

A Passively Complaint Idler Mechanism for Underactuated Dexterous Grippers with Dynamic Tendon Routing

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Abstract. In the field of robotic hands, tendon actuation is one of the most common ways to control self-adaptive underactuated fingers thanks to its compact size. Either differential or direct drive mechanisms are usually used in these systems to perform synchronised grasping using a single actuator. However, synchronisation problems arise in underactuated grippers whose position of proximal joints varies with time to perform manipulation operations, as this results in a tendon-driven system with dynamic anchor pulleys. This paper introduces a novel passively complaint idler mechanism to avoid unsynchronisation in grippers with a dynamic multi-tendon routing system, such that adequate grasping contact forces are kept under changes in the proximal joints' positions. A re-configurable palm underactuated dexterous gripper is used as a case study, with the performance of the proposed compliant idler system being evaluated and compared through a contact force analysis during rotation and translation in-hand manipulation tasks. Experiment results clearly demonstrate the ability of the mechanism to synchronise a dynamic tendon routing gripper. A video summarising experiments and findings can be found at <https://imperialcollegelondon.box.com/s/hk58688q2hjnu8dhw7uskr7vi9tqr9r5>.

Keywords: Dynamic Tendon-Driven System · Underactuated Hands · In-hand Manipulation.

1 Introduction

The dexterous in-hand manipulation capability of grippers has drawn lots of research attention due to its importance in enhancing the adaptability of robotic systems. It remains an open problem whose complexity emerge from the fact that fingers often need to change their orientations, relative positions, and contact forces to perform in-hand manipulation tasks. Indeed, the optimised actuation method for robot fingers is also an open research question. For the majority of hands, the actuation of separate fingers is done using separate actuators. For

example, the GCUA Hand has two geared DC motors to actuate each finger by pulling different tendons [4]. Other cases include the JLST hand [14], the DLR-Hand II [3] and the OLYMPIC prosthetic hand [9], just to name some, which all actuate each finger with its own actuator. This solution provides higher dexterity compared to solutions based on combined underactuation [1], but is more expensive and complex to control due to the increased number of actuators.

Underactuation, that is, the control of more degrees of freedom than actuators are available [7], has been frequently leveraged for robot hand design. For instance, avoiding the use of a tendon, Cheon et al. [5] used differential gear mechanisms for underactuation, where the differential gear ratio is determined by the length of phalanges. Ma et al. [11] used a differential-driven pair in their gripper, where two fingers were connected with a single tendon and actuation was achieved by pulling a pulley in the centre. Similarly, Rossi et al. [13] used a force distribution system with a cascade of floating pulley systems, where the primary pulley is in-turn connected to another two secondary pulleys. When the primary pulley is pulled by the actuator, a quarter of the force from the motor goes to each of the four fingers connected to the secondary pulleys. Additionally, Gosselin et al. [8] attached an additional tendon to the primary pulley to actuate the thumb, and the force from thumb is hence different from the other fingers.

Alternatively, Niestanak et al. [12] proposed the closed loop tendon mechanism for multi-finger actuation where all the fingers are controlled by a single loop of the tendon. The tendon is fixed at the fingertips and different joints of the finger with pins and tubes. With a single motor winding up the tendon, the total length of the tendon loop decreases leading to the flexion of the desired joints. However, the contact forces for each finger are uneven due to the mix of directly and indirectly connected tendons to fingers. Baril et al. [2] looked into a few tendon driven systems that have single-input/multiple-output underactuated mechanisms as described above, and their combination was claimed to be most compact and efficient mechanism due to low friction and evenly distributed forces. For reconfigurable hands such as that developed by X. Cui et al. [6], the tendon length for each finger differs, thus the constant force and tendon length models mentioned previously are not longer suitable. Lu et al. [10] provided one solution to this problem by routing the tendon through the five-bar-mechanism based reconfigurable palm, ensuring the length of the tendon is independent of the palm configuration. However, this constant tendon system requires a high actuation force due to the complex routing design.

