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Development of Three-Fingered Robot Hand with a New Design Concept

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Abstract

This paper addresses the development of a three-fingered robot hand with a new design concept. Each joint is driven by the tendon-pulley transmission system which is one of most popular methods for controlling a finger joint. The basic design policy is to make the tendon length as short as possible, so that we can avoid the non-linear characteristics coming from both the compliance existing in tendon and friction in each pulley. We discuss several key design technologies for achieving the goal. Grasping experiments are also shown for various objects.

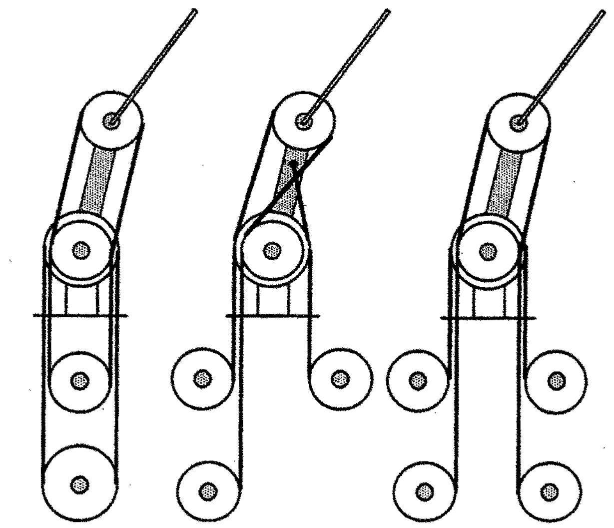
Key words: Multi-fingered Robot Hand, Torque Sensing, Compliant Motion, Enveloping Grasp.

1 Introduction

There have been a number of multifingered robot hands developed so far. All of them can be classified into two groups from the viewpoint of joint actuation. One is the remote-actuation in which each actuator is placed in other places except the joint axis, such as the palm or the fore arm, and the power is transmitted to each joint through a tendon or a gear train. The other is the direct-actuation in which each actuator is directly mounted in each joint. The remote-actuation has been adopted by most of the conventional hands. This is because the size of actuator which can produce an enough force at the finger tip level is usually too big to directly implement into each joint. One problem in the remote-actuation is the nonlinear characteristics coming from the transmission system. In case of tendon-sheath system, the nonlinear characteristic is produced by the combination of both tendon compliance and the friction between the tendon and the sheath. Kaneko, Wada, Maekawa, and Tanie [1] have shown that the nonlinearity can be modeled by the hysteresis characteristic including both equivalent stiffness and backlash whose width is the function of tendon tension. Kaneko, Paetsch, Kegel and Tolle [2] have shown that this nonlinear characteristic often produces an input-dependent stability when the torque feedback gain is increased.

While the direct-actuation is not so popular, Yasukawa Co. [3] developed a three-fingered hand in which an actuator composed of an AC servo motor and a Harmonic Drive Gear is directly implemented into each joint. Ebner and Wallace [4] have developed a direct-drive hand where each joint is driven by a direct drive motor without any gear box. Although this type of hand is perfectly released from the control problem coming from the hysteresis characteristic, it is hard to design the hand such that the joint diameter may keep small. It is also difficult to obtain an enough finger tip force by an actuator with a reasonably small size.

In this paper, we focus on the remote-actuation by taking advantage of the potentiality of smart design of finger joint and enough force at finger tip level. Even for the remote-actuation, there are still three ways, tendon-sheath driving system, tendon-pulley driving system, and gear train system. Since the gear train system inevitably includes a significant backlash, we simply omit this approach from our candidates. For two others, there are two factors producing the hysteresis, one is friction and the other is compliance existing in the transmission system. Since the compliance mostly comes from the tendon, both the tendon-sheath and the tendon pulley driving systems result in the same compliance under the same tendon length. On the other hand, the friction caused by the direct contact between the tendon and the sheath is even larger than that brought by the contact between pulley and its shaft. This means that under the same tendon length,



(a) N-type (b) $N+1$-type (c) $2N$-type

Figure 1: Classification of cablings for robotic finger joint.

the tendon-sheath driving system produces much larger hysteresis characteristic than the tendon-pulley one. Based on these considerations, we adopt the tendon-pulley driving system in our robot hand.

