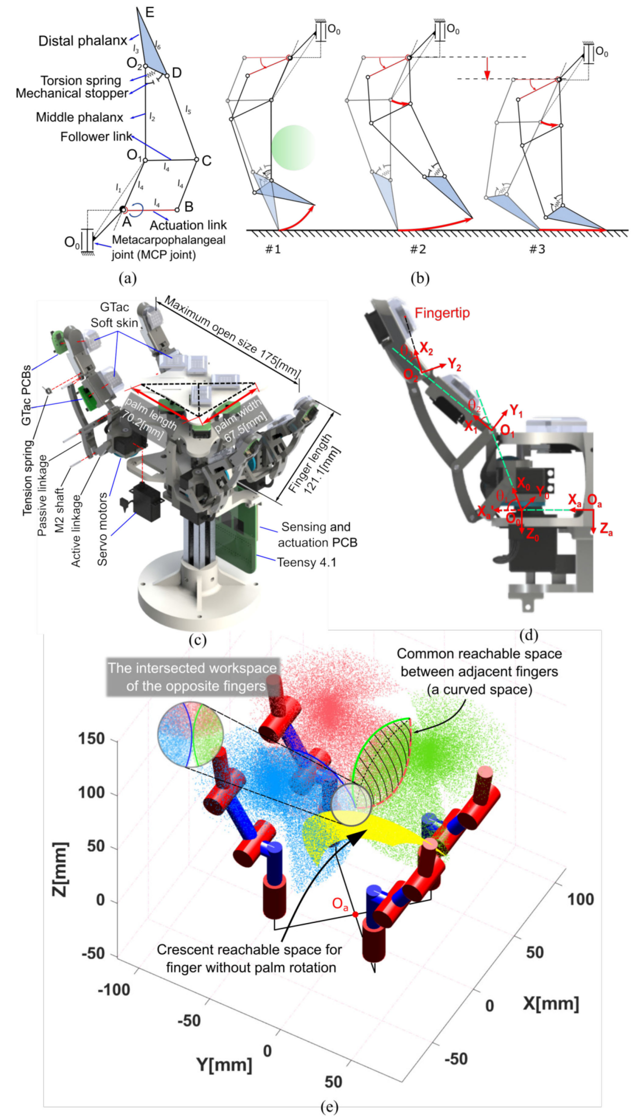

Fig. 2. (a) The finger mechanism. (b) Fingertip trajectory analysis. (c) The gripper specifications in its partial exploded view. (d) The frames following DH conventions. (e) The rendered workspace of each finger.

A preloaded torsion spring in the joint O_2 was used to maintain the distal phalanges fully extended. The mechanical stopper kept the distal phalanges aligned under the extension of spring when no external force was applied to the phalanges. Joint O_0 functioned as the metacarpophalangeal joint of human hands, allowing each finger to change its orientation with respect to the central axis of the palm independently. The trajectory of the fingertip as the finger flexes would be determined by external constraints. Fig. 2(b) illustrates the three situations during a finger flexion. In #1, the contact occurs at the middle phalanx. In #2, two phalanges behave as a rigid body and rotate around a fixed point. In #3, the fingertip moves linearly when the finger is pressed before flexion.

2) Mechanical Components: Fig. 2(c) shows the partial exploded view of the proposed GTac-Gripper. It has 4 fingers and

TABLE I
STANDARD DH PARAMETERS FOR THE FINGER

Link i	a_{i-1} [mm]	α_{i-1} [deg]	d_i [mm]	θ_i (joint limits [deg])
1	14.2	90	40.2	q_1 $(-45 — 135)$
2	0	0	42	q_2 $(50 — 135)$
3	0	0	29.2	q_3 $(22.5 — 92.5)$

8 motors, with tactile sensors integrated into the distal phalanx, middle phalanx of the fingers, and the palm. Each finger has one motor for finger flexion/extension and one for reorientation. The soft silicone skin of GTac sensors partially covered the finger surface and provided structural compliance improving grasping stability during object grasping.