In this paper, a novel passively compliant idler mechanism for managing unsynchronised multi-tendon actuation in underactuated grippers is proposed. By maintaining the tension in the tendons, the force provided by the fingers on an object is sufficient to keep the object in a stable grasp during dexterous in-hand manipulations. In Section 2, we discuss the design and development of the introduced idler system. We then demonstrate the design of the reconfigurable hand used for testing the idler system in Section 3. Next, in Section 4 and 5, we evaluate and discuss the idler performance in in-hand manipulation tasks. Lastly, we conclude in Section 6.

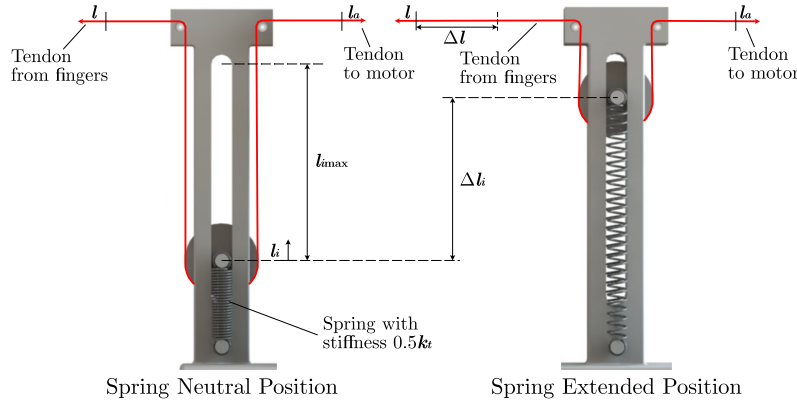


Fig. 1. Schematic of the proposed passively compliant idler mechanism

2 Development of the Idler System

Idlers are usually used in flexible mechanical transmissions such as belt or chain drive systems. The main purpose of including idlers in the system is to increase the wrap angle on the smaller pulley/sprocket so that the force-transfer capacity can be maximised. In addition, to ensure the performance of the flexible drive, the belts or chains must be kept in tension during operation. However, in practice belts or chains are purchased at fixed lengths and it is common to have them with excess length. With the addition of adjustable idlers, the excess slack length can be taken up and the additional tension improves the transmission efficiency.

A similar concept can be applied to the tendon actuation for grippers. When the tendon is routed, the total length is fixed. For robot hands with reconfigurable palms, it is common for finger positions to change relative to the actuators, which means the fixed tendon lengths would either become too long or too short for the same finger posture, hence the fingers might lose contact with the grasped object. This is further complicated in underactuated grippers that only use a single actuator for multiple fingers as different tendons can have different slack lengths. To prevent this, a passively compliant idler pulley system (schematics shown in Fig.1) was implemented before connecting tendons to the actuator to keep all the tendons in tension and maintain the necessary contact force between the finger tip and the object.

2.1 Static Modelling of the Idler System

As shown in Fig. 1, the idlers are free to move linearly with a range of $l_{i_{max}}$ and they hold each tendon in tension with springs pulling them downwards with a total stiffness of k_t . Since the idler system is connected between the fingers and the actuator, the forces applied to the fingers are provided by the springs until the idlers have reached their top-most position. The force applied by the springs

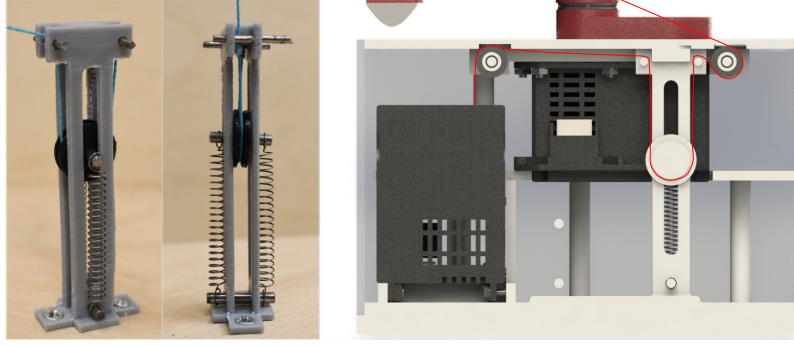


Fig. 2. **Left:** Single idler structure view. **Right:** Sectional CAD view of the idler system with tendon routing (red).