This paper begins by discussing the design policy of the mechanical structure of multi-fingered robot hand after briefly reviewing the conventional works. Then, we explain the whole structure of the hand including both sensor and control systems. Finally, we show a couple of experimental results to show how well it work.

2 Related Work

Development of robot hands can be classified into two historical flows. Before 1980, most of robot hands had the configuration of two-fingered gripper capable of simple open-close motion only. This type of grippers were widely used in the industrial area, since they could achieve the basic purpose, namely, grasping and releasing an object. Since the late 1970s, however, a number of researchers started to point out that simple open-close grippers are not dexterous enough to complete the task requested in nuclear power plants, space application, and even in automation line in industries. Due to this reason, a number of research projects on multi-fingered robot hand started in various institutes, such as Electro-Techical Laboratory [5], Stanford University [6], MIT [7], University of Utah [7], Mechanical Engineering Laboratory [8], University of Bologna [9], Technical University of Darmstadt [10], University of Karlsruhe [11], Yasukawa Co. [3] and so on. Most of the developed hands except [3, 4, 11] adopt the tendon transmission system which belongs to the remote-actuation. For classification of tendon transmission, there are three methods, N-type, $N+1$-type and $2N$-type, as shown in Fig.1. In N-type [5, 8, 9, 10], each finger joint is driven by one actuator as shown in Fig.1(a). In $N+1$-type [6], N joints are controlled by $N+1$ actuators, and every actuator is coupled each other, as shown in Fig.1(b). In $2N$-type [7], each joint is controlled by two actuators, as shown in Fig.1(c).

3 Design Policy

Each type as shown in Fig.1 has each advantage and disadvantage. N-type needs pre-tension to keep a suitable operation. However, it is normally difficult to keep tendon tension since it often looses for a long term use. It is not necessary for both $N+1$ and $2N$-type to impart such pre-tension, since each actuator itself is a tension controller as well. However, one big disadvantage for them is that we have to implement more actuators than the number of joints. While $N+1$-type seems to be a compromise between N and $2N$-type, the coupling among actuators makes the finger control complicated. This is the reason why $N+1$-type is not widely utilized in the world.

Apart from the actuating method, let us now consider another classification from the viewpoint of the transmission mechanism. One is tendon-sheath system and the other is tendon-pulley system. It is well known that the tendon-sheath system produces a heavy hysteresis characteristic due to the friction between tendon and sheath [1]. Based on these considerations, hereafter, we focus on N-type with tendon-pulley transmission system.

The hysteresis characteristic appears more or less in tendon-pulley transmission system as well. Our former analysis [1] showed that the hysteresis can be suppressed by utilizing a stiff tendon. Under the utilization of tendon with the same diameter, we should design the tendon length as short as possible, since the tendon stiffness is determined by its length. This can be achieved by mounting all actuators extremely close to the base joint. This design policy also contributes to constructing a multi-fingered hand with compact size. For easily changing a hand configuration, we design our robot hand such a way that it is composed of completely same finger units, where each finger unit includes three actuators, three tendon transmission routes, and a serial link mechanism with three joints. The joint axes are parallel to each other and the swing joint is not included in the finger unit, which means that each finger can move in 2D plane only. When a 3D motion is really necessary, it is possible to add one more degree of freedom by utilizing the connector joint between units. The size of finger part is almost similar to that of our index finger, which may bring a hard requirement for designing the mechanical structure including the transmission system and sensors.