3) Workspace Analysis: The workspace analysis was performed to evaluate the manipulation range and dexterity of the GTac-Gripper. The motions of joint O_1 and O_2 were coupled because of the underactuated finger design. To analyze the reachable workspace of the fingertip, we assumed that the motion range of the fingertips depends on the mechanical limits due to the underactuated characteristics. Thus the finger kinematic model was configured as a RRR mechanism [21] and the coordinates were placed for obtaining Denavit-Hartenberg (DH) parameters. As shown in Fig. 2(d), each finger can rotate around joint O_0 in the X_0Y_0 plane by 180°. Link O_1C and link O_2D can achieve a motion range of 85° in the X_1Y_1 plane and 70° in the X_2Y_2 plane respectively. The DH parameters for the finger were listed in the Table I and can be used by (1) and (2) to obtain the workspace of fingertips. The transformation matrix was defined as

$$ {}^0_3T = {}^0_1T {}^1_2T {}^2_3T \tag{1}$$

with

$$ {}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

By applying the Monte Carlo numerical algorithm, the workspace of each fingertip was obtained (Fig. 2(e)).

B. Tactile Sensor Integration

1) Sensing Solution: The GTac sensors [19] are integrated in the distal phalanx and the middle phalanx of each finger and in the palm of the GTac-Gripper, as shown in Fig. 3. Taking inspiration from the multilayered structure of FA-I and SA-II mechanoreceptors between the epidermis and dermis of human skin [22], the GTac sensor adopts a similar arrangement consisting of an extrinsic sensing layer and an intrinsic layer, the FA-I layer and the SA-II layer. The FA-I layer consists of 4×4 matrix piezoresistive sensors for normal force sensing. The SA-II layer is a 3D magnetic sensor realized by a Hall sensor for gross 3D forces sensing. Therefore, each GTac sensor can perceive 19 tactile sensing signals (16 from the FA-I layer and 3 from the SA-II layer) and the GTac-Gripper with 12 GTac sensors can acquire 228 tactile sensing signals at 150 Hz.

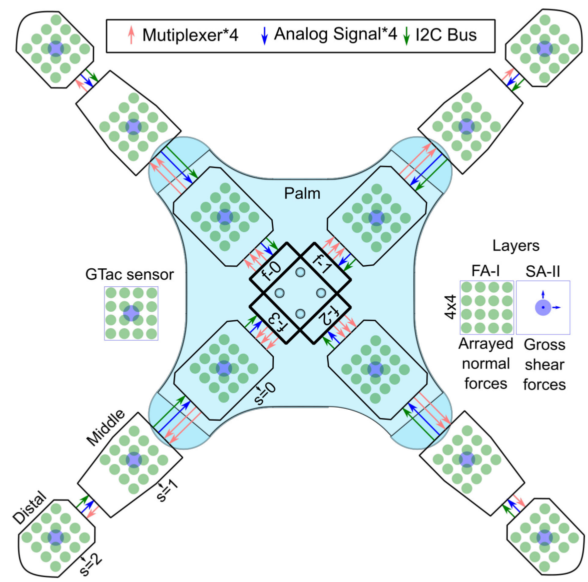

Fig. 3. Overview of tactile sensing solution and signal transmission for GTac-Gripper. f is the finger ID and s is the GTac sensor ID.

2) GTac Circuits and PCB Design: In each GTac sensor, the Hall sensor (MLX90393) placed at the center of the front is used to acquire the local magnetic flux density and transmit the digital signals in I2C bus. Four-channel operational amplifiers (MCP6004) are used to acquire analog signals from the piezoresistors. There are four parallel sensing branches for the four fingers of the GTac-Gripper. The uploading multiplexer signals, the downloading digital and analog signals, and power supply (5V) are serially transmitted in each branch. 12-pin, 16-pin, and 20-pin 0.5 mm pitch jumper cables are used to connect the GTac sensors at the distal phalanx (s = 2), middle phalanx (s = 1), and the palm (s = 0), respectively.

C. Versatile Grasping Configurations

The inter-finger distance between the finger bases are related to the gripper's stability and grasping/manipulation capabilities in precision grasping (pinch) and caging, especially for underactuated mechanisms [23], [24]. Similarly, the gripper can continuously control its MCP joints to accomplish different grasping configurations and change the inter-finger distance. As shown in Fig. 4(a), there are four distinct inter-finger distances, p_l, p_w, d, and $d/2$. Five grasping configurations can be achieved with the different inter-finger distances (Fig. 4(b)). The gripper can perform cage grasp (#1) for spherical or irregular objects, parallel pinch (#2 and #3) for cylindrical objects or small objects, clasped pose (#4) when the stability of grasping is emphasized, and T-shape grasping (#5) for T-shaped objects such as the drill.

