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Under-actuated passive adaptive grasp humanoid robot hand with control of grasping force

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Abstract **– Conventional dexterous hands have too many DOFs, their driver systems are too big to be installed in a humanoid robot arm, and their controls are too complex. This paper develops an under-actuated passive adaptive grasp humanoid robot hand named TH-1 Hand with control of grasping force. With the humanoid appearance and size, TH-1 Hand is light, fewer DOFs, and can be easily controlled. Its motors and driver circuit boards are embedded in itself. These features make it fit to be installed in a humanoid robot arm. In addition, for stably grasping operation, a mechanical finger with control of grasping force is designed and applied in TH-1 Hand's index. To get more DOFs with fewer drivers, a novel under-actuated passive adaptive grasp mechanical finger is designed and applied in TH-1 Hand's thumb.**

Keywords **– Humanoid robot hand, Under-actuated finger, Finger with control of grasping force**

I. INTRODUCTION

All of the power supply, drivers, control system, sensors and information processing system are installed in the humanoid robot itself, which provides very strict requirement on many aspects, such as the hand's weight, volume, power cost and real-time control.

Many robotic hand devices focus on simulating the overall appearance and movement of a human hand while neglecting other equally important features such as the size, weight and real-time control. Conventional robotic devices, such as the hand in [3], are relatively complex, large, cumbersome and difficult to be installed in a humanoid robot arm. The complexity of conventional robotic devices also makes the robotic hand be more expensive and difficult to manufacture and maintain.

Under the condition of present control methods, one of the key points on humanoid robot hand design is how to simplify and arrange a human hand's DOFs reasonably, so that the hand will be more personified and dexterous. The similar character on the hand design of those advanced humanoid robots as P2, P3, ASIMO is their fewer DOFs[1]. Hand of P2 has 3 fingers, only 2 DOFs. P3 has 2 fingers, only 1 DOF. ASIMO has 5 fingers, only 1 DOF, does not fit to grasp objects.

Another key point on humanoid robot hand design is how to decrease the volume, weight, power cost. Because too big volume may influence appearance, too heavy and too much power cost may add the burden of the robot's arm and legs, also add the robot's total power cost. The number of a hand's DOFs, the driver's style, the transmission mode, the joints mechanism, the material of links and the kinematics character are quite important.

The main function of a robot hand is to grasp objects. The grasping force of a robot hand should be changeable according to an object's weight and surface status, such as brittleness and coarseness. That means the design of the robot hand with control of grasping force is very significative. For example, the hand in [4] adopted a spring to generate and control grasping force, but it only fits the tendon transmission mechanism.

At present, the hand's driver and control system have to be gigantic and it is difficult to control if the hand has many DOFs, so fewer drivers should be designed in the hand. Above-mentioned two aspects are partly contrary. In addition, an important feature of the human hand and particularly the fingers is the ability to bend around an object and adapt to its shape. It is better if some fingers are passive adaptive to the shape and size of objects on grasping objects. Some mechanical hands have the architecture that combines three cases, taking advantage of them through the concept of under-actuation. Their design is based on a large number of DOFs but with a reduced number of actuators. Indeed, under-actuated hands are defined as what have more degrees of freedom than actuators. This leads to flexible grippers without the complexity associated with a large number of actuators. Under-actuation can be achieved using tendons, but the grasping forces are limited and the tendons give rise to friction and compliance. The hands in [5,7,8] also have under-actuated functions.

II. TH-1 HUMANOID ROBOT HAND

Supported by "985" significant project of Tsinghua University, the under-developing TH-1 humanoid robot must be capable of wireless control which means its power supply is equipped on-board and communications between mater computer and slave controllers are wireless. Therefore, the aim of TH-1 hand includes: lighter than 1 kg in weight; 0.5 kg working load at least; no more than three drivers; more than two fingers; the appearance, size and actions are similar to a human hand; actions like extending, making a fist, shaking hands, grasping some ordinary cylinder objects could be done.

