A Tendon-Driven, Preloaded, Pneumatically Actuated, Soft Robotic Gripper with a Telescopic Palm

Jiawei Meng, Lucas Gerez, Jayden Chapman, and Minas Liarokapis

Abstract—In this paper, we present a highly adaptive, 3-fingered, soft robotic gripper with a reasonably low weight (657 g) that is capable of grasping various everyday life objects. The employed soft, pneumatically actuated robotic fingers are able to grasp objects of different shapes without damaging them, and the extendable, soft, telescopic palm is able to absorb the high impact forces of the grasped objects, protecting the onboard sensor and providing adaptation to the object shape. The gripper is tendon-driven and it employs a quick-release mechanism that allows grasping of objects at high speeds. The deformability of the soft robotic fingers and the telescopic palm is evaluated by tracking their motions with an appropriate motion capture system. The proposed gripper facilitates the execution of smooth pre-contact motions. The high working volume of each finger allows for grasping of objects with a variety of shapes and sizes. The behaviour of the gripper and its performance are experimentally validated with grasping experiments that involve a plethora of everyday life objects.

I. INTRODUCTION

Currently, numerous studies concentrate on designing soft robot hands with pneumatic mechanisms [1]–[4], or adaptive robot hands with tendon-driven mechanisms [5], [6] for different kinds of every day grasping tasks. Soft and adaptive (underactuated and/or compliant) grippers are of low-cost and low-complexity, and they provide simplified solutions for the execution of robust grasping tasks with everyday life objects by employing a minimal number of actuators. By combining best practices from both fields, we are able to maintain the benefits of both sides while optimizing the total number of the pneumatic actuators and motors on the proposed gripper. More specifically, we focus on a new, hybrid type of robot hand which is lightweight, easy-to-control, and rapidly actuated by integrating pneumatic and tendon-driven mechanisms. We also investigate the incorporation of soft telescopic mechanisms in the palm module and how they increase conformability to the object shape.

Compared with rigid-bodied robot hands, soft-bodied robot hands are safer when interacting with everyday objects in unstructured and dynamic environments. Additionally, the lack of rigid elements helps soft-bodied robot hands to conform to objects with relatively larger contact areas, improving grasping performance [7], [8]. Whilst progress has been made within the field of soft robot hands in laboratories across the world, relatively little work exists on combining soft components such as pneumatic fingers and palms with tendon-driven mechanisms.

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II. RELATED WORK

Robotic end-effectors evolved from simple parallel jaw grippers to complex robot grippers with multiple degrees of freedom (DOF) that are capable of reproducing a large variety of grasps. Over the last decades, a new class of adaptive robot hands has emerged, facilitating the execution of robust and stable grasps in unstructured and unknown environments. Such an advantage is due to a combination of underactuation and inherited compliance that allows these grippers to conform to the object geometry [9]. Underactuated designs are usually simple to operate and control, and consume less power as the number of motors is reduced. Thus, adaptive hands are affordable, lightweight, and of low complexity, being an attractive option [10]. In [11], the
authors proposed several open-source adaptive hand designs that can be easily fabricated and replicated by the community. In [12], the authors optimized the design parameters of an adaptive tendon-driven robot hand based on genetic algorithms by taking into account a series of geometric constraints. In [13], the authors proposed a tendon-driven finger for an anthropomorphic robot hand, which mimics and reconstructs the anatomical model of a human finger.

However, adaptive robotic hands also have their limitations and drawbacks. More precisely, they exhibit limited dexterity since they employ a limited number of actuators to control multiple DOFs independently. Also, since it is difficult to estimate and control the contact forces applied along the robotic finger, they are not the most suitable solution for grasping and manipulating delicate objects. More recently, following the path of intrinsic compliance in robotic devices, soft grippers based on completely soft pneumatic actuators (SPAs) have received increased interest from the research community due to their flexibility, customizability, and environmental adaptability [14]. The popularity of soft, pneumatic actuators has increased over the last years after the dissemination of open source projects, such as the Open Robotics Toolkit (a library of soft robotic designs for researchers and enthusiasts) [15]. Soft robotic actuators can be used in many different environments to grasp a wide range of objects. In [16], the authors describe an underwater robotic gripper that employs soft fingers to grasp and manipulate fragile species on the deep reef. In [17], the authors use soft actuators composed of elastomeric materials with integrated channels to produce bending motions that can conform with the human finger motion in the design of a hand rehabilitation glove. In [18], the authors propose a soft robotic gripper with a compliant structure for delicate surgical manipulation. Similar to tendon-driven adaptive robot hands, SPAs also have several limitations and disadvantages. Pneumatic actuators are usually bulky, difficult to control and manufacture, and suffer from leakages. For these reasons, we propose a hybrid approach combining characteristics of tendon-driven adaptive grippers and soft pneumatic actuators to design a highly adaptive, 3-fingered robotic gripper with a quick-release mechanism.