D. Fabrication

The linkages of the finger were 3-D printed (Form 2, Formlabs) with a resin material (Tough 2000, Formlabs) and then ultraviolet cured (Form Cure, Formlabs) for better stiffness. The linkages were connected using M2 pins. The palm and motor frame were 3-D printed (S2+, Ultimaker) using polylactic acid

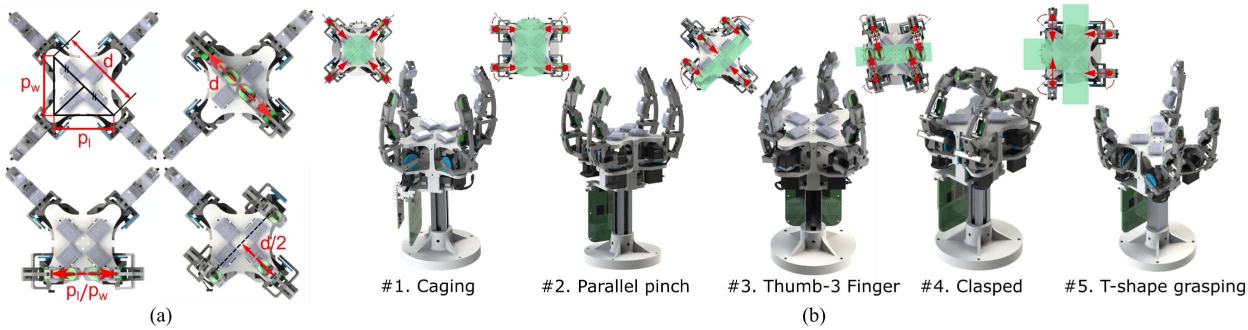

Fig. 4. (a) Explanation of inter-finger distances for different grasping. (b) Five main grasping configurations that GTac-Gripper can realize and the varied inter-finger distances were indicated by the red edges.

(PLA). The torsion spring was preloaded and placed between the middle and distal phalanges. Motors driving MCP joint were first mounted on the motor frame, then the finger module was connected in serial. Bearings (MR52ZZ, NSK) were used to help align the rotation center of the MCP joints. The GTac sensors were attached to the phalanges of the fingers and the palm by using an adhesive, Cyanolube Cyanoacrylate (Electrolube Co. Ltd). The silicon skin (Ecoflex 00-50, Smooth-On Inc.) and PCBs of GTac sensors were mounted on both surfaces of finger phalanges and the palm. For more information about the fabrication of GTac sensors, refer to [19].

III. Experiments

A. Experimental Setup

The GTac-Gripper was mounted on the Universal Robot Arm (UR10). The trajectory of UR10 was pre-programmed for grasping different objects in the grasping tests. To evaluate the grasping capabilities of the GTac-Gripper with reconfigurable mechanism and integrated tactile sensing capabilities, a set of objects with different shapes and sizes were selected from the YCB object set [25].

B. Grasping Capability Assessment

To evaluate the grasping capability, we carried out the YCB Gripper Assessment Benchmark [12], [25]. The objects, including round objects, flat objects, articulated objects and tools (Fig. 5), were placed on a table. The grasping configuration of the GTac-Gripper was determined by the shape and size of the object and was preset before the grasping. The gripper would approach to grasp each object on the table and raise it, then remain in the air for 3 s. Finally, the robot arm would rotate the gripper and the grasped object by 90° about the y-axis and stay for 3 s. The lifting and rotating processes are assigned 2 points respectively. There could be three scenarios: (1) if the object is dropped, no point is earned; (2) if the object is successfully grasped but with visible motion, one point is earned; and (3) if the object remain stable throughout the process, two points are earned. To simulate the uncertainty in real-world grasping, the object was placed at four different locations (one at the origin and the other three at 1 cm displacement along x-, y-, and z- axis respectively). A 1 cm thick plate at the bottom was removed

Fig. 5. The everyday objects from YCB benchmark used in the grasping tests.

to implement the displacement along the z-axis. The gripper attempted to grasp the objects at the four locations using the same grasping strategy, and the score was given respectively. For articulated objects, the objects were grasped and raised by 15 cm for 3 s. The score is 0.5 for each success, where no part of the object touches the table when lifted. This process is repeated 20 times, so a total score for each articulated object is 10.