to the pulley is given by Hooke's law $F = k_t \times \Delta l_i$ where Δl_i is the extended length of the springs. Since each idler is a moving pulley, the tension force is hence $F_t = \frac{1}{2}k_t \times \Delta l_i$. In addition, the actuated tendon length l_a is twice of the spring extension length l_i . When the finger has grasped an object, and then the tendon is loosen by a length of Δl , the following equation must be satisfied in order to keep the grasp:

$$F_{grasp} \leq \frac{1}{4}k_t(l_a - \Delta l) + f_{static} - F_{restore} \quad (1)$$

where F_{grasp} is the minimum grasping force required, f_{static} is the total static friction in the tendon system and $F_{restore}$ is the restoring force by the fingers. Therefore, when actuating the fingers, extra tendon length would be wound in order to compensate for the potential tendon slack during manipulation.

The minimum spring extension to ensure a grasp can be derived:

$$l_{i_{min}} = \frac{2(F_{grasp} + F_{restore} - f_{static})}{k_t} \quad (2)$$

Thus, the actual range for idlers to move during manipulation is $l_{i_{max}} - l_{i_{min}}$. For each specific tendon, Δl_{max} is constant and is determined by the design of the gripper. Therefore, it is important to make sure that

$$\Delta l_{max} \leq 2(l_{i_{max}} - l_{i_{min}}) \quad (3)$$

For unsynchronised multi-tendon systems, there would be different Δl_{max} for each tendon and there would be different Δl during manipulations as well. Each tendon was connected to the actuator pulley separately based on corresponding Δl_{max} and when actuating the tendons for a grasp, the maximum Δl among all tendons should be used in calculation to make sure that all the fingers will not lose contact with the object.

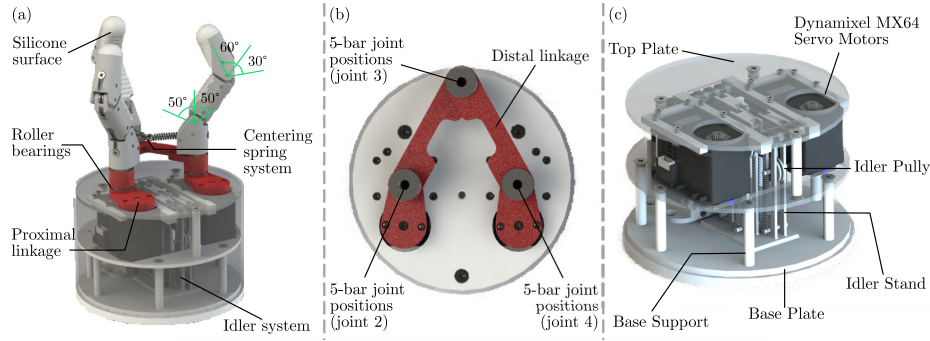


Fig. 3. (a) CAD model showing the overall gripper structure with the idler base. Finger joint angle limits are also shown. (b) CAD Model showing the palm. (c) CAD model shows the idler system structure in the base of the tested reconfigurable hand

2.2 Implementation of the Idler System

Three idler stands are used in the case study, namely a robotic hand with reconfigurable palm. The design of this robot hand is detailed in the section 3. Fig. 2 shows the single idler structure and the tendon routing, in which all three tendons pass through a small hole on the top plate and are routed through several tendon pulley. When the palm is reconfigured during manipulation, the tendon can loosen or tighten such that the idlers would move up or down for compensation. In the implemented prototype, the idler stands have a minimum range of $l_{i_{max}} = 50mm$, which fully utilised the spaces between top and base plate. The Δl_{max} is calculated to be approximately 60 mm for the reconfigurable palm. Therefore, the relationship stated in Equation 3 is satisfied. The sum of restoring forces $F_{restore}$ and static friction f_{static} was measured to be 7.075 N. Two springs with stiffness of 1000 N/m were used for each idler. The tendons were fixed to the tendon actuator pulley when palm is at the closest position (minimum tendon length) with reference to Equation 2 for relative idler positions. During manipulation, the tendon actuator is set based on Equation 1 in order to provide enough force to maintain a stable grasp.

