DoraHand: a novel dexterous hand with tactile sensing finger module

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Abstract

Purpose – This study aims to introduce the DoraHand, and the basic capability and performance have been verified in this paper. Besides the idea of sharing modular design and sensor design, the authors want to deliver an affordable and practical dexterous hand to the research area to contribute to the robotic manipulation area.

Design/methodology/approach – This paper introduced the DoraHand, a novel scalable and practical modular dexterous hand, which, adopting modular finger and palm design, fully actuated joint and tactile sensors, can improve the dexterity for robotic manipulation and lower the complexity of maintenance. A series of experiments are delivered to verify the performance of the hand and sensor module.

Findings – The parameters of the DoraHand are verified and suitable for the research of robotics manipulation area, the sensing capability has been tested with the static experiment and the slip prediction algorithm. And, the advantage of modular design and extensible interface have been verified by the real application.

Research limitations/implications – The authors continue improving the DoraHand and extend it to more different applications. The authors want to make the DoraHand as a basic research platform in the robotic manipulation area.

Practical implications – The DoraHand has been sent to more than ten different research institutes for different research applications. The authors continue working on this hand for better performance, easier usage and more affordability.

Social implications – This kind of dexterous hand can help researchers get rid of complex physical issues and pay more attention to the algorithm part; it can help to make robotic manipulation work more popular.

Originality/value – The key design in the DoraHand is the modular finger and sensing module. With the special design in mechanical and electrical parts, the authors build reliable hardware and can support the diversity requirement in the robotic manipulation area. The hand with tactile sensing capability can be used in more research and applications with its extensibility.

Keywords Grippers, Robot design, Dexterous hand

Paper type Technical paper

1. Introduction

The dexterous hand is a kind of end-effector that can make the robot more universal but not widely developed in the past several decades. The development of artificial intelligence (AI) technology, including reinforcement learning, is trying to drive the application of the dexterous hand to the commercial level. Researchers in the OpenAI (OpenAI *et al.*, 2019) have physically solved the Rubik's cube by the Shadow Dexterous Hand (Shadow Robot Company, 2017).

Despite the advancement from the algorithm part, existing dexterous hand solutions are still facing challenges to complete complex manipulation tasks, especially when there are constraints from the hardware. Hardware limitations make most works can only be performed in simulators (Zeng *et al.*, 2018). To solve these challenges, some points of the dexterous hand, including the driven method, material, mechanical design and sensor, should be discussed.

The driven method is highly relevant to the solution the dexterous hand is applied. Taking advantage of material and manufacturing solutions, there are increasing types of soft end-effectors that have been invented (Catalano *et al.*, 2014; Melchiorri

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et al., 2013; Tavakoli and de Almeida, 2014), and some adopt tendon-driven methods that have taken account of the maintenance issue for the user (Liow *et al.*, 2019). Compared with the tendon-driven soft hand, the hand with soft material is also popular. There are many different hands with novel material and manufacturing solutions. These hands are easier to control, but lifetime and maintenance are still critical (Homberg *et al.*, 2015; Deimel and Brock, 2016; Yang *et al.*, 2020; Meng *et al.*, 2020).

Dexterous hand using rigid material broadly adopts the human-hand-like design. However, there is still a topic of whether the human-hand-like is the best universal end-effector for a robot. We want to find a solution to reach the balance of high universality and low cost. With rigid surface and structure, the manipulation relationship between the dexterous hand and items can be less uncertain, and it can make the simulation easier, and the results are more valuable. There are two options considering the driven strategy – more actuators for more degrees of freedom (DOFs) and fewer actuators for more DOFs. The first method is applied in renowned products, including Shadow Hand, Allergo Hand (SimLab, 2012) and DLR-HIT hand (Liu *et al.*, 2008). The other one is supported by some industrial hand products like Robotiq (2022). Both methods are available, and we may need to make a better design according to the actual requirements and limitations.

The modular design has been widely used in general mechanical design, and it can help reduce the cost and improve scalability. The modular design can be used in the structure inside the device and make it cheaper, and it can also use for an independent module for easier usage. Some dexterous hands like the Sandia Hand and the Eagle Shoal take the finger as the basic module, which can mount with the palm easily (Quigley *et al.*, 2014), (Wang *et al.*, 2019a).

The sensor is a critical feature for a robotic end-effector. As the source of the environment data acquiring, research of more sensing data will help improve the dexterous hand manipulation performance. An increasing number of vision-based sensors have been studied, including the Gelsight (Yuan *et al.*, 2015), Gelslim (Donlon *et al.*, 2018), cross-modal tactile sensor (Fang *et al.*, 2019), tactile sensor with thermochromic material (Sun *et al.*, 2019), tactile muscularis (Van Duong *et al.*, 2019) and multicurved robot finger (Piacenza *et al.*, 2020). The primary mechanism is similar, use the vision to detect more features that can help the robot. Even though the vision sensor is so hot in the current stage, some traditional sensors are still valuable to be studied and used as robot components (Yousef *et al.*, 2011; Sadun *et al.*, 2016). Like the piezoresistive mechanism used in BioTac (Fishel and Loeb, 2012), it can help manufacture more stable and cheaper sensors.

Based on these studies on related area, we want to solve some issues with the DoraHand. This paper will introduce a newly designed scalable and practical modular dexterous hand, the focus of which is to achieve the balance of function and cost, and provide a well-performed dexterous hand for robotic manipulation research and eventually for industry application. This paper is structured as follows. Section 2 will introduce the requirement analysis for this dexterous hand. Section 3 will show the detailed design and analysis. Section 4 validates the functions from different sides. Section 5 shows the conclusions.

2. Requirement analysis

With the idea of designing a scalable and practical modular dexterous hand, some basic requirements should be considered: the DOFs, the hand layout, the payload (Ponce and Faverjon, 1995), the maintenance capability and the sensing ability.

