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The Design and Development of an Anthropomorphic Worm-Gear Driven Robotic Hand: BIT-JOCKO*

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***Abstract*— A lightweight dexterous robotic hand named BIT-JOCKO with twenty degrees of freedom is presented in this paper. Each knuckle of the hand is equipped with an individually controlled servomotor to enable both-direction bending movements in the range of 0 °-100 °. The specially designed worm-gear of the drive system not only enlarge the torque of the motor shaft but also equip it with special ability when holding items. Each servomotor is connected with a worm gear. Compare to other forms of a driving system like direct-drive joint, bevel gear joint and harmonic joint. Such characteristics of the worm gears enable the dexterous hand to keep its pose even when the motor forces are turned off after seizing objects. That means this hand is capable of holding weight with considerable self-locking torque. The total weight of BIT-JOCKO is only 1.1 kilograms. The mechanical design and the philosophy behind is illustrated in detail.**

I. INTRODUCTION

With the continuous progress of science and technology and the emerging interdisciplinary emerging, such as medical equipment [1], nuclear energy development [4], space exploration [8] , and so on the robot technology has put forward higher requirements. Generally, the human hand is far better than the dexterous hand. In some special occasions, the latter will play an irreplaceable role. The grabbing devices of the conventional industrial robot have some drawbacks, such as poor flexibility, low perception, low control-accuracy. Conventional under-actuated dexterous hands cannot detect the specific location of the knuckle, so it is difficult to achieve accurate grasping. The ordinary built-in motor-driven gripper has a weak holding capacity. The volume of the knuckle without fine design and restriction is too large. some special application field address that the robot actuator should bear high torque when holding some over-load objects. That is quite a challenge for the mechanical design as well as motor control. Motor with high reduction rate can take over it by adding cumbersome mechanical addition like reduce box and any other gear. Paper [6] introduces us a harmonic-based joint, this kind of hand can be mounted at some typical robot arm acting as an end-term component. it may be a suitable size and weight for a robot as it always a good choice for industry and research field. When it is translated to those disabled humans, the size and structure are not practical in daily life.

Paper [5] introduces a human-like hand using a combination of reduction gear and worm-gear .this hand using a built-in motor in each knuckle and using worm gear so that the output shaft is orthometric with the motor shaft. This mechanical design reserved the quick movement ability of motor can suffer a light-weight load. Such design pays more attention to athletic ability.

Some dexterous hand [7] [3]combined with tendon rope is applied in medicine filed helping the disabled equipped with an artificial limb. The palm-size of the traditional tendon-rope-driven dexterous hand can be very small, however, its subsidiary drive mechanism is very bulky. As the tendon-rope-driven joint can only bend and swing, achieving the fine operation requires a complex structure and more independent drive unit. The using of linkage reduces the design of a complex drive structure at the expense of freedom. Our dexterous hand JOCKO has 20 degrees of freedom, including 14 fine-designed worm gearing finger-knuckle module. and 3 screw-motor-driven joints mounted at palm. As it is designed with no subsidiary of the cumbersome drive mechanism, the whole hand weights 1.1kg. Table I lists several typical robot hands in the world and makes a more detailed comparison.

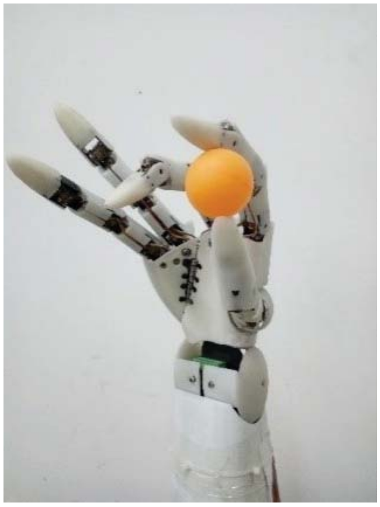

Fig. 1. The BIT JOCKO dexterous hand

Gifu hand has some similarity with ours. The structure of each finger is a little different from each other. Some of its finger knuckles are using linkage to instead of the independent knuckle for simplicity in some degree sacrifice