2.1. Fingers and DOFs

Majority grasp tasks can be completed by two "virtual fingers"[2], so TH-1 Hand is designed as a hand with two fingers. Its other main design ideas are listed below. Its kinematics structure is shown in Fig.1.

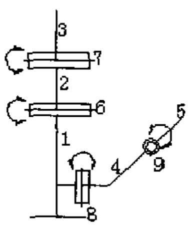


Fig. 1. TH-1 kinematics structure

(1) In majority grasping tasks, action of human index is to rotate towards the palm center, hence two joints 6-7 which turn towards the palm are designed in the index.

(2) In order to increase the personification and stability of grasping action, the appearance of the Index 6-2-7-3 is designed as four fingers (index, middle, ring and little finger), so that the hand looks like a human hand.

(3) Generally, the top segment of a human thumb bend at the middle knuckle, with bigger bend range, this action is efficacious on grasping objects, therefore an under-actuated joint 9 at the middle of thumb is designed to increase the stability of grasp and the personification of TH-1 Hand.

(4) A human thumb usually bends towards palm at its root knuckle in a big range, not very efficacious on grasping tasks but this bend may greatly influence the personification, so a swing joint □ at the thumb's root is designed. In the process of grasping objects, the thumb has already arrived at the position facing against the palm in advance, the joint does not need to be controlled any more.

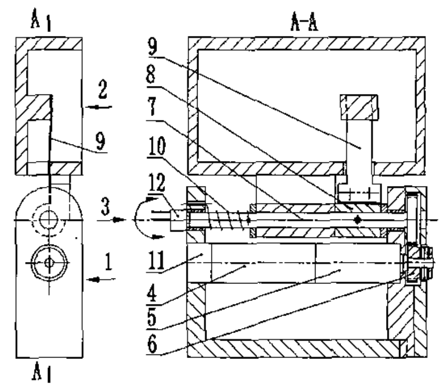
(5) The surface of fingers are covered with high friction coefficient elastic material which is helpful to increase the touch area between fingers and an object by their distortion, and increase the restrictions force, friction force and grasping stability.

2.2.Actuators and transmission style

According to calculating and experiments, DC motors with 3 watt of rated power and corresponding reducers and encoders are adopted in TH-1 Hand. They are smaller in volume, the inner space of TH-1 Hand is relatively bigger. Therefore, the motors, reducers and encoders are arranged near corresponding joints and gear transmission style is adopted.

2.3. Finger with control of grasping force

A novel mechanical finger with control of grasping force is designed and applied in two joints of TH-1 Hand's index. Hereinafter, "control of grasping force" is abbreviated to "CGF".



(a) Main view (b) A-A slice view

Fig. 2. Finger with control of grasping force

The finger with CGF can not only fetch objects stably, but also change the grasping force according to different objects. The motor continues rotating after the finger segment touches the object, the motor shaft's angle is varied, thus CGF to different object is produced. Furthermore, accurate control of the grasping force can be realized through combination of finger and a pressure sensor.

As shown in Fig.2, the finger with CGF is composed of First Segment 1, CGF Joint 3 and Second Segment 2. First Segment and Second Segment are all hollow. CGF Joint is plugged between First Segment and Second Segment. Second Segment includes a motor 4, a reducer 5, a transmission mechanism, a joint shaft 7, sliding bearings, Driver Block □ and a spring piece 9.

The connections of these components are described as: the joint shaft is plugged between First Segment and Second Segment; the motor's output shaft connects with the reducer's input shaft, they are all installed into First Segment and are parallel to the joint shaft; the reducer's output shaft connects with the transmission mechanism; the transmission mechanism connects with the joint shaft; Driver Block is fixed with the joint shaft; one end of the spring piece is fixed with Driver Block, the other end is plugged into Second Segment, but is kept free. Initially, the spring piece should be a little bended to eliminate the gap between the spring piece and Second Segment.