2.1 Degrees of freedom requirement

The DOFs is one of the essential criteria of a dexterous hand. Although, researchers can use low-DOFs hand finish manipulation tasks with appropriate control in a specific environment (Hou and Mason, 2019). High DOFs is still the basic and more efficient way to realize stable grasping and manipulation tasks (Kim *et al.*, 2020), and can support the in-hand manipulation task. The DOFs types and distribution should be decided by the use case, which can be the same or different with human hand (Yuan *et al.*, 2020).

To provide better manipulation performance, a bigger motion range is required. Ref to the DOFs of most hands, we set the joint limitation of $\pm 90°$, the motion range of two fully actuated DOFs fingertip shown in Figure 1. In comparison, the underactuated finger can only provide the motion with one curve. The joint status can only be changed with the external force, which is hard to control. Two fully actuated joints can make the finger reach a bigger motion range and more diverse poses.

Two fully actuated DOFs in one finger can only provide the motion in a plane. Adding one DOF in the palm can make the fingertip move in 3D space and offer more manipulation skills.

As discussed, two fully actuated DOFs in the finger and one rotation DOF in the palm are essential characteristics of the DoraHand.

2.2 Layout requirement

Limited by the actuator and material, more fingers always mean bigger dimensions, more complex system and higher cost. With this idea, a layout with suitable finger numbers may be better. A three-finger layout is a good choice that can meet the basic stable grasping with three grasping points (Ponce and Faverjon, 1995). There are three main kinds of three-finger layouts shown in Figure 2 that can be considered (Townsend, 2000; Schunk, 2015).

The red dot or arrow in the coordinate in Figure 2 represents the rotation axis of each palm joint, the dashed line with the arrow represents the motion range of the joint.

Figure 1 2D motion space of the underactuated and fully actuated finger

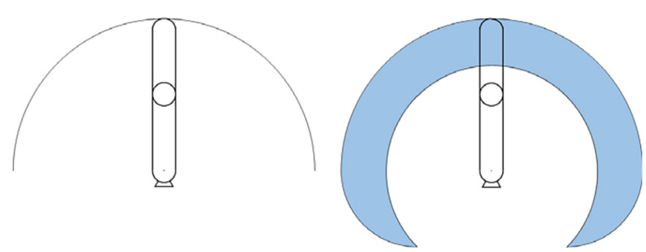
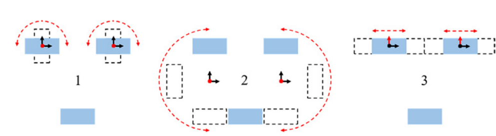


Figure 2 Three different three-finger dexterous hand layout



The first and second layouts with the rotation can better adapt to the special shape item, and two-finger grip mode can be more stable. The third layout is simplified and has a limitation to the rotation range. The first layout takes smaller space when changing the pose, and second can adjust the three fingers on one side to reach the power grasp pose.

In the aspect of more diverse poses, the first layout can provide more poses when the front and back fingertip surfaces are asymmetric. The asymmetric structure can be designed according to the different scenes.

With these points, we choose the first layout in the three-finger DoraHand for more diverse poses and smaller dimension.

2.3 Payload requirement

Application industries and scenarios have a decisive influence on the dexterous hand payload. With the requirement of safety and cooperation with the human worker, collaborative robots have been widely adopted, and most payloads are in the range of 5–10 kg. A hand with such a payload can help more researchers make the best usage of the collaborative robot.

With the estimation of dexterous hand self-weight is around 1–2 kg, a payload of 6 kg is suitable and can cover most grasping and manipulation requirements.

2.4 Maintenance requirement

Due to the complex structure of most dexterous hands, the maintenance of dexterous hand is a complex and risky task that makes the physical experiment costly and difficult. Trying to make the maintenance easier can help to lower the difficulty and help people deliver more diverse physical experiments. We want to design a modular finger to make the user replace the broken finger easier.

A simple enough maintenance solution may give the robot the capability of maintaining the hand by itself. This capability can help the robot finish more tasks and be fully autonomous.

2.5 Sensing requirement

Sensors in dexterous hand have many types, including position, temperature, force, torque and tactile sensors (Tomo *et al.*, 2015).

The position sensor in the joint is already the essential sensor. The torque sensor in the joint is also widely used in current robotic hardware design, and estimating torque through the current feedback is a low-cost standard solution. We also use the motor current to realize this function.

Tactile sensing is popular and may become a new essential sensing capability of dexterous hand like the joint position feedback. We take the tactile sensor as the critical feature, which can improve the robot manipulation capability and keep the interface of replacing with different kinds of sensors.

3. Design and analysis

With the analysis on the requirement of dexterous hand, we have our design introduced in the following four directions.

3.1 Mechanical design

Compared with the other modular fingers, we want to make the assembly and maintenance process easier and design with good scalability. We design the hot-swap function that uses the finger module through simple plug and unplug action. With the hot-swap function, it is possible to make the robot finish some tasks by itself. We keep the scalability in the joint and tip level, which can help to change the design with different requirements easily.

The design for hot-swap function is realized by the pogo pin and locking mechanism. The pogo pin provides the transmission of power and signal. The locking mechanism makes the connection more stable and reliable, and provides a locking force sufficient to lock the finger with palm during the task. What is more, when a force is added to the finger body, the friction force will gain and help the finger not be plugged out. The force analysis and requirement are shown in Figure 3 and equation (1); equation (1) is a simplified equation that ignores the finger width and assumes the point contact situation.

The locking mechanism includes two main aspects, the location part and the force adding part. The spring plunger acts as the primary location component and helps locate the finger. When the ball in the plunger mates with the hole in the finger, the plunger can provide around 0.6 kg force. The force adding part is mainly completed by the magnet, the magnet at the bottom helps to provide 2.5 kg force. Figure 4 displays the locking mechanism structure with the spring plunger.