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TABLE I
COMPARISON BIT-JOCKO WITH SOME FAMOUS ROBOT HANDS

name	DOF	movement	size and weight
UBH-3 [7]	13	hinges and tendon	mostly up to drive part
Shadow hand [3]	20	air muscle	human size about 4.2kg
Gifu Hand [5]	16	worm gear and bar linkage	about 273mm and 1.4kg
DLR-Hand [2]	13	harmonic drive	about 224 mm and 1.5kg
BIT-JOCKO	20	worm gear and bar linkage	220mm and about 1.1kg

the DOF While we design each knuckle modularly and reserve its independent Movement ability.

II. Design philosophy

After millions of years of evolution, human hands can complete a variety of fine complex movements with a rich sense of feedback.

A. The natural skeleton structure of human hand

The natural skeleton structure of a human hand is shown in Figure 2 gives the name of each bone joint of a human natural hand. The natural hand consists of five free fingers, palms, wrist, etc., a total of 27 bones, each finger joints in accordance with a specific order of action, has a range of activities. In addition to the thumb, the other four fingers are similar in structure. The function and structure of a human hand give us inspiration, we can design our dexterous hand mimic the human hand with the flexible movement ability and improve its holding ability when grasping items. We analyze the characteristics of the human skeletal structure why it can easily grip objects in different shapes. The palm of the hand with the perfect structure of the arc so that it can be easily adapt to the different surface.

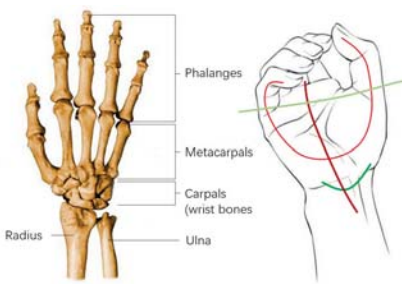

Fig. 2. The structure of human hand

B. Natural hand movement characteristics

We pick up some typical actions of the human hand in daily life. As shown in Figure 3, (a)$\sim$(d) different posture holding a pen, (e)grasping a flat stuff,(f) holding a ball, (g) holding a heavy steel,(h) grasp a bag.

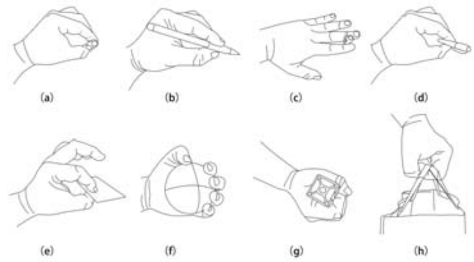

Fig. 3. Mode of human hand operation

III. Mechanical design

In order to achieve the dexterous hand's movement function and the pose maintaining function under high load, a power-off self-locking worm-gear motor module was used to design the structure of the 4-DOF finger structure and the palm structure.

A. Design of Wobble and Worm Knuckle Module

BIT-JOCKO uses the worm-gear motor as the module power. The basic structure of the worm-gear reducer is including the transmission parts worm, gear, shaft, bearings, cabinets, and accessories. As shown in Figure 4, the box is the base of all the accessories in the worm-gear reducer. It is an important accessory to support the fixed shaft parts, ensure the correct relative position of the transmission parts and support the load on the reducer. The worm-gear group can transfer motor output power, change the direction of the output force. Bearing and shaft act as transmission part. The end of the shaft is in D shape which corresponds to the D shape pole of the potentiometer to feedback the position. The features of the module body are: (1) compact mechanical structure, compact size, small size, and high efficiency; (2) smooth operation, low noise, durable; (3) power-off self-locking function, controllable performance. As there is a nonnegligible backlash in the gear transmission. The knuckle backlash mainly from the worm-gear.The average backlash of the designed knuckle is approximately 2 °.