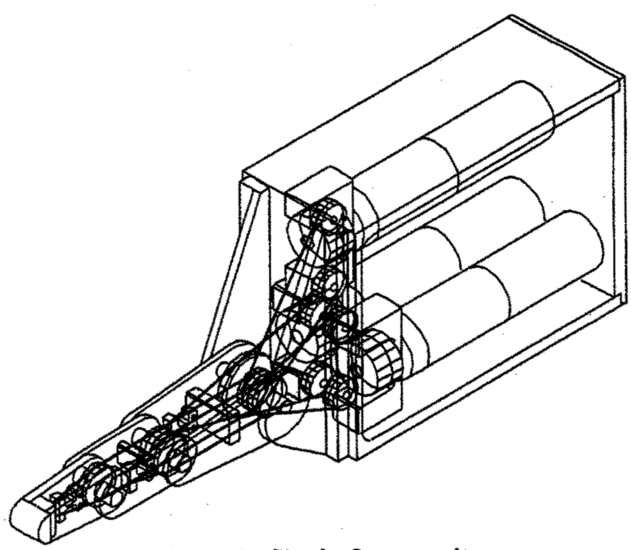


Figure 2: Single finger unit.

4 Design of Finger Unit

4.1 Power transmission system

Figure 2 shows a single finger unit. One unique design is taken for the actuator arrangement. We utilize the actuator composed of a DC servo motor and a Harmonic Drive Gear. One big advantage to utilize the Harmonic Drive Gear is that it has nearly no backlash. Due to such a structure, the actuator has a long length compared with its diameter. Therefore, if we mount each actuator such that its longitudinal direction is parallel to the axis of each finger joint, the finger unit may have an ugly look. To avoid such a situation and have a nice look, we mount all actuators whose longitudinal direction exist in the working plane of the finger motion, as shown in Fig.2. Through two idler pulleys, the tendon route is changed with 90 degrees near the drive pulley of actuator, such that it may be parallel to each finger link. Such cabling largely contributes to making the hand with a nice look. Since this type of transmission needs a pretension, we add a tension adjuster for each transmission system where each actuator can be moved slightly in its longitudinal direction by a screw.

4.2 Sensors

For controlling a robot finger, there are two essential sensors, namely, joint position sensor and joint torque sensor. For measuring joint position, we utilize an encoder directly attached with the shaft of motor. For sensing joint torque, we implement a specially designed torque sensor for tendon drive joint, as shown in Fig.3. The basic working principle of the torque sensor is based on the idea that each joint torque is proportional to the tension difference between two tendons

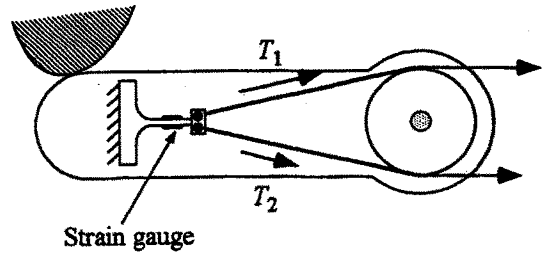


Figure 3: Principle of torque sensing.

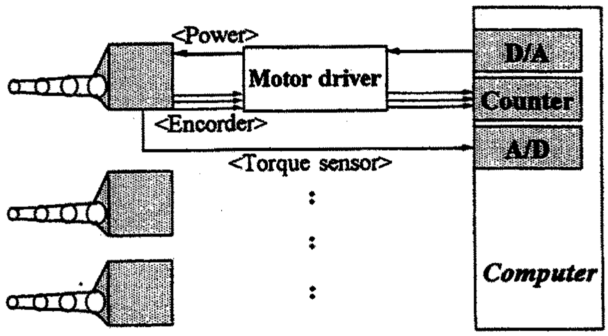


Figure 4: The control system of the robot hand.

driving the associated joint. This type of torque sensor is termed with the tension-differential type torque sensor [12], since it can directly measure the tension difference irrespective of the tendon pre-tension. This sensor arrangement allows us to achieve compliance control as well as force control, which are useful for avoiding a large interaction force between the hand and an object (or environment).

4.3 Control system

Figure 4 shows the control system of the robot hand. Computer sends the velocity signal to each motor driver through a D/A converter. Instead of utilizing a driver based on PWM, we choose a driver with a linear type power amplifier, so that we can avoid the high frequency noise coming from the switching operation in the PWM based controller. The pulse signals from the encoder and the torque sensor signals are fed into the computer through a pulse counter and an A/D converter, respectively. Each finger has a completely same control system and mechanical configuration, so that we can save the total cost for designing and manufacturing the hand system.