Figure 3 The force between finger and palm, and the spring plunger and coupling

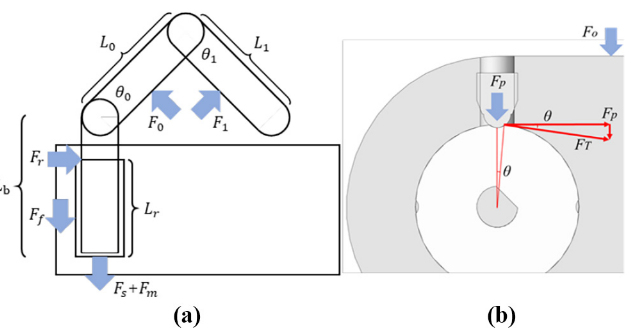
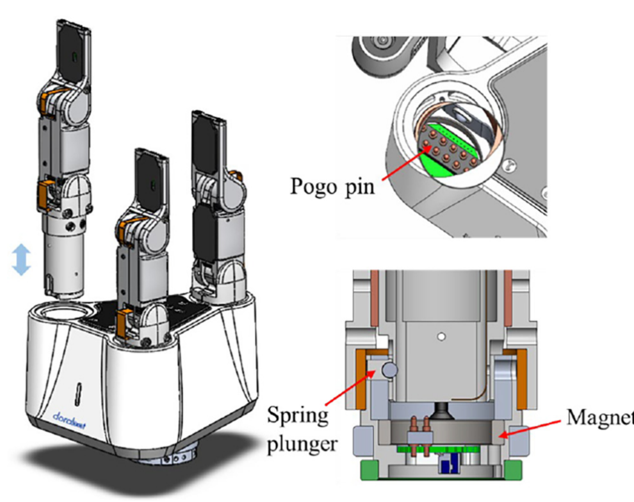


Figure 4 Hot-swap finger, asymmetric tip and locking design



Calculated from equation (1), μ is the friction coefficient, θ_0 and θ_1 are joint angles and combined force F_c is bigger than 3.1 kg for one finger in the worst situation. For a three-finger hand with the 6 kg payload, each finger should guarantee a 2 kg payload, and F_c can meet the requirement:

$$\begin{cases} F_c = F_s + F_m + F_f \geq F_0 \sin\theta_0 + F_1 \sin(\theta_0 + \theta_1) \\ F_f = \mu F_r \\ F_r = \begin{pmatrix} F_0 L_0/2 + F_1 L_1/2 + F_1 L_0 \sin\theta_1 + \\ L_b(F_0 \cos\theta_0 + F_1 \cos(\theta_0 + \theta_1)) \end{pmatrix} / L_r \end{cases} \quad (1)$$

To simplify the structure and keep precision, the motors drive the joint through rigid coupling directly, which causes the external force impact F_o may destroy the motor easily. We design the structure in Figure 3(b) to protect the joint. The spring plunger provides a fixed force F_p to connect the coupling and joint. When the external force F_o is too big, and the force F_T is bigger than $F_{T\max}$, the ball in the spring plunger will push the spring and go up. The contact force between the ball and coupling will be rolling friction. The finger can recover when the ball rotates back to the coupling curve. $F_{T\max}$ is defined by the spring plunger force F_p and the curve angle θ.

To make the hand use more sceneries and cooperate with different hardware, we design a replaceable thin and asymmetric tip. The thickness of the fingertip is 5 mm and can be used in some narrow space. The fingertip part can be replaced by other designs for more diverse usages. This function can make the researcher design the most practical tip according to their requirements. The detailed design and extension sample of the fingertip is shown in Figure 5, these two changes were made with 3D print components for linkage structure and high-friction tip separately.

With the DOFs, layout and fingertip design we defined, the DoraHand can support different grasp poses. We separate nine different basic poses shown in Figure 6. The difference in one row is the touchpoints in the three poses are different, and the grasp range is gradually bigger from left to right. The (a) row shows the poses with three fingers, the (b) row shows the poses with two fingers and can grasp item with the front tip face, the (c) row shows the poses with two fingers and can grasp an item with the back tip face.

Figure 5 Fingertip can be extended or replaced with different components

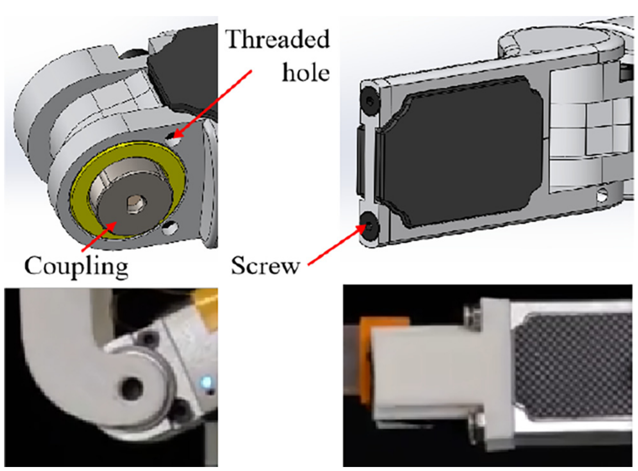
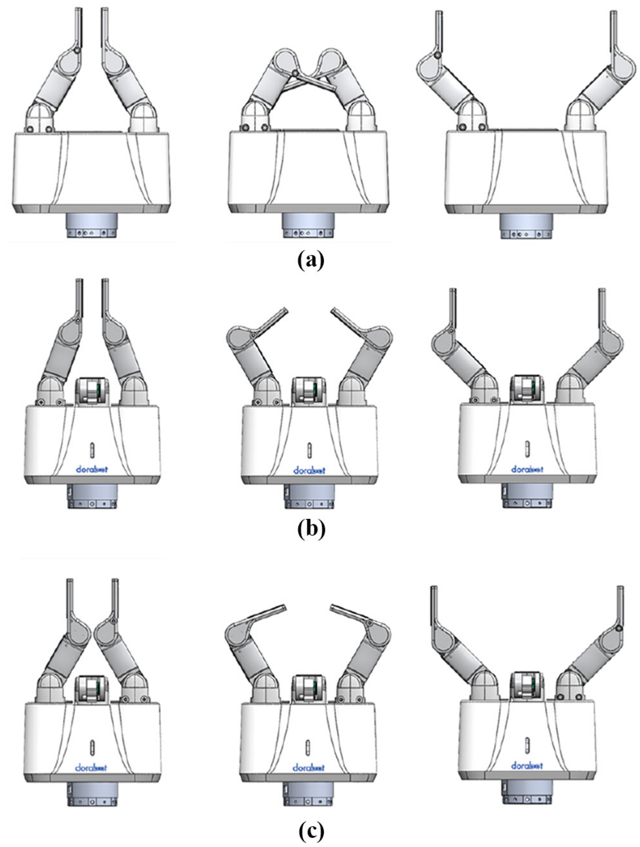