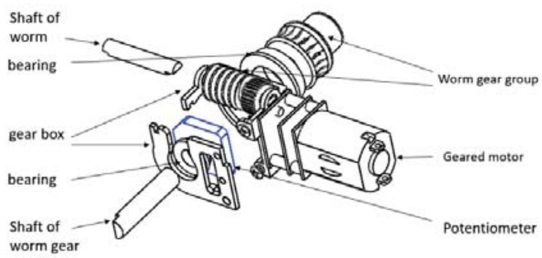

Fig. 4. The worm gear reducer module

B. BIT-JOCKO finger structure design

The dexterous hand is modularly designed. Each worm-gear motor is a knuckle module, and such 2 to 3 knuckle

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modules assemble a finger module in series form through the joint connector (Figure 5). The biggest feature of the finger structure is its adjustable length. The length of the knuckle of each finger can be adjusted by the joint connector. The joint connector is composed of left and right parts. This two-part fasten together by bolts.

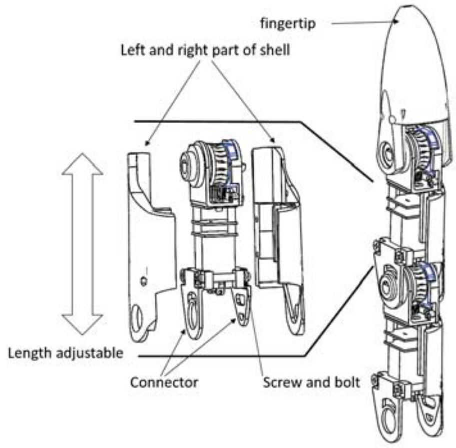

Fig. 5. The single finger structure

C. The palm Structure design

The palm is a very important part as its design directly influences the appearance of dexterous hands and the ability to grasp the object. The four-finger layout, that is, dexterous hand index finger, middle finger, ring finger, and little finger mounted relative to the palm of the hand. The layout of palm can be specified as shown below:

1) The index finger root mechanism: The rotational movement of the root of the index finger is driven by the leading screw motor and the movement of the index fingerroot pendulum [50°, -30°]. The rotation angle is feedback by the potentiometer mounted at the root shaft of the index finger. The position is limited by the slider. The screw motor with a large reduction ratio also equipped with self-locking characteristics. Thrust bearing fastens the structure of screw and slider to ensure the mechanical structure reliability.

2) The ring finger and little finger linkage design: The main movement of the robotic hand is completed by the thumb, index finger, middle finger. The ring finger and little finger play an auxiliary role. We observe a large number of human hand actions find an interesting fact that in the vast majority of cases, the ring finger and little finger is open and close at the same time. We can use a linkage mechanism to mimic the form of movement. Therefore, we design a link-based linkage structure. Link 1 connects the end of the motor fixture of the ring finger and the little finger, thus forms the four-bar linkage with the rotating shaft 1, 2 on the fixing frame. The slider drives link 2 to move. The connecting rod 2 drives the connecting rod 1 to move so as to realize the similar movement form like the ring finger and the little finger.