III. DESIGNS AND FABRICATION

In this section, we present the design of the tendon-driven, preloaded, pneumatically actuated, soft robotic gripper. We also present the molding process of the soft parts of the gripper and we analyze how they respond to pressure.

A. Hybrid Soft Gripper

The overall structure of the proposed gripper in this paper can be divided into three main parts: the soft fingers, the soft, telescopic palm, and the gripper base, as shown in Fig. 1. The gripper base contains a micro-controller (Robotis, OpenCM-9.04) to control a quick-release mechanism and monitor the real-time data acquisition from the IR sensor, which is embedded on the top surface of the gripper base. Moreover, the tendons attached to the soft fingers are connected with the wheel of the quick-release mechanism, as shown in Fig. 2. Based on this design, the quick-release mechanism with the wheel are able to open the soft gripper. It is worth noting that the soft fingers and the soft palm are preloaded by two separate pressure supplies. The operation principle of the proposed gripper is shown in Fig. 3.

B. Quick-release Mechanism

The quick-release mechanism is the main component of the tendon-driven system and is based on a previous design of an aerial grasper [19]. The interaction between the soft gripper and the quick-release mechanism is shown in Fig. 2. The three tendons of the soft fingers are connected to the same wheel and their motions are coupled. In addition, the motor horn and the wheel rotate together when the quick-release mechanism is not triggered (the mechanism is engaged) and the wheel rotates freely (disengaged) when the mechanism is triggered. This allows the fingers to close rapidly. When the IR sensor detects an object at a distance lower than a threshold, the quick-release mechanism is triggered. Therefore, the object can be quickly grasped by the proposed hybrid robotic gripper. As the quick release mechanism requires little force to activate (to be triggered), a small Dynamixel motor with precise position control was used for triggering, while a larger, more powerful motor was used to drive the tendons.
C. Telescopic, Pneumatic Soft Palm

The telescopic, pneumatic, soft palm proposed in this paper is used to avoid damage to the IR distance sensor that could be caused by a potential collision. The square palm has a side length of 25 mm and an initial height of 10 mm, which is extendable up to 50 mm (total extension is 40 mm). In order to manufacture the telescopic palm, the hybrid deposition manufacturing (HDM) technique is applied during the molding process [20]. To achieve greater flexibility and decrease the manufacturing complexity, we selected a high-performance silicone rubber (Smooth-On, Dragon Skin 30). The multi-stage molding process of the telescopic, pneumatic soft palm contains three main steps, as shown in Fig. 5.

Firstly, the bottom and middle chamber molds are connected so that silicone material can be poured into them. Once the air bubbles have been removed from the silicone material, the top half of the mold is inserted into the rest of the mold with excess silicone overflowing out of the mold where required. Meanwhile, silicone material is also used to attach part A and B together to obtain the complete telescopic palm. In order to empirically evaluate the expansion performance of the telescopic, pneumatic soft palm, an experiment was conducted by recording the motion of the different layers of the telescopic mechanism, as shown in Fig. 6. Markers were installed on each layer of the mechanism to help record the corresponding motion during the extension process. Data was gathered for five trials involving a wide range of pressures from 0 to 35 kPa, as shown in Fig. 4. Based on our observations, we notice that the height of the first layer of the telescopic mechanism is relatively stable during the entire inflation process. The heights of the second layer and the third layer of the soft, telescopic mechanism experience significant displacements. At 15 kPa (between 40 s and 60 s in Fig. 4), the second layer extends \( \sim 20 \) mm, and at 35 kPa (between 100 s and 120 s in Fig. 4), the third layer extends \( \sim 15 \) mm. The total extension of the third layer is 40 mm (between 0 s and 130 s in Fig. 4).