Figure 6 DoraHand layout and nine different grasp poses



3.2 Sensor design

The sensing capability is a unique part of our hand design. To detect the combined force, we use a lower-cost design to meet the sensing requirement. To choose the best sensor used in the module, sensing precision, creep and dimension have been considered.

To give the robot sensing capability like a human, tactile sensing is essential, and if the sensor can sense the force and position simultaneously, it can benefit the algorithm better. Unlike the sensor that can sense the distributed force in the whole surface, we choose the solution that can only sense the combined force added to the surface. We design the tactile sensor that can sense the force and position simultaneously and act as the tactile sensing of the robot.

We choose the film force sensor with a thickness of 0.3 mm and good sensitivity. The basic structure of the sensor is shown in Figure 7. With the rigid top plane, the combined force $F_c = F_1 + F_2$ will be divided into F_{s1} and F_{s2}. The force, position and velocity can be calculated by equation (2):

$$\begin{cases} \sum_{i=0}^{n} F_{si} = F_c = \sum_{j=1}^{m} F_j \\ x_c = \sum_{i=0}^{n} F_{si} l_{si} / F_c \\ v_c = \dot{x}_c \end{cases} \quad (2)$$

With equation (2), the position of combined force can be calculated, and the moving speed v_c can show more

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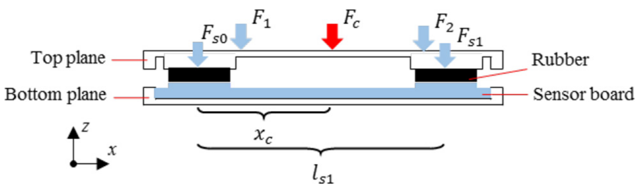
Figure 7 Tactile sensor design



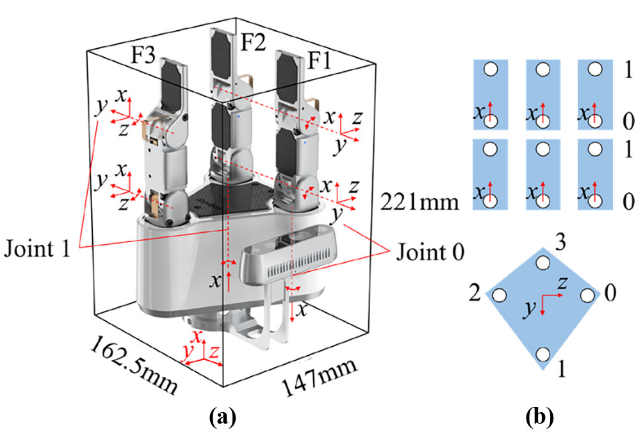
information about the relative motion between the hand and item. These calculation results can be used in the slip prediction part.

We can extend the sensor layout to the palm plane and use four sensors to calculate the force distribution on this plane. With the similar definition of F, y, z, l for Sensors 0 to 3, we can get the calculation of equation (3). The distribution of joint and sensor was shown in Figure 8(a), the coordinate of each module is shown in the figure. The sensor module is located in the black area of the hand, and the sensor coordinate is shown in Figure 8(b). Each white dot represents one sensor. There are seven sensor modules and 16 sensors in one three-finger DoraHand.

$$\begin{cases} \sum_{i=0}^{n} F_{si} = F_c = \sum_{j=1}^{m} F_j \\ y_c = (F_{s1}l_{s1} - F_{s3}l_{s3})/(F_{s1} + F_{s3}) \\ z_c = (F_{s0}l_{s0} - F_{s2}l_{s2})/(F_{s0} + F_{s2}) \end{cases} \quad (3)$$

The rubber and force boss are necessary for acquiring a stable sensing result, and the sensor should be fixed in the sensor module to ensure output consistency. With these structure designs, calibration solutions are also critical. We calibrate each sensor individually and calibrate the whole sensor module after assembly. The first step is to calibrate a single sensor, and the second step is to calibrate the sensor module assembly errors. These two steps can make the final sensor module precise enough force and position feedback.

Figure 8 Joint and sensor layout in the three-finger DoraHand with RealSense



Notes: The (a) shows the six joints in the fingers and the two joints in the palm; the (b) shows the coordinate defined in each sensor module

3.3 Electronic and embedded design

With the basic idea of modular design and easier maintenance, the idea of hot-swap was introduced. With this idea, the fingerboard in each finger module should work individually with power supply and communication.

To gain the scalability of the whole design, the board in the palm should adapt to the different number of devices. The communication and control function have been divided into two boards. The mainboard provides the communication function and power supply, which can support up to six fingers and 98 W power support. The pico board has a similar function as the fingerboard and can be overlayed with one more board according to motor number.