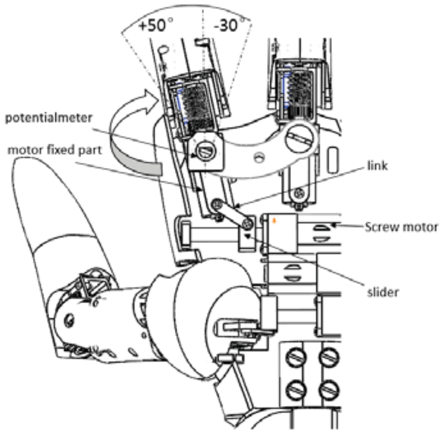

Fig. 6. The root of the index finger design

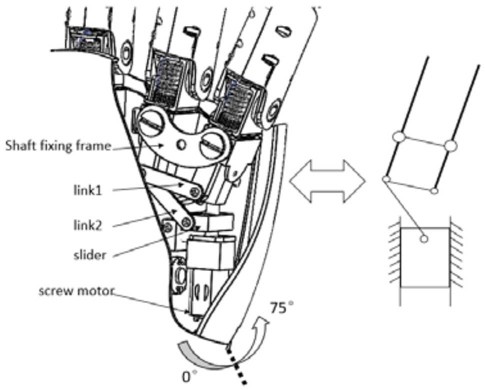

Fig. 7. Linkage mechanism of the deputy palm

3) Palm turning mechanism design: In order to better adapt to the shape of objects to be crawled, we designed the structure of the flip palm, which enables the adjusted curve of palm to fit the different surface improve the flexibility of the grasping. The mechanism consists of a self-locking screw motor, the main palm, the deputy palm, the linkage, and the hinge. Deputy palm and the main palm connected by the hinge connection. There is a stand fixed on the deputy palm and the stand is driven by the link. The other end of the link is connected on the slider and the slider is driven by the screw motor. By this mechanism, the deputy palm can bend [0°, 75°]. The ring finger and little finger of the reachable domain increased by about 30 percentage analyzed from the cad software. The reachable domain is shown in Figure 9.

IV. Control System Design

A. Three-loop PID Control of the knuckle in simulation

In order to achieve high-precision motor control, we establish a precise mathematical model on the brush motor. Its output shaft angle and the input voltage $U_a(s)$ relationship is shown as:

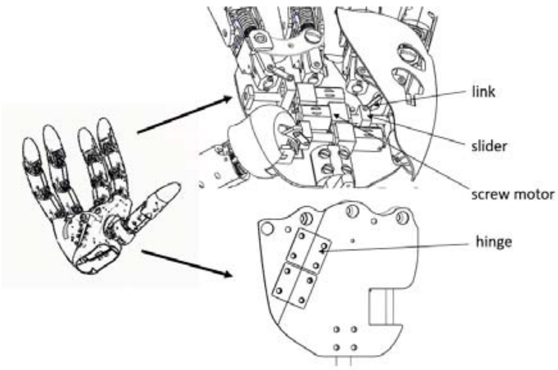

Fig. 8. Mechanism of the Flipped palm

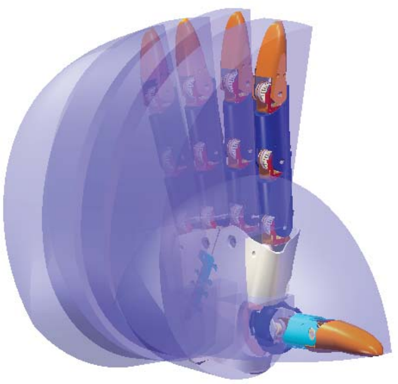

Fig. 9. the reachable domain of the Flipped palm

$$\frac{\theta\,(\mathrm{s})}{U_a\,(s)} = \frac{\frac{1}{K_b \cdot i}}{\tau_m \cdot \tau_e s^3 + \tau_m s^2 + s} \tag{1}$$

We control each knuckle by using the three-loop PID control and the output of each PID loop is limited according to the actual situation. We simulate the response in Simulink. A sinewave signal is given to the input. Under the applied load condition, the relation between response and input is shown in Figure10.

As we can see from Figure 10, the output has a fast response with tiny overshoot amplitude. A $0.05N \cdot m$ load is set in the t = 3s and the position of motor output shaft almost remain unchanged. Actually, Once we get the position before the load takes effective, the position will no longer change unless we power the motor due to worm gear self-locking characteristics. Another case is that the torque is loaded while the motor is running to aim position. By exerting external torque gradually in a simulation environment, the motor with worm and gear can drive 0.05N.M under 12v voltages condition. Beside it, we exert dynamic signal 5HZ and 8HZ sinewave position loop cmd, it turns out to be well responded at the simulation environment.