D. Plastic-reinforced Finger

The plastic-reinforced finger that we used in this design is based on the design described in [15]. It contains two layers (inner skin and outer skin), a low stretch braid that is wrapped around the inner skin from the top the to bottom, and a 3D-printed inextensible plastic layer that is embedded between the inner skin and outer skin. The length of the finger is 150 mm and the radius of the semicircular surface at both ends of the finger is 15 mm.

The HDM technique is also used during the molding process of the plastic-reinforced finger [20]. High-performance silicone rubbers (Smooth-On, Dragon Skin 30 and Dragon Skin 10) were used as the outer and inner skin material, respectively. Different materials have been used for
Fig. 7. The molding process of the plastic-reinforced finger: In the end, before obtaining the entire plastic-reinforced finger, the two ends of the outer skin of the finger are sealed by using the same material.

Fig. 8. Bending profile of the plastic-reinforced, pneumatically actuated, soft, robotic finger. The lines are used to denote the links of the finger and the circles denote the joints.

Fig. 9. Two different states of the soft finger. The left subfigure demonstrates its initial state and the right subfigure demonstrates its fully bent state.

Fig. 10. Grasping experiments: From subfigure a) to f), the gripper is grasping a red cardboard box, a Starbucks cup, a yellow plastic bottle, a yellow baseball, a red football, and a potato chips can.

**IV. GRASPING EVALUATION**

In order to evaluate how well the proposed gripper design performs grasping tasks, a robot arm (UR5, Universal Robots) was used and the developed gripper was installed on its end-effector in order to perform various experiments. Table I shows objects of various dimensions, weights, shapes, and materials that were used during these experiments.

**A. Daily Grasping Tasks**

The vertical grasping capability of the proposed gripper was first tested by using it to grasp various everyday objects and to hold them stably in the air for approximately five seconds, as shown in Fig. 10. Furthermore, each object from the object set presented in Table I was grasped ten times so that the average grasping time could be calculated. In these experiments, all the target objects were grasped by the proposed gripper with a high success rate and short average grasping time (see Table II).
TABLE I

<table>
<thead>
<tr>
<th>Object</th>
<th>Dimension (mm)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper box</td>
<td>215x60x160</td>
<td>56.46</td>
</tr>
<tr>
<td>Starbucks cup</td>
<td>70x143</td>
<td>16.28</td>
</tr>
<tr>
<td>Plastic bottle</td>
<td>200x100x55</td>
<td>46.31</td>
</tr>
<tr>
<td>Baseball</td>
<td>95</td>
<td>173.26</td>
</tr>
<tr>
<td>Football</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Paper can</td>
<td>80x235</td>
<td>31.13</td>
</tr>
</tbody>
</table>

Note: The objects that have only one value in the dimension section are spheres, and the objects that have two values in the dimension section are cylinders (the first value represents the diameter of the top and bottom surfaces and the second value represents the height).

TABLE II

<table>
<thead>
<tr>
<th>Object</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper box</td>
<td>0.46</td>
</tr>
<tr>
<td>Starbucks cup</td>
<td>0.61</td>
</tr>
<tr>
<td>Plastic bottle</td>
<td>0.70</td>
</tr>
<tr>
<td>Baseball</td>
<td>0.65</td>
</tr>
<tr>
<td>Football</td>
<td>0.34</td>
</tr>
<tr>
<td>Paper can</td>
<td>0.41</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a highly adaptive, 3-fingered, soft robotic gripper that is capable of grasping various everyday objects. The use of a compliant soft finger allowed grasping of objects of different shapes, sizes, and materials without damaging them. The extendable, soft, telescopic mechanisms are able to absorb the impact forces of oncoming objects, protecting the on-board IR distance sensor and providing better grasping conformability. The experiments also demonstrated that the tendon-driven system combined with the quick release mechanism was able to help the gripper to grasp the objects with reasonably high speeds without damaging them.

Regarding future directions, we plan to improve the manufacturing process of the soft structures, decreasing the number of steps required to fabricate them, and reducing the stress concentration regions to avoid leakages in the system. We also plan to optimize the position of the IR distance sensor and the positions of the soft telescopic mechanisms to better grasp objects.

REFERENCES