For the hot-swap function, the inserting process is unstable and easy to cause a surge current. We design the power circuit with a millisecond-level delay to protect the finger module. With the idea of making the finger universal, the device ID for each finger position is not related to the finger and is decided by the resister in each palm device port. The protection and recognition at the hardware level make the system more reliable and easier to use.

We use the controller area network (CAN) communication among fingerboards and mainboard. We use the serial peripheral interface (SPI) among the pico boards and mainboard. The communication framework can be checked in Figure 9. It is easy to find that the port leave for the finger and pico boards are redundant for the three-finger hand, which is the extension part for more fingers and actuators. Due to several clients in the communication loop, we use the hardware trigger to ensure the action time of each device is synchronized. With the position, current and force data, each joint supports the loop control of position, velocity, current and force.

The hand can support universal serial bus (USB) and Ethernet communication. The communication frequency between the hand and PC is 60 Hz, and the related code of the DoraHand can be checked in DoraHand (2020).

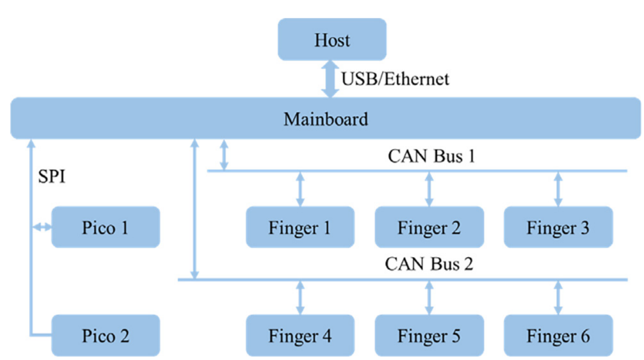
4. Validation and discussion

To evaluate the design of the DoraHand, we plan to validate the performance from four different aspects, basic parameter, sensing capability, grasping capability and scalable design.

4.1 Basic parameters

The basic function of the dexterous hand includes the essential motion capability and payload parameter. We test

Figure 9 DoraHand communication framework



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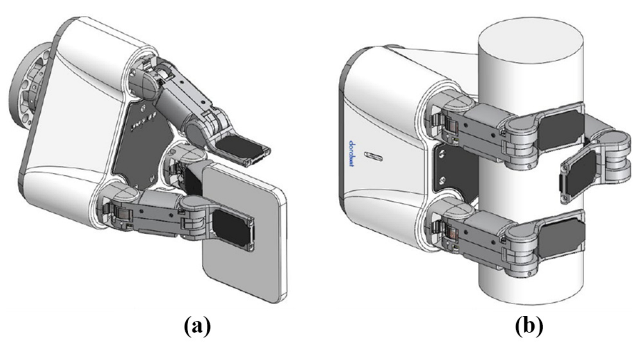
the basic motion capability with motion precision. The joint sensor feedback can provide 0.01° resolution and 0.1° precision, and the joint motion precision can reach the level of 0.5°.

The payload is verified from two aspects, the fingertip force and compassing force in Figure 10. The fingertip force is the force applied by the tip part, and using the similar method shown in Ma *et al.* (2013), the tip force is measured around 25 N. The payload is highly correlated with the friction between the hand surface and the target items when testing the compassing force. We set the grasp pose as Figure 10(b), using a cylinder bottle with 62 mm diameter and adding weight gradually until the slippage happens. Details of the parameters are available in Table 1.

The comparison of the DoraHand three-finger version and some dexterous hands is shown in Table 2.

The DoraHand has the advantage in the DOFs, weight and payload. The sensing ability can also meet the most requirements in robotic manipulation research and support integration with other types of sensors and components.

Figure 10 Tip and encompassing grip payload test



Notes: (a) Use a scale to measure the force between two fingertips; (b) grasp the cylinder with maximum current, and gain the weight until slippage happens

4.2 Sensing capability

The tactile sensor should be evaluated from three different sides, force sensing precision, position sensing precision and the data application.

Regarding force sensing precision, we evaluated the force sensing precision of the sensor and the sensor module. The precision of the single sensor can reach ±3% and the creep in 10 min around 1.5%. The precision of the sensor module is around ±5%, which may be influenced by force adding direction and the mechanical structure precision. Besides the value, the sensor can react with very small deformation and can sense the minimum force of 100 mN, and the force change with 10 mN, it can help the hand to manipulate with soft items and sensing the stiffness difference of objects.

Regarding the position sensing precision, the device we used to evaluate the precision is the jig in Figure 11. The force adding part in the jig can move horizontally with precision higher than 0.01 mm, and the force is controlled with the force sensor feedback. The position can be calibrated and can reach the precision of ±5%, which is around a 1 mm distance in the finger module. The output position is shown in Figure 12, and the position ratio corresponds to the position in 22 mm length. The most significant error happened at the edge of the testing area. It was caused by the contact condition difference between sensor and rubber.

The data application part is mainly about the usage of the force data. With the grasping and manipulation-related application, the slip prediction can present the dynamic performance of force sensing. Referring to the work of slip prediction with force data (Wang *et al.*, 2019b), we acquired the force data during slip motion. The 60 Hz force data obtained by the sensor are shown in Figure 13. The force shows a grasping process starting from 0.1 s, and the force increases rapidly from 0.35 to 0.45 s, and the force balance process continues from 0.5 to 1.0 s, and has a significant change in 1.0 s. The slip motion in hand can be detected with such data and the long short-term memory (LSTM) process (Wang and Kirchner, 2021).