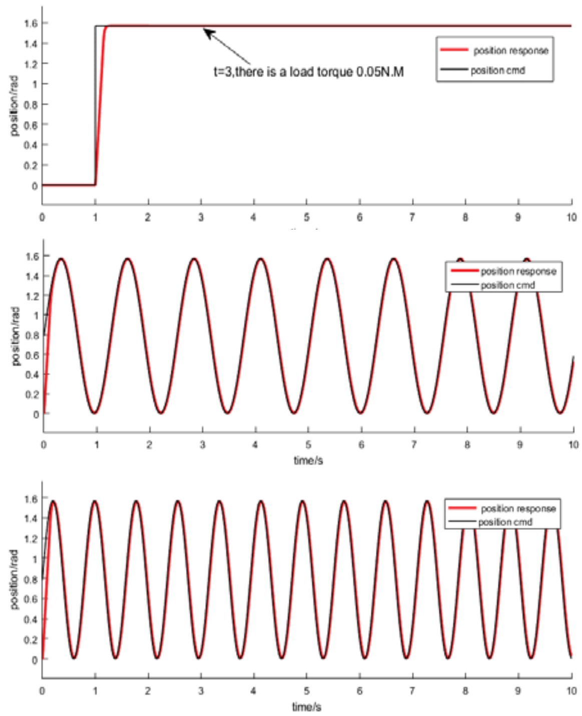

Fig. 10. Input and output response of single knuckle in simulation

B. Mathematics model for controller design

As the motion of thumb and index finger is representative, we take the grasping state of thumb and index finger as the object to analyze. In the position control mode, the system takes the joint angle as the system input variable, and the output variable is the position of the fingertip relative to the base axis. As is shown in Figure 11, we analyze the grasping statement and simplify the thumb and index finger grasping model. The D-H transfer array of the two joints are

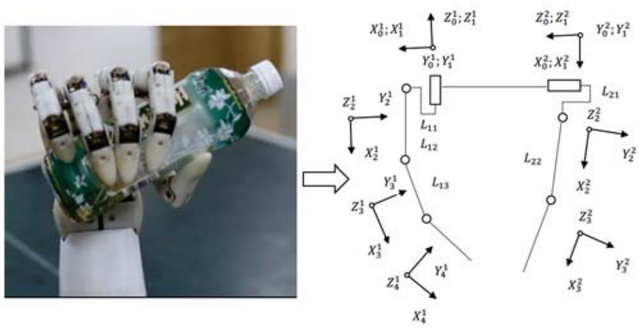

Fig. 11. Simplified grasping model

$${}^{i-1}T_i = \begin{vmatrix} c\theta_i & -s\theta_i & 0 & \alpha_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{2}$$