4.4 Possible hand configuration

Since each finger unit has a complete set in not only mechanical but also control structure, we can built up a hand with an arbitrary number of fingers by combining the finger unit. Figure 5 shows a couple of examples of the possible hand configuration and explains various

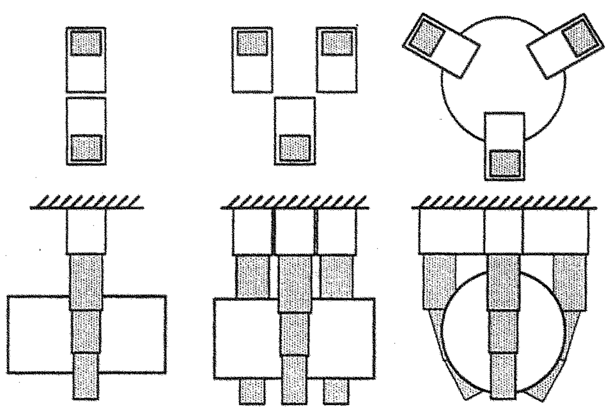


Figure 5: Examples of the hand configuration.

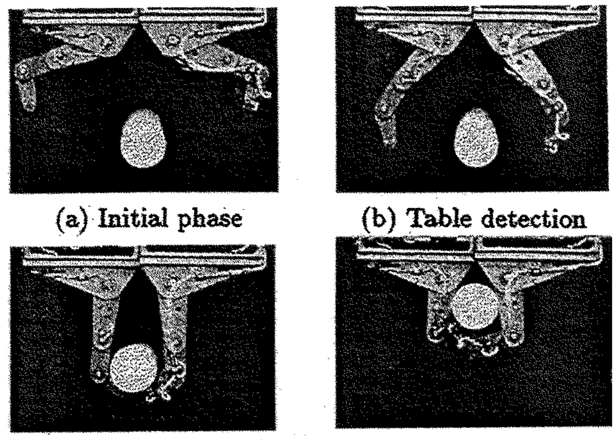
grasping tasks. Since the finger unit does not have any swing degree of freedom, the robot hand constructed by the finger unit can not achieve the same dexterity as human does. Instead, we can expect some dexterity for grasping column objects in enveloping style, which will be precisely explained in the later chapter. When the swing degree of freedom is really necessary for the developed hand, we can implement one more actuator to the connecting part between finger units.

5 Grasp Experiments

We have done a couple of experiments by utilizing the developed three-fingered robot hand where each finger unit is combined as shown in Fig.5(b). Although each finger unit does not have the swing degree of freedom, the robot hand can grasp a column object in enveloping style. This is the reason why we choose the enveloping grasp of all grasp styles. Even for the enveloping grasp, there have been a number of works, such as the analysis of contact force, the robustness of grasp, the contact point sensing, and so forth. While most of conventional works have focused on the grasping phase only, we are particularly interested in the whole grasping procedure for an object placed on a table. The procedure includes the approach phase, the detaching phase, the lifting phase, and the grasping phase, where the detaching means to isolate the object from the table as terminology.

5.1 Cylindrical objects

Figure 6 shows the grasping experiment for a cylindrical object, where the object surface is covered by a drawing paper so that the contact friction may be small. The finger first approaches the object until the finger tip detects the table, where the robot can recognize the contact with the table by monitoring each torque sensor output. The moment the finger tip makes contact with the table, the torque sensor output will sharply increase. The finger tip then follows the table until a part of finger makes contact with the object. We again utilize the torque sensor output for detecting the contact between the finger and the object. For a cylindrical object, there usually exists an enough space to insert a finger tip between the bottom part of object and the table, unless the object's diameter is smaller than that of finger tip. Under such situation, each finger tip pushes the object each other, so that we can make the most use of wedge-effect. For such a pushing motion, the finger tip can easily produce the upward force, which is what we call wedge-effect. As a result, the object will be automatically lifted up by the slip between the finger tip and the object's surface. At the same time, each link is closed to remove the degrees of freedom of the object gradually. Constant torque control can be utilized effectively for achieving both lifting and grasping phases. Whether the object really reaches the palm or not, and how firmly the hand grasps the object, strongly depend on how much torque command is imparted to each joint. Figure 7 shows the success and failure map when changing the commanded torque for each joint, where each mark corresponds to the final finger posture as shown in the top of the figure, respectively, and the horizontal and vertical axes denote the command torque for the first and the second joints, respectively. To avoid the complicated display, the command torque for the second and the third joint torque are chosen equally. There are a couple of failure modes. Under small command torque, of course, the object can not be lifted up, as shown by $\diamond$. When the command torque for the second joint increases under a small command torque for the first joint, the finger tip often makes slip over the object surface. When the command torque for the first joint is relatively larger than that for the other joints, the first link rotates faster than the others. As a result, the grasp system results in the final state shown by $\times$. From Fig.7(a), we would note that under a small friction coefficient ($\mu = 0.7$), there ex-