3 Design of the Gripper

The gripper that was implemented with the idler system has a five-bar linkage with three underactuated fingers located at its moving joints. Therefore, when re-configuring the five-bar linkage, which is the gripper's palm, the fingers would move relative to the base where the tendon actuator is mounted. The length of the tendons would hence need to be adjusted in order to maintain the grasp forces. In addition, the tendon length change of each finger is different from each other which provides more problems for the actuation. The idler system introduced in section 2 is therefore incorporated with the gripper and the final prototype is shown in Fig. 3(a).

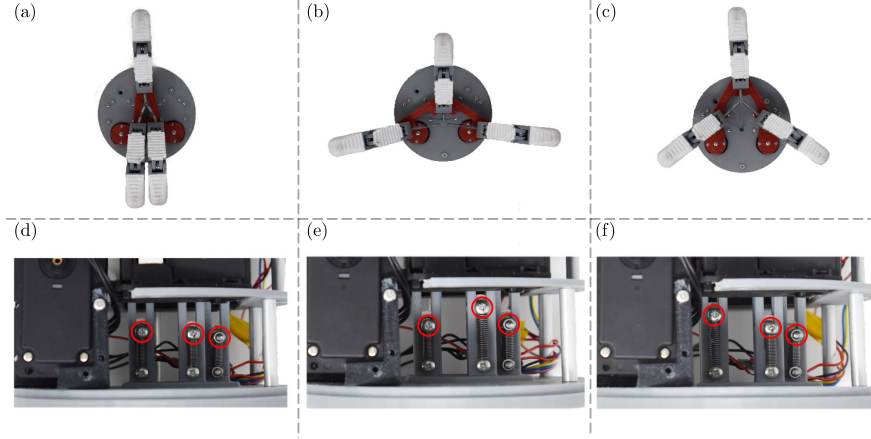


Fig. 4. Different types of grasps achievable with the reconfigurable gripper: **(a)** Parallel, **(b)** T-shape, and **(c)** Trigonal planar. **(d-f)** indicate the positions of the idler pulleys (indicated by red circles) corresponding to each of the grasping configurations.

3.1 Five-Bar Reconfigurable Palm

With the five-bar linkage as the palm of the gripper shown in Fig. 3(b), dexterous in-hand manipulation can be performed. By actuating two proximal linkages, the relative positions of the fingers can be changed and different configurations can be achieved (Fig. 4), e.g. parallel, T-shape, trigonal grasping etc. A symmetrical structure with two proximal bars and two distal bars having the same length was used for the five-bar linkage. In addition, the motor separation (the fixed link in the five-bar palm system) was set to have the same length of the distal linkage, which is 70 mm, so that fingers can easily grasp objects in a equilateral triangle (trigonal) configuration. When selecting the length of proximal bars, the avoidance of singularities and collision during operation became the main considerations. The proximal bar lengths were hence set to be 20 mm. A caster wheel was used in the palm to support the gripper during operation. Roller bearings (20 mm) were added between the faces of the links to reduce the friction and improve the performance of the five-bar linkage.

3.2 Underactuated Fingers

6 mm machine screws were used to affix three identical fingers with two phalanges which were fixed at the joints of the five-bar linkage that allowing the rotation of the fingers. For each finger, the proximal phalanx has $\pm 50^\circ$ and the distal phalanx has $+60^\circ / -40^\circ$ range of motion as shown in Fig. 3(a). The linear springs with stiffness of 65 N/m were fixed at the back of the fingers in order to provide the restoring forces for the underactuated fingers. To enhance the contact friction force between the fingers and the objects, the fingertips and

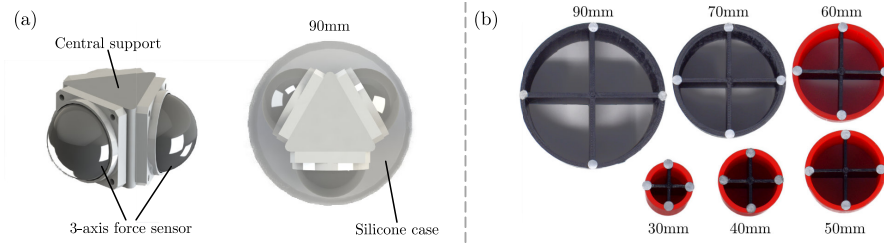


Fig. 5. Objects used to evaluate the performance of the gripper with and without the idler system. **(a)** A soft cylindrical object with embedded trigonal 3-axis force sensors and **(b)** regular cylindrical objects in various sizes.

the proximal phalanges were coated in textured silicone (SmoothOn Eco-Flex 00-10).