This kind of finger is adapted to many kinds of transmission styles, such as gear (e.g. TH-1 Hand's index), tendon, chain wheel, etc. CGF Joint may also include a twist spring 10, whose two ends are separately fixed with the joint shaft and First Segment, in order to eliminate the gap of transmission mechanism. The surfaces of the two segments may be covered by some pressure sensors or by tactile sensors so as to measure the pressure force exerted on the object by the segments. A potentiometer 12 is installed at one end of the joint shaft to measure the rotational angle of the joint shaft for position close-loop control. An encoder 11 is fixed at the end of the motor to sense the rotational speed of the motor's output shaft for speed close-loop control. The surface of the two segments can be covered with the elastic material with high friction coefficient.

The designed fingers with CGF has been successfully applied in TH-1 Hand's index, gear transmission mechanism has been utilized. Through the example of the second index joint of TH-1 Hand, the working principle of the finger is described below:

(1) When the hand grasps an object, the motor rotates, the joint shaft rotates due to the effect of gear transmission mechanism, Driver Block and the spring piece also rotate, Second Segment rotates until it touches the surface of object. When Second Segment stops, Driver Block, the spring piece and Second Segment have already rotated by a same angle θ.

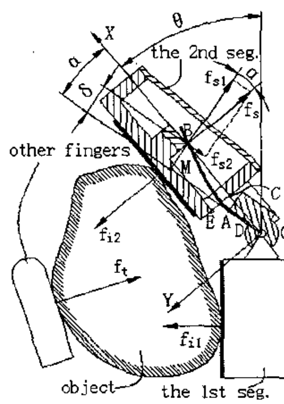


Fig. 3. The mechanism principle of the 2nd joint of index

(2) The motor rotates continuously, and then the joint shaft and Driver Block rotate by an angle α, which will make the spring piece bend because Second Segment cannot rotate any more. Hence an elastic force is produced by the bended spring piece, which will make Second Segment generate a pressure force f_{i2}, exerted on the object, as shown in Fig. 3. The force f_{i2} will increase along with the increasing of the angle α. When the force f_{i2} is strong enough, the motor will stop. Here, the transmission mechanism is locked by itself, thus the joint shaft will not rotate back, the distortion and the elastic force of the spring piece are kept, and the grasping force is maintained. When the hand loosens the object, the process is exactly in reverse order.

The Mechanical principle of the finger with CGF is shown in Fig. 3, in which symbols are explained below:

f_{i2}: the force exerted on an object by Second Segment, N

f_S: the force on the spring piece by Second Segment, N

f_{S1} and f_{S2}: the results of decomposing the f_S, N

δ: the flexibility of the spring piece at B point, mm

Some formulas can be obtained to determine the value of these variables:

$$f_{i2} = f_S = \frac{f_{S1}}{\cos\alpha} \tag{1}$$

$$f_{S1} = \frac{3\delta EI}{\left|\overline{AM}\right|^3} \tag{2}$$

$$\left|\overline{AM}\right| = \left|\overline{OB}\right|\cos\alpha - \left|\overline{OA}\right| \tag{3}$$

$$\delta = \left|\overline{OB}\right|\sin\alpha \tag{4}$$

E: the modulus of elasticity of the spring piece, M Pa

I: the moment of inertia of the spring piece, mm^4

From these formulas, the relation between f_{i2} and α is induced in the formula:

$$f_{i2} = \frac{3\left|\overline{OB}\right|\sin\alpha EI}{(\left|\overline{OB}\right|\cos\alpha - \left|\overline{OA}\right|)^3} \tag{5}$$

The grasping force f_{i2} is relative to number, material, size and arrangement of the spring pieces. For example, E=120 G Pa (the material is QSn4-3); the shape of the spring piece is a rectangle, and its thickness is 0.5mm, its width is 5mm; in addition, the length of OB is 33mm, the length of OA is 12mm, then according to the formula 5, we can find the relation between f_{i2} and α that increase of f_{i2} will be accelerated by the increase of α. Fig. 5, 6 separately show the influence of the length variety of OB and OA to the relation of f_{i2} and α.