(a) Initial phase (b) Table detection

(c) Lifting phase (d) Grasping phase

Figure 6: Grasping a cylindrical object, with small friction.

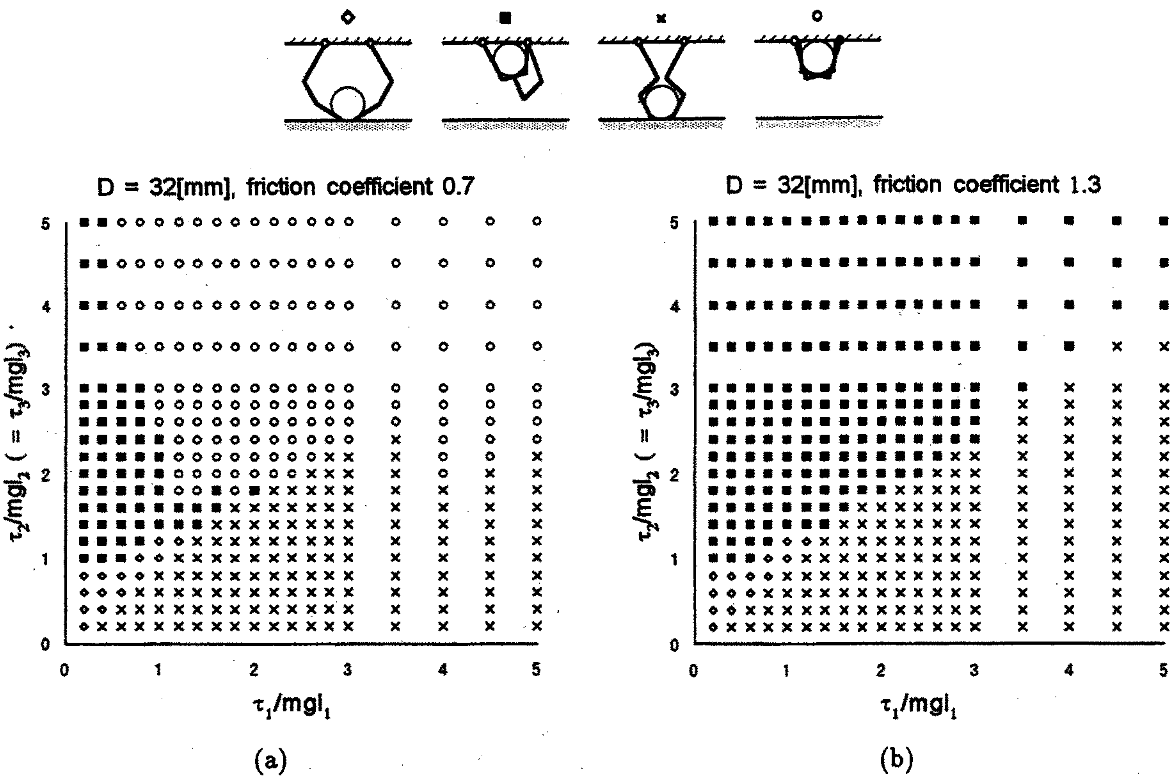


Figure 7: The success and failure map when changing the commanded torque. (m: mass of object, l_i: length o link i, τ_i: torque of joint i)

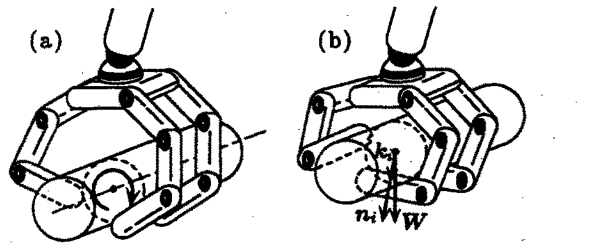


Figure 8: Rolling motion based grasp under significant friction.