Table 1 Basic parameters of three-finger version

Input power	Joint precision	Joint speed	Joint range
24V/2A	±0.1°	70°/s	±90°
Tactile sensor number and range	*Communication rate*	*Dimension (L * W * H mm)*	*Encompassing grip payload*
16 & 10 N	60Hz	126 × 143 × 221	6kg

Table 2 Hand comparison

Hand	Finger/actuator	Grasp range (mm)	Tactile sensor	Weight (g)	Grip force (N)
SDH Hand	3/7	239	Yes	1950	/
Barrett Hand	3/4	240	Yes	1200	15
Robotiq 3-Finger	3/2	155	/	2300	15–60
Allergo Hand	4/16	238	/	1500	/
Eagle Shoal	3/8	212	Yes	790	10
BLT gripper	3/5	206	/	1200	10
DoraHand	**3/8**	**200**	**Yes**	**1250**	**25**

Figure 11 Jig for calibrate and evaluate the finger and palm tactile sensor

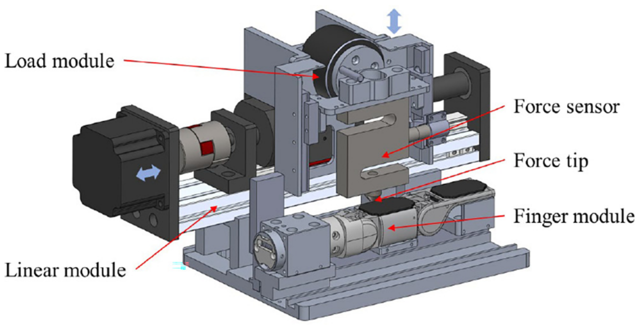
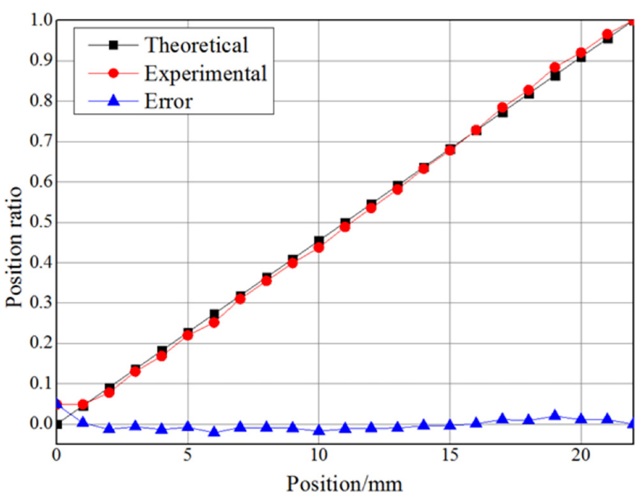


Figure 12 The comparison between the theoretical and experimental value



4.3 Grasping capability

To test the grasping capability of the DoraHand, the hand was used to grasp the Yale-CMU-Berkeley (YCB) object set (Calli *et al.*, 2015) and some groceries. The grasping capability can be easily proven with different dimension items and different grasp poses. The grasping postures are shown in Figure 14.

The DoraHand already meets the requirement of grasping daily life objects for the basic grasping capability. The advantage of fully actuated and diverse loop control can enable more grasping and manipulation usage.

With the unique design of the fingertip, this hand can be used in a narrow space, and with a good control strategy, the item can be easily grasped from a tightly arranged queue. The force control mode can help the robot release the item with zero force situation, which can help the robot improve the efficiency of space and time.

Figure 13 The force data acquired by the tactile sensor

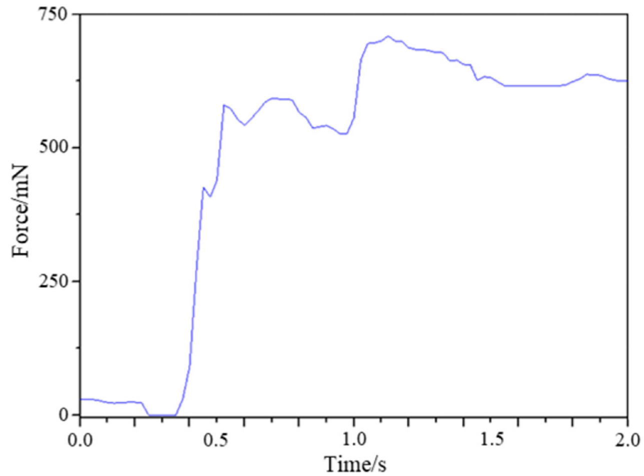
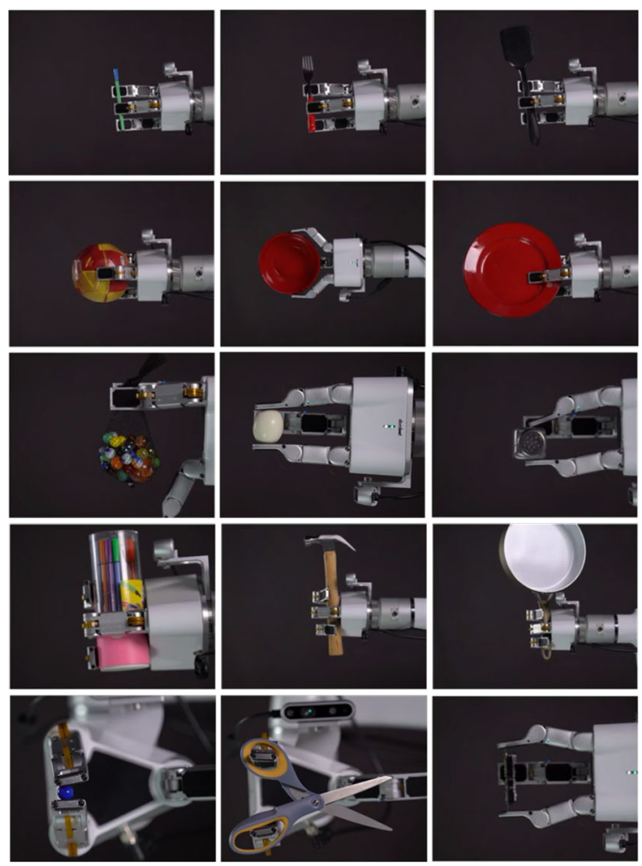