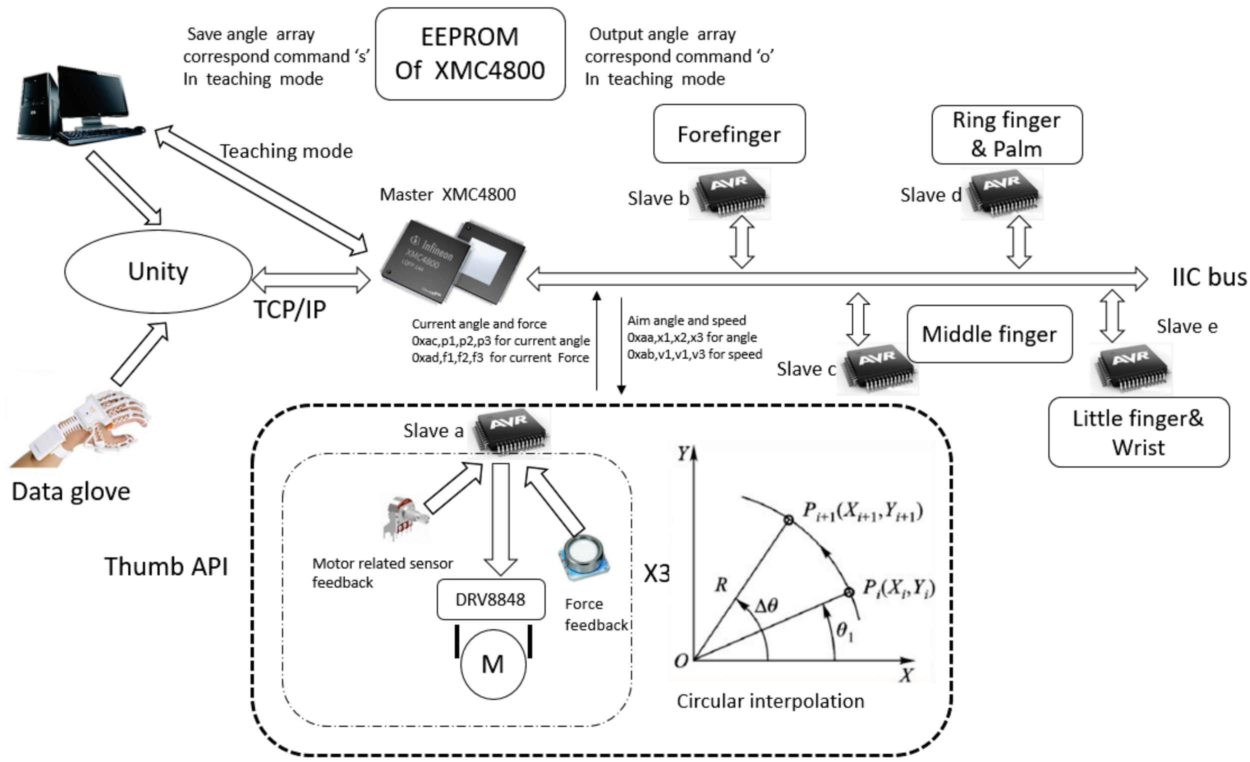

Fig. 12. System control flow chart

According to the positive kinetic formula, we can get it

$$ {}^{0}T_i = {}^{0}T_1 {}^{1}T_2 \cdot\cdot\cdot\cdot\cdot\cdot {}^{i-1}T_i \quad (3)$$

Applying this formula on the left and right finger model, respectively, we can get the transfer array

$$ {}^{01}T_4, {}^{02}T_3 $$

The kinematic analysis between the left and right two rod coordinate systems need to be carried out in the same coordinate system, and the generalized transformation operator can be obtained by formula derivation:

$$ T^A = \begin{vmatrix} \cos\theta & -\sin\theta & 0 & q_x \\ \sin\theta & \cos\theta & 0 & q_y \\ 0 & 0 & 1 & q_z \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (4)$$

We can take the index finger position input as:

$$ \phi_1 = \begin{vmatrix} \theta_1 & \theta_2 & \theta_3 & \theta_4 \end{vmatrix}^T \quad (5)$$

and the thumb position input as:

$$ \phi_2 = \begin{vmatrix} \theta_5 & \theta_6 & \theta_7 \end{vmatrix}^T \quad (6)$$

And we get a union input :

$$ \phi = \phi 1 U \phi 2 = \begin{vmatrix} \theta_1 & \theta_2 & \theta_3 & \theta_4 & \theta_5 & \theta_6 & \theta_7 \end{vmatrix}^T \quad (7)$$

the entire system transfer array:

$$ \begin{vmatrix} {}^{01}T_4 \\ {}^{01}T_3 \end{vmatrix} = \begin{vmatrix} 1 & T^A \end{vmatrix} \begin{vmatrix} {}^{01}T_4 \\ {}^{02}T_3 \end{vmatrix} \quad (8)$$

So we can get an output

$$ P = \begin{vmatrix} {}^{1}P_x & {}^{1}P_y & {}^{1}P_z & {}^{2}P_x & {}^{2}P_y & {}^{2}P_z \end{vmatrix}^T \quad (9)$$

relative to the input.