The grasping tests were implemented to show not only the grasping capabilities of the GTac-Gripper but also how the tactile sensing feedback and the reconfigurable mechanism of the GTac-Gripper facilitate the design of the controller and enlarge the range of objects that the gripper can grasp.

C. Control Strategy

The GTac-Gripper can perceive the arrayed normal forces and the gross shear forces of each GTac sensor. We leveraged the tactile sensing feedback from the fingers by [Eq. (3) shown at the bottom of the next page] where $a = 0.3$, finger index $f \in [0, 1, 2, 3]$, $s \in [1, 2]$ for the sensor in the middle or distal phalanx (Fig. 3). $\Delta B^{x,y,z}$ is the 3D magnetic force feedback where $\Delta B^{x,y}$ represents the shear forces feedback and ΔB^{z} represents the normal force feedback from SA-II layer. $R^{r,c}$ are the matrix normal force signals at row (r) and column (c) from the FA-I layer. Regarding the variable a, because the SA-II layer has a redundant DoF in force sensing along the z-axis, we weighted the redundancy on normal force estimations by the

FA-I layer and SA-II layer which was conducted regardless of the physical units of the two digital signals. The tactile feedback of each finger is condensed into a single value of g_f as per in (3) to be used in a threshold-based controller. In the controller, the finger f performs flexion when $g_f < T_{th}$ to contact closed-loop grasping, where T_{th} is a hand-tuned parameter.

IV. Results and Discussion

A. Reconfigurable Grasping

The gripper was designed to grasp different everyday objects with various shapes and sizes. Humans rely on reconfiguring their dexterous hands to perform various configurations for grasping different objects. In Fig. 6, the proposed gripper was used to grasp everyday objects of different shapes and sizes, including regularly shaped objects (cubic, spherical, and cylindrical), and irregularly shaped objects. The five grasping configurations were implemented by the gripper to grasp the objects according to their shapes and sizes. For round objects, such as soccer balls and small marbles, the caging grasp (#1 configuration in Fig. 4) was implemented. Using the pinch configuration (#2), a cylindrical bottle was stably grasped. Due to the multifingered property, the gripper can achieve multi-object grasping by pinching two smaller objects, e.g., a lemon and a cubic box, as shown in Fig. 6. The #3 configuration can be used to pinch longer objects and be adjusted to fit in the orientation of the object. We implemented it twice to pinch the pen in two orientations. For stable grasping, the #4 configuration (clasped) was used to grasp a hammer and a banana, both of which were in an elongated shape, and force the objects towards the palm. For the ease of everyday use, some objects are T-shaped, such as a drill and a fan with a handle. We implemented the #5 configuration to grasp the T-shaped objects by adapting the fingers to the contour of the objects. The adaptive design of the underactuated finger also makes the fingers passively elastic along the direction of its flexion. Therefore, we found that the grasping capabilities can be improved for smaller objects by pressing the fingers against the table before grasping. In this scenario, the trajectory can be changed to better pinch the object (Fig. 7).

B. Tactile Enhanced Grasping and Manipulation

When the gripper approached the object (in Fig. 8), the palm could perceive the feedback of the contact forces and the area, because the distribution of tactile sensors in the palm was known. Subsequently, the gripper began to grasp the object with closed-loop control using a simple threshold controller (explained in Section II) enabled by the tactile sensing capabilities. The object was grasped and raised without manually adjusting the range of finger flexion.