Figure 14 Grasping different items in daily life, including items like pen, fork, spatula, ball, bowl, plate, net bag, egg, bottle, pen container, hammer, pan, marbles, scissors and circuit board



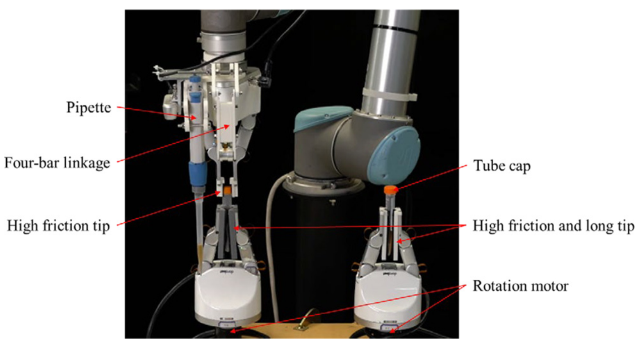
4.4 Modular design

The hot-swap function is the critical part in the modular design with the hot-swap function. The finger can be plug and insert easy and operate with power-on state; this process can make the finger usage easier, and researcher can control the robot complete the finger replace and maintain by itself.

With this finger module, we can easier design the hand with different layout and different finger number. The main board in the palm can support the maximum number of six fingers, and each finger can be exchanged. The designs of two- and five-finger hand are shown in Figure 15.

Figure 15 Two- and five-finger hands

Figure 16 Manipulate with the tube cap and the pipette



The two-finger version keeps the rotation DOF in the three-finger version palm, and it can use in some narrow and light load cases. The five-finger version gains two DOFs in the thumb rotation and two DOFs in the palm and finger rotation. It can use in some cases that need more complex manipulation capability.

Besides the two- and five fingers, the researcher can treat the finger and main board as the basic motion module, and extend the finger and main board with more diverse usages.

4.5 Finger manipulation

The hand can also manipulate some tiny objects with the big enough tip force, including the tube gap.

With the purpose of anti-virus, we have used the DoraHand to build an anti-virus robot that can help to transfer the sample to the standard tube. This robot needs to open the tube cap, operate the pipette to transfer the sample and close the tube cap. With the module tip design function in DoraHand, the hand can be modified with the pipette and high friction tip.

For the three-finger DoraHand, we change the middle finger joint 0 to drive a four-bar linkage to operate the pipette and replace a high friction tip to the other two fingers to provide enough rotation torque. For the two-finger DoraHand, we change the fingertip with high friction and long positioning tip and add a rotation base under the hand to provide the rotation force. With these changes, the function of reagent sampling shown in Figure 16 was realized by the three- and two-finger hand.

5. Conclusion

This paper introduced a novel dexterous hand with a tactile sensing finger module. The performance and capability were evaluated and shown in this paper. The DoraHand can meet the most research requirements from the parameters and functions in the robotic manipulation area. The modular design can easily scale to different finger layouts and support mounting other modules in the joint and tip parts for more customized requirements. The finger with the hot-swap function can help researchers or robots maintain fingers by themselves and help realize a fully automated solution.

We hope this dexterous hand can help researchers eliminate the hardware issues and focus on the algorithm. We will provide affordable DoraHand and deliver more diverse functions to contribute to the robotic manipulation area.

References

Calli, B. Walsman, A. Singh, A. Srinivasa, S. Abbeel, P. and Dollar, A.M. (2015), "Benchmarking in manipulation research: the YCB object and model set and benchmarking protocols", arXiv preprint.

Catalano, M.G., Grioli, G., Farnioli, E., Serio, A., Piazza, C. and Bicchi, A. (2014), "Adaptive synergies for the design and control of the pisa/IIT SoftHand", *The International Journal of Robotics Research*, Vol. 33 No. 5, pp. 768-782.

Deimel, R. and Brock, O. (2016), "A novel type of compliant and underactuated robotic hand for dexterous grasping", *The International Journal of Robotics Research*, Vol. 35 Nos 1/3, pp. 161-185.

Donlon, E., Dong, S., Liu, M., Li, J., Adelson, E. and Rodriguez, A. (2018), "Gelslim: a high-resolution, compact, robust, and calibrated tactile-sensing finger", *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1927-1934.

DoraHand (2020), "DoraHand", available at: https://github.com/dorabot/DoraHand (accessed 30 April 2022).

Fang, B., Xue, H., Sun, F., Yang, Y. and Zhu, R. (2019), "A cross-modal tactile sensor design for measuring robotic grasping forces", *Industrial Robot: The International Journal of Robotics Research and Application*, Vol. 46 No. 3, pp. 337-344.

Fishel, J.A. and Loeb, G.E. (2012), "Sensing tactile microvibrations with the BioTac – comparison with human sensitivity", *2012 4th IEEE RAS & EMBS international conference on biomedical robotics and biomechatronics (BioRob)*, pp. 1122-1127.

Homberg, B.S., Katzschmann, R.K., Dogar, M.R. and Rus, D. (2015), "Haptic identification of objects using a modular soft robotic gripper", *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1698-1705.

Hou, Y. and Mason, M.T. (2019), "Robust execution of contact-rich motion plans by hybrid force-velocity control", *2019 International Conference on Robotics and Automation (ICRA)*, pp. 1933-1939.

Kim, Y.J., Song, H. and Maeng, C.Y. (2020), "BLT gripper: an adaptive gripper with active transition capability between precise pinch and compliant grasp", *IEEE Robotics and Automation Letters*, Vol. 5 No. 4, pp. 5518-5525.