C. *Master-slave control mode*

As Figure12 shows, the dexterous hand has the data glove pattern, the instruction control pattern, the teaching reproduction mode and so on the nimble control way. In the data glove mode, the data glove collects the movement information of the human fingers and transmits the action position information of these fingers to the computer according to the pre-programmed protocol. The computer program in the unity analysis glove transmission data from the serial com and display the dexterous hand movement real-time. The low-level driver is a master-slave control system connected by the I2C bus. the XMC4800 chip in the control unit works as master receiving the data. The chip analyses the data from the computer and sends the data to the slave according to the pre-agreed protocol containing different slave address. The structure of the protocol is the same, and the data of the start frame is different to distinguish the different commands. The protocol contains the position and velocity information of each finger or joint. In the command mode, the computer sends data to the master chip through the computer interface. The master sends the analytical data to the corresponding slaver through the I2C protocol. Slaver complete the corresponding action by servo control. Teach mode is developed on the basis of the command mode for the dexterous hand. To implement it we utility additional memory function. Responding to the specific computer's command, the main control chip will save current position and store in the EEPROM. The next time the command of the same action will directly call the corresponding action saved in EEPROM. Slaver's function is to analyze the master data, and output 4-channel PWM wave through the 4-channel PID algorithm and respectively, control the four knuckle motor servo movement. Since the aimed position is a discrete target position. In order to achieve the continuity of action, we use the circular interpolation algorithm in position decompose. Through such a control system, master and slaver carry out their duties and reduce the workload of the master. Each finger or joint operates parallel in the same control loop to improve the control flexibility. Through the grasping experiments on common items, BIT-JOCKO shows fine adaptability to the different surface shape of the object. Experiments also show that the smart hand has a strong ability to maintain the position, once the smart hand locks state, only to change the control signal can it be unlocked

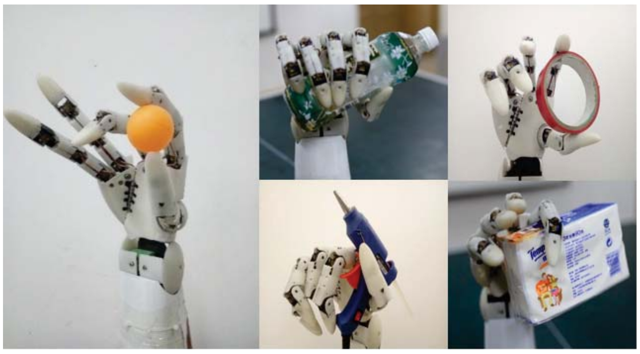

Fig. 13. Grasp the common stuff

V. Conclusion

We have presented the compact and modular mechanical design of a human-like robotic hand BIT-JOCKO which has 20 degrees of freedom. Tiny worm gears are used so as to provide holding torque even when power off. Currently, it can hold the stuff maximum weighted about 1kg without damaging the structure at zero output torque. Each knuckle is fully controllable in torque, velocity, and position. The total weight of the hand is only 1.1 kilograms. An extra degree of freedom in the palm is provided to enlarge the working space in 30 percents. Such designing of the palm can increase the reachable domain of the last two fingers. and we can enable the hand to do more action mimicking the human operation and more adaptive to a different surface of an object. Experiments show that our dexterous hand is able to grasp objects with different size, shape, and weight with a human-like gesture. However, due to the limited mechanical structure, we haven't exerted a high load to the robot hand. To do the experiment with more strictly situation, we are designing a more compact one. This paper is attached with a simple demo video. In the future, we need to increase the output torque of each knuckle to grasp heavier objects and strengthen the mechanical structure of the hand and do more work related to algorithm.

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