In addition, humans can deal with situations where multiple objects need to be grasped and manipulated simultaneously, for instance, writing with a pen while holding another object. To have such capabilities, as shown in Fig. 9, we implemented a simple threshold controller ($T = 200$) to pinch two objects with different shapes, i.e., an apple (corresponding fingers: f0 and f1) and a cubic box (f2 and f3). Afterward, the gripper can translate the box to the left by 32 mm and to the right by 32 mm while holding another object closed-loop using the front pair of fingers (f2 and f3). In the closed-loop translation controller, a threshold ($T = 200$) and a tolerance ratio ($t = 50\%T$) were hand-tuned and applied to determine the incremental direction (flexion or extension) of the corresponding fingers (Fig. 9(c)). The object in-hand translation was a dynamic process, so it was important to monitor and control the gripping force. If the sum of the leveraged tactile feedback of both fingers, i.e., $g_{f2} + g_{f3}$, was below T, both fingers conducted flexion to increase the gripping force to avoid dropping the object. If the sum was in the tolerance range ($[T, t + T]$), the object would continue to be translated from the flexion finger to the extension finger. If the sum was above the tolerance range, the flexion finger temporarily stopped the flexion until the sum was back to the range, which helped avoid a large contact force between the object and the fingers. The control strategy can be interpreted as that one finger moves to achieve the motion while the other one moves to control the grasp force. When the motor rotation of the flexion finger reached 50°, the translation direction switched. Because of the tactile sensing capabilities used in object in-hand manipulation, the gripper can achieve such a task with different objects of various shapes and sizes without modifying any parameters of the controller (Fig. 10). In addition to translation, the GTac-Gripper can also rotate a small soccer ball on a table (Fig. 11), because of the reconfigurable mechanism and tactile sensing. The selected two fingers (f0 and f2) performed closed-loop flexion to grasp the object. After the preset threshold was met ($T_{th} = 200$), both fingers actuated their MCP joint to rotate the object clockwise and then returned to the original grasping position. After four cycles, the soccer ball on the table was rotated by $\pi/2$ along its z-axis.

C. Grasping Capabilities for Various Objects

During the grasping tests following the YCB Grasping Benchmark [25], the GTac-Gripper tried to grasp all of the objects (Fig. 5) using different grasping configurations and tactile sensing feedback. The results (Table II) demonstrated that GTac-Gripper can grasp various everyday objects of different shapes and sizes. Relying on the tactile feedback, the gripper can adjust the finger flexion to provide gripping force through a simple threshold-based grasping controller. The results showed that full marks were achieved with larger round objects in the four positions using the caging configuration and tactile grasping.

$$g_f = \sum_{s=1}^{2} \sqrt{\Delta {B^x_{s,f}}^2 + \Delta {B^y_{s,f}}^2 + \left[a\Delta B^z_{s,f} + (1-a) \sum_{r=1}^{4} \sum_{c=1}^{4} R^{r,c}_{s,f} \right]^2}, \tag{3}$$

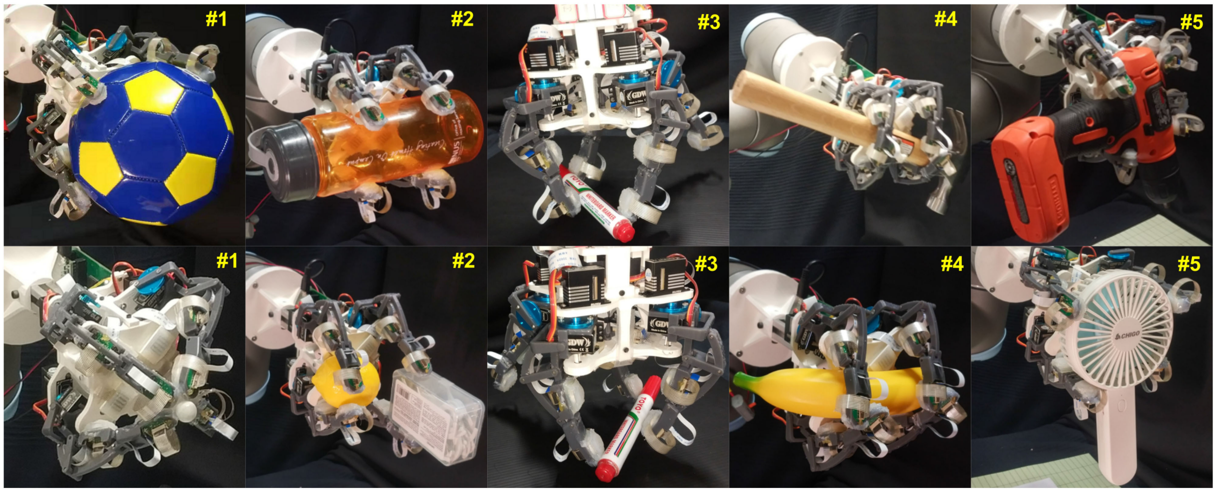

Fig. 6. The GTac-Gripper can grasp various everyday objects relying on its reconfigurable mechanism. The grasping configuration used is indicated.