Liow, L., Clark, A.B. and Rojas, N. (2019), "Olympic: a modular, tendon-driven prosthetic hand with novel finger and wrist coupling mechanisms", *IEEE Robotics and Automation Letters*, Vol. 5 No. 2, pp. 299-306.

Liu, H., Meusel, P., Hirzinger, G., Jin, M., Liu, Y. and Xie, Z. (2008), "The modular multisensory DLR-HIT-hand: hardware and software architecture", *IEEE/ASME Transactions on Mechatronics*, Vol. 13 No. 4, pp. 461-469.

Ma, R.R., Odhner, L.U. and Dollar, A.M. (2013), "A modular, open-source 3D printed underactuated hand", *2013 IEEE International Conference on Robotics and Automation*, pp. 2737-2743.

Melchiorri, C., Palli, G., Berselli, G. and Vassura, G. (2013), "Development of the ub hand iv: overview of design solutions and enabling technologies", *IEEE Robotics & Automation Magazine*, Vol. 20 No. 3, pp. 72-81.

Meng, N., Kun, W., Mingxin, L., Ke, Y. and Zhi, W. (2020), "Design, analysis and experiment of finger soft actuator with nested structure for rehabilitation training", *Advances in Mechanical Engineering*, Vol. 12 No. 11.

OpenAI, A.I. Andrychowicz, M. Chociej, M. Litwin, M. McGrew, B. Petron, A. Paino, A. Plappert, M. and Powell, G. (2019), "Solving Rubik's cube with a robot hand", arXiv preprint.

Piacenza, P., Behrman, K., Schifferer, B., Kymissis, I. and Ciocarlie, M. (2020), "A sensorized multicurved robot finger with data-driven touch sensing via overlapping light signals", *IEEE/ASME Transactions on Mechatronics*, Vol. 25 No. 5, pp. 2416-2427.

Ponce, J. and Faverjon, B. (1995), "On computing three-finger force-closure grasps of polygonal objects", *IEEE Transactions on Robotics and Automation*, Vol. 11 No. 6, pp. 868-881.

Quigley, M., Salisbury, C., Ng, A.Y. and Salisbury, J.K. (2014), "Mechatronic design of an integrated robotic hand", *The International Journal of Robotics Research*, Vol. 33 No. 5, pp. 706-720.

Robotiq (2011), "3-finger adaptive robot gripper", available at: https://robotiq.com/products/3-finger-adaptive-robot-gripper(accessed 30 April 2022).

Sadun, A.S., Jalani, J. and Sukor, J.A. (2016), "Force sensing resistor (FSR): a brief overview and the low-cost sensor for active compliance control", *First International Workshop on Pattern Recognition*.

Schunk (2015), "SDH servo-electric 3-finger gripping hand", available at: www.schunk-modular-robotics.com/en/home/products/servo-electric-3-finger-gripping-hand-sdh.html (accessed 3 December 2021).

Shadow Robot Company (2017), "Shadow dexterous hand", available at: www.shadowrobot.com/products/dexterous-hand/ (accessed 30 April 2022).

SimLab (2012), "Allegro hand is a low-cost and highly adaptive robotic hand", available at: https://robots.ros.org/allegro-hand/ (accessed 30 April 2022).

Sun, F., Fang, B., Xue, H., Liu, H. and Huang, H. (2019), "A novel multi-modal tactile sensor design using thermochromic material", *Science China Information Sciences*, Vol. 62 No. 11, pp. 1-3.

Tavakoli, M. and de Almeida, A.T. (2014), "Adaptive under-actuated anthropomorphic hand: ISR-SoftHand", *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1629-1634.

Tomo, T.P., Somlor, S., Schmitz, A., Hashimoto, S., Sugano, S. and Jamone, L. (2015), "Development of a hall-effect based skin sensor", *2015 IEEE SENSORS*, pp. 1-4.

Townsend, W. (2000), "The BarrettHand grasper–programmably flexible part handling and assembly", *Industrial Robot: An International Journal*, Vol. 27 No. 3, pp. 181-188.

Van Duong, L., Asahina, R. and Wang, J. (2019), "Development of a vision-based soft tactile muscularis", *2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)*, pp. 343-348.

Wang, T. and Kirchner, F. (2021), "Grasp stability prediction with time series data based on STFT and LSTM", arXiv preprint.

Wang, T., Geng, Z., Kang, B. and Luo, X. (2019a), "Eagle shoal: a new designed modular tactile sensing dexterous hand for domestic service robots", *2019 International Conference on Robotics and Automation (ICRA)*, pp. 9087-9093.

Wang, T., Yang, C., Kirchner, F., Du, P., Sun, F. and Fang, B. (2019b), "Multimodal grasp data set: a novel visual–tactile data set for robotic manipulation", *International Journal of Advanced Robotic Systems*, Vol. 16 No. 1.

Yang, Y., Li, Y., Chen, Y., Li, Y., Ren, T. and Ren, Y. (2020), "Design and automatic fabrication of novel bio-inspired soft smart robotic hands", *IEEE Access*, Vol. 8, pp. 155912-155925.

Yousef, H., Boukallel, M. and Althoefer, K. (2011), "Tactile sensing for dexterous in-hand manipulation in robotics – a review", *Sensors and Actuators A: Physical*, Vol. 167 No. 2, pp. 171-187.

Yuan, S., Epps, A.D., Nowak, J.B. and Salisbury, J.K. (2020), "Design of a roller-based dexterous hand for object grasping and within-hand manipulation", *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 8870-8876.

Yuan, W., Li, R., Srinivasan, M.A. and Adelson, E.H. (2015), "Measurement of shear and slip with a GelSight tactile sensor", *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 304-311.

Zeng, A., Song, S., Welker, S., Lee, J., Rodriguez, A. and Funkhouser, T. (2018), "Learning synergies between pushing and grasping with self-supervised deep reinforcement learning", *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 4238-4245.

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