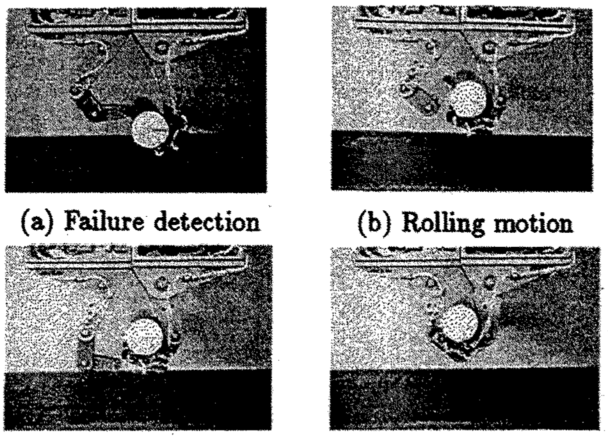
ists a large area where the combination of the selected command torque results in a success mode. However, as the friction coefficient increases, the area leading to the success reduces and finally it disappears as shown in Fig.7(b), where the object surface is covered by a rubber. Since the wedge-effect based grasping assumes a slip between the finger tip and the object's surface, it finally fails as shown by ■. Under significant friction, we switch from a slip motion based strategy to rolling motion based strategy. Figure 8 shows an example of rolling motion based grasp, where it is assumed that the center of gravity exists between the two right fingers. First, the left finger starts to make the object roll over along the surface of right fingers being in slowly closing until the following conditions are confirmed.

$$\boldsymbol{W} \otimes \boldsymbol{n}_i < 0 \quad \cap \quad \boldsymbol{W} \otimes \boldsymbol{k}_i < 0 \qquad (1)$$

where $\boldsymbol{W}$, $\boldsymbol{n}_i$ and $\boldsymbol{k}_i$ are the gravitational vector, the inward normal vector of link surface at i-th contact point, and the vector with minimum norm from the gravitational center axis to i-th contact point, respectively and $\otimes$ is a scalar operator computing $\boldsymbol{x} \otimes \boldsymbol{y} = x_1 y_2 - x_2 y_1$ for two vector $\boldsymbol{x} = (x_1, y_1)^{\mathrm{T}}$ and $\boldsymbol{y} = (x_2, y_2)^{\mathrm{T}}$. The above condition is a sufficient one for not making the object falling down from the right fingers without any support from the left finger. After confirming this condition, the left finger is removed and finally an enveloping grasp is completed. Figure 9 shows continuous photos for grasping a cylindrical object, where the cylindrical object is covered by rubber such that we can purposely increase the surface friction. In Fig.9 (a), the robot first recognizes the failure mode, where the height between both finger tips is no longer small. Such a behaviour happens when we increase the pushing force under a compliant joint. Once the robot detects such situation, the object is put down on the table and then the rolling motion based approach starts as shown in Fig.9(b), (c) and (d).

5.2 Column objects

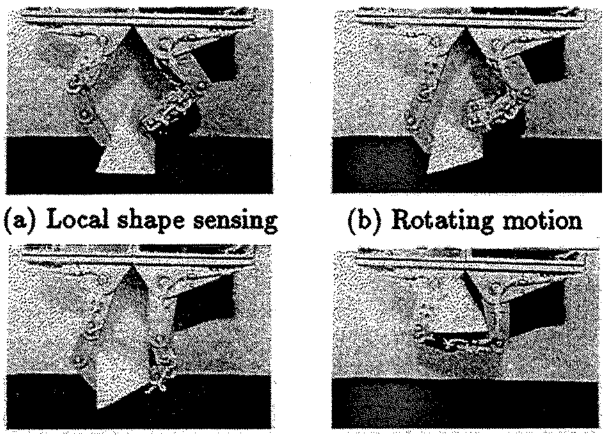
Suppose a general column object whose cross section is a polygon composed of n equi-length. For a column object with $n \geq 5$, we can apply a similar approach taken for a cylindrical object for enveloping the object. For an object having either rectangle or triangle cross section, however, wedge-effect based approach can not be applied any more. This is because a simple push-



(a) Failure detection (b) Rolling motion

(c) Finger release (d) Grasping phase

Figure 9: Grasping a cylindrical object with significant friction.