To maintain the grasp capabilities of the gripper, ideally fingers must face towards to the centre of the triangle formed by the three finger base positions (joints 2, 3 and 4 shown in Fig. 3(b)) in the x-y plane. To achieve this, three high stiffness springs were attached to the base of each fingers and the other end is connected to each other, where the holding point of all three springs is located at the centre of the triangle. Therefore, no matter how the five-bar linkage system is reconfigured, the springs would always adjust the finger position, turning them towards to the centre of the palm.

3.3 Design of the Prototype

The prototype is mainly constructed from the 3D printed parts on a single nozzle desktop printer. Polylactic Acid (PLA) was used to print the mounting plates, motor supports and the fingers. To increase the rigidity of the structure, the five bar linkages were printed using Polyethylene Terephthalate Glycol (PETG). Three Dynamixel MX 64 servo motors were used to control the gripper, two for five bars and one for all three underactuated fingers. An Arduino Nano micro-controller was used to control the gripper by using a software serial connected tristate buffer (74LS241N) to communicate using half-duplex UART protocol with motors.

4 Performance Evaluation

4.1 Experimental Setup

The sensors used for the experiments are shown in Fig. 5(a). Three OMD-30-SE-100N force sensors were fixed to the central support block. A silicone case was then made to provide the housing for the sensors and also made the testing object easier to grasp. The sensors log the data with a frequency of 100 Hz and the compression force in vertical direction of each sensor were taken and plotted

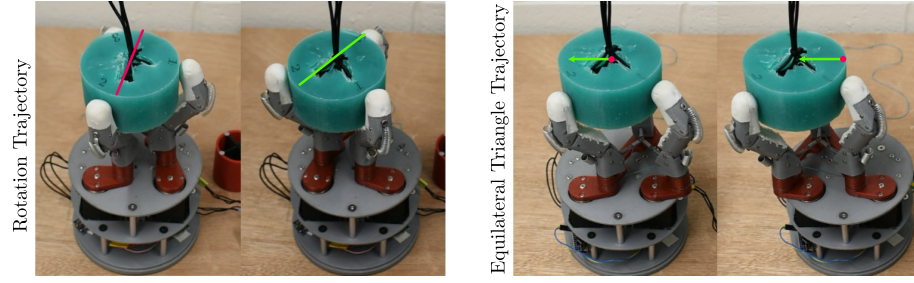


Fig. 6. Illustration of the experimental trajectories by highlighting the starting and ending positions of the testing object.

against time for comparison. Moreover, testing objects with a variety of sizes, 30 - 90 mm as shown in Fig. 5(b), were employed to prove the gripper’s capability for in-hand manipulation.

In the experiments, two trajectories were performed as shown in Fig. 6. Namely, an equilateral triangle co-planar movement and a pure rotational movement. The actuation of the equilateral triangle co-planar movement was achieved by keeping the proximal bars parallel (hence keeping the fingers at equilateral triangle configuration) and rotate 180° , from positive x to negative x direction, with the same speed. The rotation trajectory ideally can rotate the object around 68° . The rotation range of the proximal bars are based on the inverse kinematic values output from the simulation of the gripper manipulation workspace. Each experiment was repeated three times to provide reliable results and another set of data was obtained for the same gripper but using a direct drive mechanism (i.e. without the idler system—routing the tendons straight from the fingers to the actuation motor) for comparison.

4.2 Idler Performance

Fig. 7 presents the data taken by the three sensors for two different trajectories. For each trajectory, first three rows of graphs show the variation of compression forces received by each sensor during manipulation of the gripper with idler system incorporated, while the last row of data shows that of the gripper without the idlers. Sensors 1, 2 and 3 correspond to the finger at joint 4, 2 and 3, (as labelled in Fig. 3(b)) respectively. Three data sets shared a similar trend of force variation and at the end position of the trajectory, all the fingertips were still in contact with the sensor assembly and the sensors were still held in place.