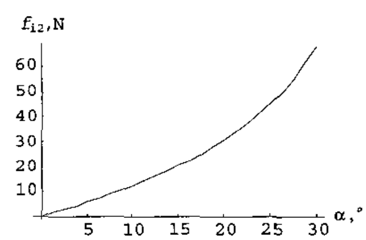


Fig. 4. The relation between f_{i2} and α

The key parameters of the spring piece can successfully designed according to the principle mentioned above. By the way, how to confirm the maximum of α is another important question. Observing the bend curve of the spring piece in Fig 3, its shape is a spine curve fit with the three key points: D, A and B. Suppose the curve of the spring piece is an arc, maximum of α corresponding with the maximum of f_{i2} and the space limit of the finger is calculated quickly and approximately.

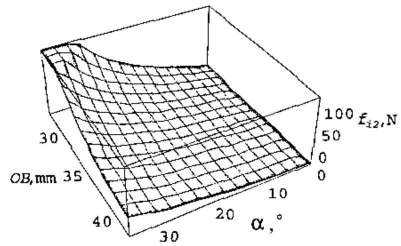


Fig. 5. Relation of f_{i2}, α, and the length of OB

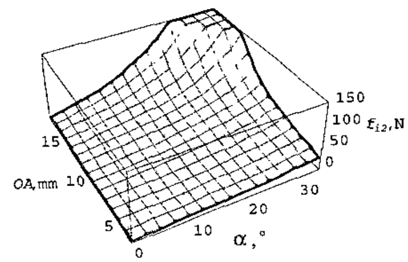
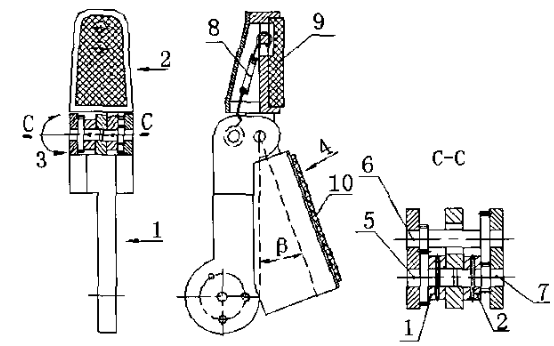


Fig. 6. Relation of f_i, α, and the length of OA

2.4. *Under-actuated passive adaptive finger*

This paper develops a novel under-actuated passive adaptive mechanical finger, namely under the precondition without increasing an actuator, the finger can increase DOFs of a hand, then improve the stability of grasping objects and increase the personification of the hand. The finger is applied into TH-1 Hand's thumb.

The under-actuated passive adaptive thumb, shown in Fig. 7, includes First Segment 1, Active Board 4, Second Segment 2, Under-actuated Joint 3. Under-actuated Joint is plugged in First Segment, Active Board and Second Segment. Under-actuated Joint includes a big-gear shaft 5, a double-gear shaft 6, a small-gear shaft 7 and a spring 8. The big-gear shaft meshes with the smaller gear in the double-gear shaft, and the small-gear shaft meshes with the bigger gear in the double-gear shaft. The three gear shafts are all plugged in First Segment. The big-gear shaft is fixed with Active Board. The small-gear shaft is fixed with Second Segment. The spring is connected between First and Second Segment. The surface 9, 10 of Second Segment and Active Board are covered with elastic material with high friction coefficient. The main link material is nylon, which provides strength, is light and has good enough lubricating effect, thus none of bearings is used. At first, the spring is in original status, and there should be an initial angle: β between First Segment and Active Board, which is recommended as 10° to 30° (e.g. it is 20° in TH-1 Hand's thumb). The principle of the mechanism is described below:



(a) Main view (b) Left view (c) C-C section

Fig. 7. Under-actuated passive adaptive thumb

The hand is shown in Fig. 7 when it does not grasp an object. When the hand grasps object, due to the grasping force of the index, the object may press Active Board and make Active Board rotate by an angle: α. Through the gear transmission mechanism, whose rate of reduction is defined as i (e.g. i = 0.25 in TH-1 Hand's thumb), Second Segment will rotate by an angle: θ $(\theta=\alpha/i)$, shown in Fig. 8, until it touches the object, so the grasping is passive adaptive to the shape and size of objects. Because the gear transmission is a accelerate transmission, the angle θ is much bigger than the angle α, thus it seems there is an actuator in thumb when Second Segment rotates and grasps the object quickly. When the hand loosens the object, due to the index loosening the object, the object does not press Active Board any more, the spring can make Second Segment rotate back, and under the action of the gear transmission, Active Board is restored to the original status.

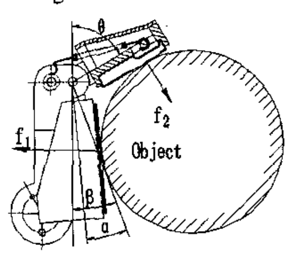


Fig. 8. Under-actuated passive adaptive thumb works

In addition, if the object, such as a pen, is too small to touch Active Board when the hand grasps it, Second Segment of thumb and Second Segment of index can be adopted to pinch the small object, at this time, Second Segment of thumb may not rotate. Interference between Active Board and the grasped object or other finger may not occur.

The mechanical principle of the under-actuated finger is shown in Fig. 9, in which symbols are explained below:

f_1: the force brought to Active Board by the object, N

r_1: the distance between f_1 and the rotation center of Active Board, mm

f_2: the force brought to the object by Second Segment, N

r_2: the distance between f_2 and the rotation center of Second Segment, mm

l_1: the original length of the spring, mm

l_2: the length of the spring, mm

r_s: the distance between the force of spring and the rotation center of the second segment, mm

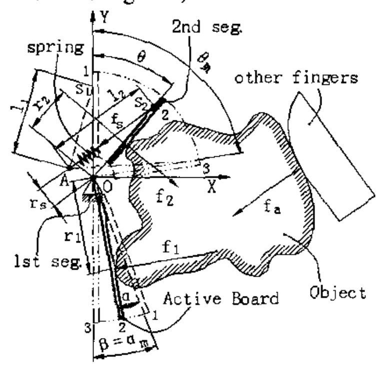


Fig. 9. Mechanical principle of under-actuated finger

A coordinate system fixed with First Segment is established. The rotation center of Second Segment is named as the origin: O, Y-axis is towards the end of Second Segment when the hand does not grasp object, X-axis is towards the index and perpendicular to Y-axis. So: A (X_A, Y_A), S_1 (0, Y_{S1}). In addition, the angle of Second Segment is defined as θ, the angle of Active Board is α, and the original angle between Active Board and First segment is β. Then these formulas can be obtained:

$$f_2 = \frac{f_1 r_1 i \eta - k(l_2 - l_1) r_s}{r_2} \quad (6)$$

$$l_1 = \sqrt{(Y_x - Y_A)^2 + X_A^{\ 2}} \quad (7)$$

$$l_2 = \sqrt{\left[\sqrt{X_A^{\ 2} + Y_A^{\ 2}} - Y_s t\right]^2 + (Y_s q)^2} \quad (8)$$

$$r_s = \frac{q Y_s \sqrt{X_A^{\ 2} + Y_A^{\ 2}}}{l_2} \quad (9)$$

$$t = \cos(\arctan\frac{-X_A}{Y_A} + \theta) \quad (10)$$

$$q = \sin(\arctan\frac{-X_A}{Y_A} + \theta) \quad (11)$$

$$\theta = \frac{\alpha}{i} \quad (12)$$

η: the gear transmission efficiency

k: the coefficient of the spring, N/mm

From these formulas, the conclusion can be obtained: increasing i can result in increasing f_2, decreasing k can result in increasing f_2.