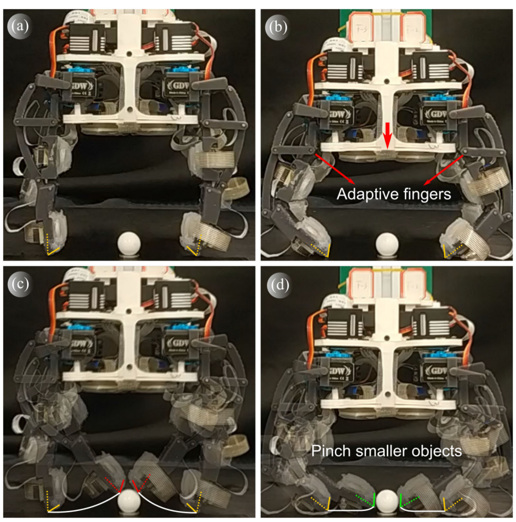

Fig. 7. Adaptive fingers can be used to grasp smaller objects.

TABLE II
SCORING OF GRIPPER ASSESSMENT USING YCB OBJECTS

	Object	Origin	Δx	Δy	Δz	Tactile[1]	Config[2]	Score
Round Objects	Soccer Ball	4	4	4	4	Y	1	134 / 144
	Softball	4	4	4	4	Y	1	
	Tennis Ball	4	4	4	4	Y	1	
	Racquetball	4	4	4	4	Y	1	
	Golf Ball	4	4	4	4	Y	1	
	Marble XL	4	4	4	4	Y	1	
	Marble L	4	4	4	2	N	1	
	Marble M	4	4	4	0	N	1	
	Marble S	4	4	4	0	N	1	
Flat Objects	Washer 1	0	0	0		-	-	0 / 96
	Washer 2	0	0	0				
	Washer 3	0	0	0				
	Washer 4	0	0	0				
	Washer 5	0	0	0				
	Washer 6	0	0	0				
	Washer 7	0	0	0				
	Credit card	0	0	0				
Tools	Pen	4	4	4	2	N	3	100 / 128
	Scissors	4	0	3	0	Y	1	
	Hammer	3	3	3	2	Y	4	
	Screwdriver	4	4	4	0	Y	4	
	Drill	4	4	4	0	Y	5	
	Peg XL	4	4	4	4	Y	1	
	Peg M	4	4	4	4	Y	1	
	Peg S	4	4	4	0	Y	2	
Articulated	Chain	8				Y	1	18 / 20
	Rope	10				Y	1	

[1]Whether tactile information is utilized in control.
[2]The type of grasping configurations employed (refer to Fig. 4).

Because of the limitations on the tactile sensing coverage and the finger linkage parameters, the contacts between the object and fingertip were out of the tactile sensing area when the gripper was grasping smaller objects on a table such as marbles. Therefore, such smaller objects are grasped by manually presetting the finger flexion range. However, in the cases of smaller marbles at z offset, the gripper was not able to pick them up. The gripper achieved a score of 134/144 (93%) for round objects. None of the flat objects were able to be picked up.

In cases of tools, the reconfigurable mechanism provided more choices of grasping configurations to enable the fingers to fit the contour of objects. We chose the configuration according to the object's properties, such as its shape, size, and weight. For instance, in the case of the pen with a thin cylindrical shape and its light weight, we managed to pick it up using the thumb-3 finger configuration, because this configuration has the shortest inter-finger distance compared to other configurations (Fig. 4), which made it suitable to pinch a long and thin object. Another feature of the gripper in the thumb-3 finger configuration is that any finger can be the thumb because of the decoupled reorientation for each finger. Therefore, the gripper may not need extra rotation to address the varying orientation of the object (pen grasping in Fig. 6). In the case of a drill with an irregular shape and heavier weight, the gripper managed to grasp it by implementing the T-shape grasping to fit the fingers in the contour of the drill. In total, the gripper achieved a score of 100/128 (78%) in the tools category. For the articulated objects, we implemented the caging configuration (#2) and achieved