From the data for both of the trajectories, it is obvious that the gripper with idler system is able to maintain a higher average grasping force during the manipulation than the gripper which the tendons are directly connected to the actuator. In addition, during the experiments for the comparison group, we found out that without the idler system, the gripper is impossible to grasp an object with different grasping configurations, let alone to perform in-hand

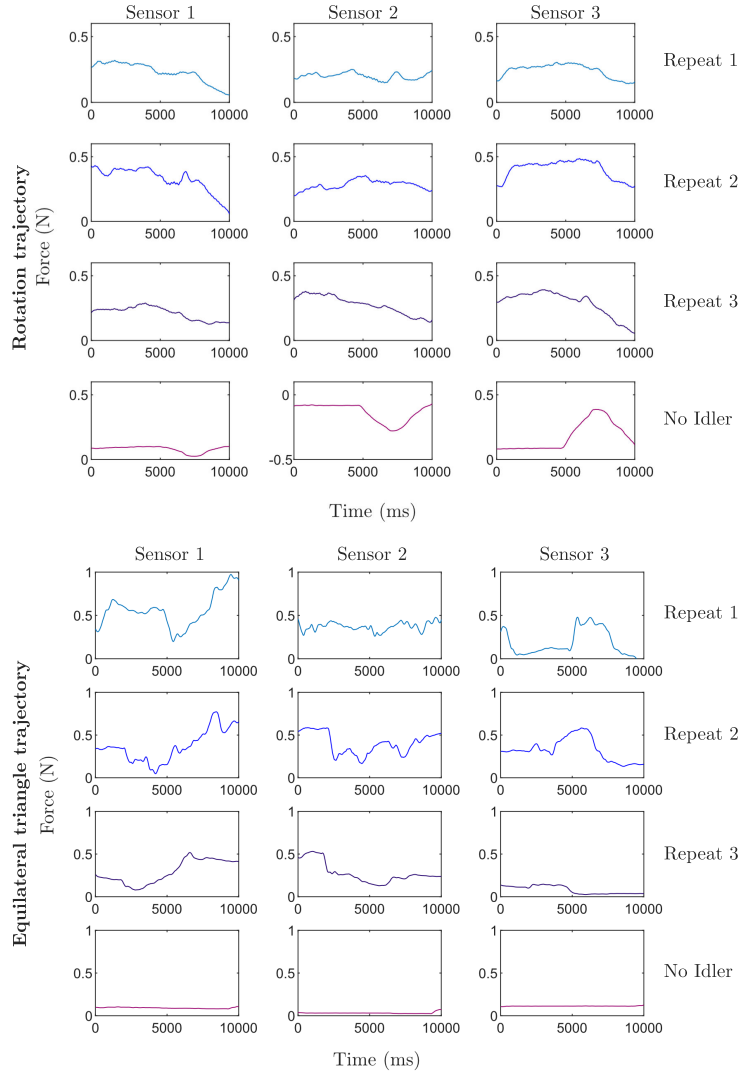


Fig. 7. Sensor data for both movements. Each column indicates each sensor's reading. Each movement has three trials of results with idler system and one trial without the idler system (last row).

manipulations. During the rotation trajectory experiments for gripper without idlers, finger 2's tip lost contact with the object completely and the sensor assembly was only supported by the proximal phalanx of the finger in vertical direction. Therefore, the sensor did not experience the vertical compression but has lateral deformation, leading to a negative value in the result (Fig. 7).

For the grasping tests for smaller testing objects (<90 mm), the gripper with the idlers successfully maintained the object for both trajectories while the gripper without idlers failed to perform the grasping at the position and the object could only sit on the proximal phalanges. The detailed implementation of the experiments can be found in the video (link provided in the abstract).

5 Discussion

According to the experimental results in Fig. 7, although there are fluctuations in the forces provided, the idler system successfully maintained the contact forces that is necessary for the grasp whereas the comparison group failed to perform the manipulation. In fact, the general trend and the fluctuations were expected for the idler system and can be explained by the mechanism of the system.