(a) Local shape sensing (b) Rotating motion

(c) Finger insertion (d) Grasping phase

Figure 10: Grasping a column object with triangular cross section.

ing motion by finger tips do not make any lifting force for such an object. Such a pushing motion always produces a downward force for the object with triangular cross section. Therefore, we have to prepare a completely different strategy for finally enveloping such an object. For such an object, human often rotates the object around an edge of the object for making a gap between the object and the table. Then several finger tips are inserted into the gap such that we may easily detach the object from the table. For the triangle object, we apply a similar approach to the robot hand. Figure 10 shows continuous photos for grasping a column object with triangular cross section.

6 Conclusions

We developed the three-fingered robot hand based on a new design policy, where the tendon length is planned as short as possible, such that the hysteresis characteristics coming from the friction and the compliance may be avoided. We packed three actuators and sensors into the finger unit together so that we can easily change the hand configuration. To achieve a compact design, a special cabling technique changing the tendon route with 90 degrees near the drive pully was adopted, immediately after the drive pulley. We also executed a couple of grasp experiments to confirm the basic motions of the developed robot hands.

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References

[1] Kaneko, M., M. Wada, H. Maekawa, and K. Tanie: A new consideration on tendon-tension control system of robot hands, *Proc. of the IEEE Int. Conf. on Robotics and Automation*, Sacramento, pp765-771, 1991.

[2] Kaneko, M., W. Paetsch, G. Kegel, and H. Tolle: Input-dependent stability on joint torque control of tendon drive robot, *Proc. of the IEEE Int. Conf. on Robotics and Automation*, Cincinnati, pp73-81, 1990.

[3] Morimoto, S., M. Kawabe, and M. Umetsu: Impedance control of multi-fingered hands, *Proc. of the 11th Annual Meeting on the Robotics Society of Japan*, pp69-70, 1993.

[4] Ebner, M. and R. S. Wallace: A direct-drive hand: Design, Modeling and Control, *Proc. of the IEEE Int. Conf. on Robotics and Automation*, Nagoya, pp1668-1673, 1995.

[5] Okada, T.: Object-handling system for manual industry, *IEEE Trans. on System, Man and Cybernetics*, SMC9-2, pp79-87, 1979.

[6] Mason, M. T. and J. K. Salisbury: Robot hands and mechanics of manipulation, *The MIT Press*, Cambridge, Massachusetts, p.165, 1985.

[7] Jacobsen, S. C., et. al.: Design of the Utah/MIT dexterous hand, *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp1986-1992, 1986.

[8] Kaneko, M and K. Tanie: Basic considerations on the development of multifingered robot hand with capability of compliance control, *Proc. of the Int. Meeting on Advances in Robot Kinematics*, pp46-52, 1988.

[9] Bonivento, C. et.al.: Control system design of a dexterous hand for industrial robots, *Proc. of the IFAC Symp. on Robot Control*, Karlsruhe, Germany, pp100-106, 1988.

[10] Paetsch, W. and M. Kaneko: A three fingered, multijointed gripper for experimental use, *Proc. of the IEEE Int. Workshop on Intelligent Robots and Systems*, pp853-859, 1990.

[11] Doll, T. J. and H. J. Schneebeli: The karlsruhe hand, *Proc. of the IFAC Symp. on Robot Control*, Karlsruhe, Germany, pp107-113, 1988.

[12] Kaneko, M., K. Yokoi, and K. Tane: On a new torque sensor for tendon drive fingers, *IEEE Trans. on Robotics and Automation*, Vol.6, No.4, pp.501–507, 1990.