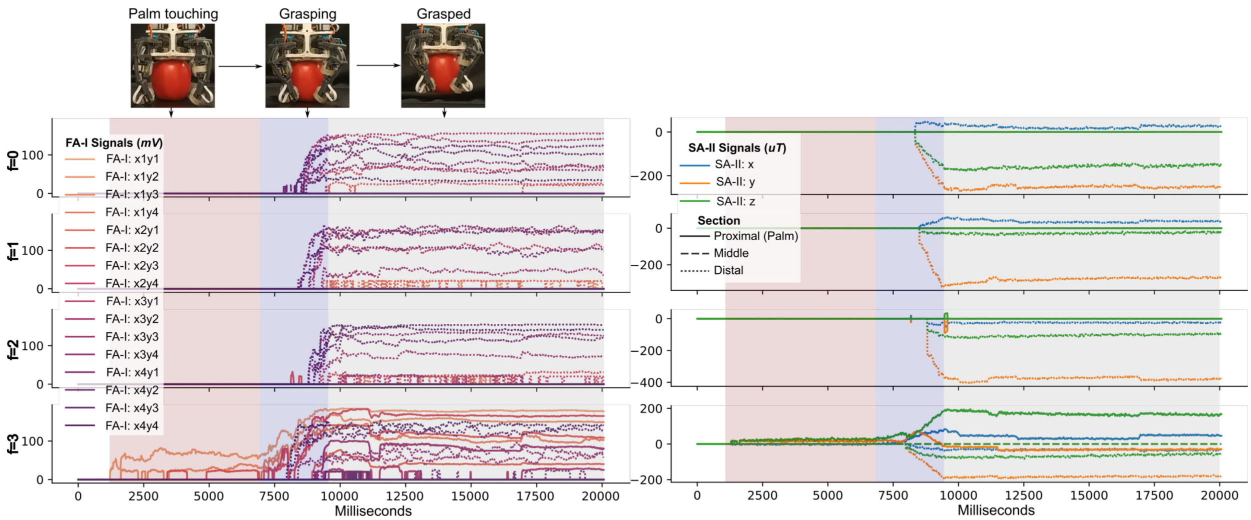

Fig. 8. The tactile sensing feedback from the palm and fingers when the GTac-Gripper was grasping an apple.