As explained in section 2, the idler positions would change actively according to the change in tendon length Δl during manipulation. Therefore, the tendon tension would be slightly different due to changes in l_i , so does the force for the grasp F_{grasp} . It is then easy to deduce that if the tendon actuator is held constant, when the fingers move further away from the centre hole on the top plate, which means the ideal tendon length is larger than the actual tendon length, the idlers would then move upwards for compensation. Although the finger posture remains the same, the actual grasping force F_{grasp} has increased due to a raise in l_i , and vice versa.

With this understanding, the fluctuations can thus be explained. For the rotation trajectory, in average, sensor 3's reading increases at the beginning and drop back to its starting position during the manipulation. It is because the distance between the joint 3 of the five-bar linkage and the centre hole firstly increases and then drops back to the initial distance during this trajectory. Similarly, sensor 2 experiences least fluctuation because in the five-bar linkage system, the distance change between position of joint 2 and the centre point during the manipulation is trivial. Additionally, during the rotation trajectory, the triangle formed by joint 2, 3 and 4 of the five-bar linkage was not maintained constant. When the geometry of this triangle changes, the contact points of the fingers would change at the same time because the fingers were designed to have spherical tips so that it has local rolling at the contact surface with the object to prevent the slipping. Therefore, the force applied by the fingertip is no longer perpendicular and at the centre of the sensors, which lead to a drop in sensor reading during the manipulation.

As for the equilateral triangle trajectory, since the geometry of the triangle formed by fingers was always maintained as equilateral, there was not any changes in the contact points that have occurred. The trend was consistent for the data set. Different from the previous trajectory, this co-planar trajectory would require much larger initial tendon actuation length because between the movement between 90° and 270° , the tendon length change Δl is the largest for the finger located at joint 3 of the five-bar linkage because it passes the furthest point. Similar to the other two fingers, the tendon length change Δl is relatively

large compare to the rotation trajectory; therefore, the force reading varies more significantly.

The initial contact points between the fingers and the sensor assembly also affected the sensor reading. For instance, the reading of sensor 3 is close to zero for the third set of data, but the forces from other two fingers were providing enough force to support the sensor assembly so that it was not falling off. In addition, if the sensor assembly was not placed horizontally at the initial point, it would lead to an un-evenly distributed force among three contact points and hence lead to the deviation in the data retrieved. The other source of the experimental error could be from the sensor assembly where as the deformation of the silicone shell would lead to a change in the force readings as it is effectively acting as a spring in the system. The silicone shell is used to create a stable grasping situation when the contact points are changing. This could be improved by using other types of force sensors which can detect the force no matter the contact points or add tactile sensors in the fingertips.

According to the results, it has been proven that by satisfying a few criteria for the spring selection, the idler system is capable to synchronise a dynamic tendon routing system to perform different grasping configurations and in-hand manipulation. However, the current idler system design is not robust enough to provide 100% successful rate. The structure rigidity, tendon routing method for fingers and system, and the spring selection criterion could be further developed for better performance and adaptability.

6 Conclusion

In this paper, a concept of passively complaint idler system was developed for unsynchronisation-prone multi-tendon systems. We presented the design, construction, and evaluation of the idler system on a reconfigurable underactuated gripper, which makes the actuation of multiple tendons with a single motor possible by incorporating an spring system. Through the use of a five-bar linkage as the palm of the gripper, the tendon system becomes unsynchronised and the routing system is then dynamic. The proposed idler system is capable of controlling the tendon length for different grasping configurations and in-hand manipulations. We experimentally evaluated the idler system by in-hand manipulating various objects with sensors. From the force sensor readings we see that with the proposed idler system, the gripper is able to maintain the grasping force for the fingers during the manipulation. Moreover, the idlers can also perform precise grasps and manipulations of small objects (30 mm diameter) without losing or dropping them. Therefore, this demonstrates that by satisfying a few criteria for spring selection, it is possible to have a single actuator adjusting different forces for each of the tendon stream. This provides a simple but efficient solution for tendon-actuated multi-finger gripper whose positions of proximal joints vary with time. Regarding future work, an optimisation of the spring selection criterion could be further developed by incorporating further considerations about friction for instance. The routing optimisation can also be

improved to reduce friction and to reduce the effects of sudden change in tendon lengths, thus minimising the fluctuations of the force provided by the fingers.

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