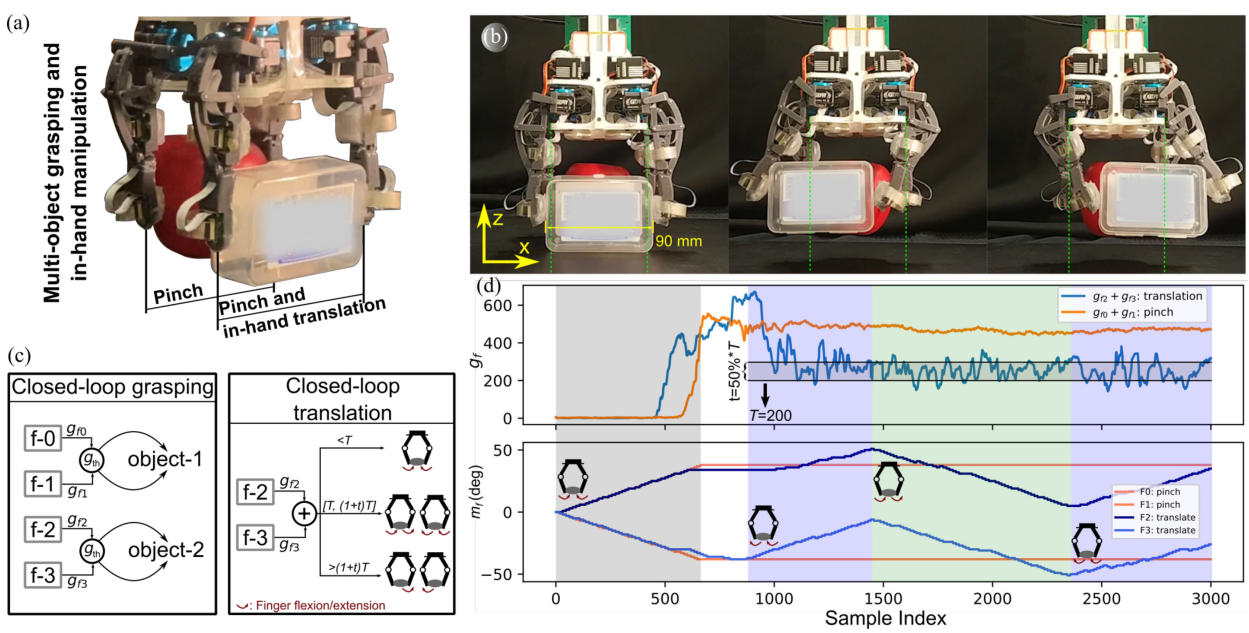

Fig. 9. (a) Multi-object grasping and in-hand manipulation. (b) The in-hand translation process with a cubic box. (c) The illustration of the closed-loop in-hand translation controller. (d) The leveraged tactile feedback and the rotated displacement of the motor for finger flexion.

a score of 18/20 (90%). For all the tests, the GTac-Gripper achieved a score of 252/388 (65%). As shown in the results, the GTac-Gripper can grasp various everyday objects by adapting its fingers to the shapes of the objects with tactile sensing capabilities and the reconfigurable mechanism.

D. Limitations

Currently, there are some limitations of the GTac-Gripper, such as the optimization of finger linkage parameters, tactile sensing coverage, and fingertip structure. The current linkage parameters of the underactuated fingers make the fingers unable to touch the palm, which limits the gripper in grasping small objects relying on the palm. They also limit the workspace of the middle phalanges, making it difficult for the GTac sensors at the middle phalanges to contact small objects. Also, the GTac sensors do not provide full coverage of the fingers and palm which potentially results in contacts without tactile feedback when grasping smaller objects or objects with irregular shapes. According to the YCB assessment results, the gripper failed to grasp all the flat objects. This is because underactuated fingers provide limited workspace, and the current fingertip with a blunt edge makes it difficult to provide enough lifting forces for flat objects.

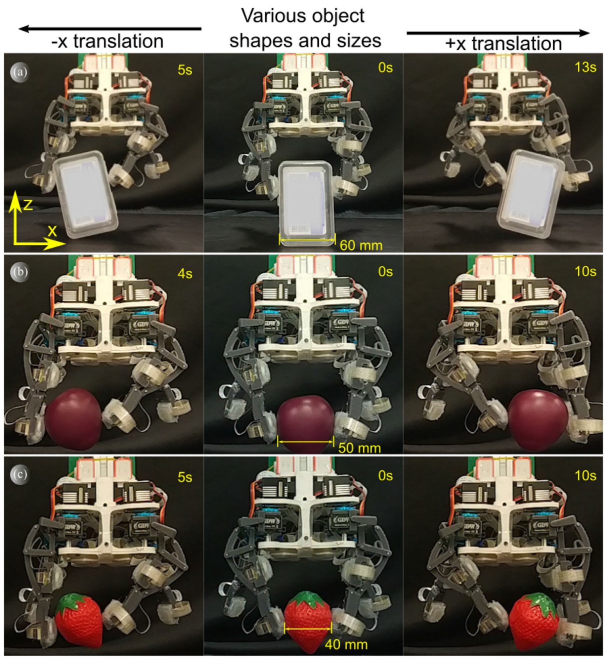

Fig. 10. In-hand translation for different objects of various shapes and sizes relying on tactile feedback.

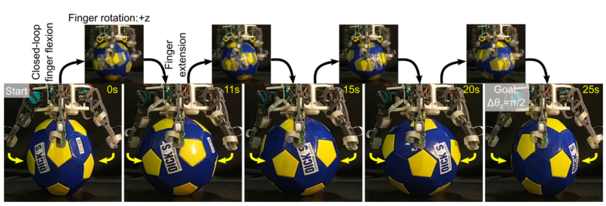

Fig. 11. The reconfigurable mechanism enabled the gripper to rotate a small soccer ball on a table.

V. Conclusion

In summary, this work presents a four-fingered gripper with reconfigurable mechanism and integrated tactile sensors in the fingers and palm. Our experiments show that the reconfigurable mechanism enables our gripper to perform five grasping configurations. The tactile sensing feedback can facilitate our gripper to achieve grasping and in-hand manipulation and adapt to various objects with closed-loop control. In future work, besides addressing the current limitations, it is important to discover how to determine the optimal grasping configuration. Also, we would like to consider developing a learning-based controller for utilizing the rich tactile feedback in the post-grasping phase, such as handover, tool usage, and interaction with the external environment.

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