There are some figures in TH-1 Hand's thumb: η=0.96, X_A=-8.925mm, Y_A=3.6mm, Y_S=35mm, k=0.741N/mm, i=0.25. Main relations of the other variables according to formulas above can be obtained. Fig. 10 shows the relation of f_2, r_1 and r_2 when α=10°, f_1=20N. The conclusion can be known: increasing r_1 or decreasing r_2 can all increase f_2. Fig. 11 shows that increasing f_1 will make f_2 increase. Fig. 12 shows that the transformation of k will greatly change the influence extent of α to f_2.

The value of α is related with the shape of the grasped object and is not necessary to know beforehand yet. The rate of reduction i can be recommended as the range of 0.2 to 0.4 according to calculating and experiments.

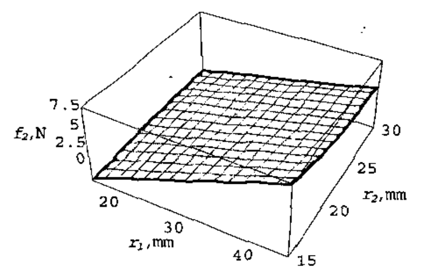


Fig. 10. Relation of f_2, r_1 and r_2 (α=10°, f_1=20N)

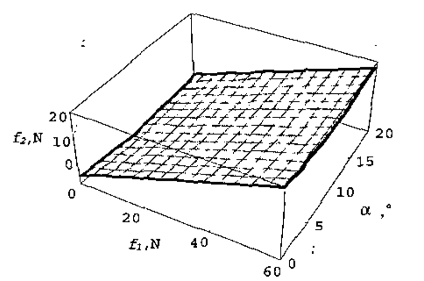


Fig. 11. Relation of f_2, f_1 and α(°) (r_1=35mm, r_2=20mm, k=0.741N/mm)

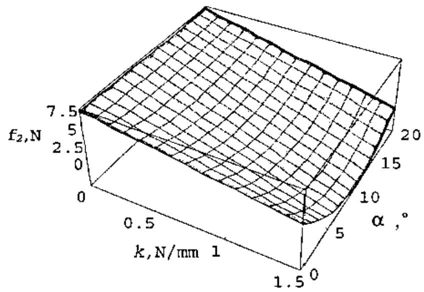
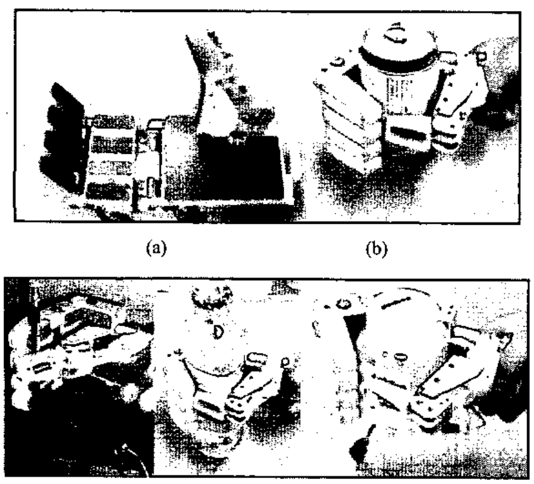


Fig. 12 Relation of f_2, k and α (r_1=35mm, r_2=20mm, f_1=20N)

III. RESULTS

The developed TH-1 Hand is shown in Fig.14a. Its weight is only 0.6 kg. Its maximum working load is 1 kg. Its appearance, size and actions are similar to a human hand. It has 5 humanoid fingers, 4 agile knuckle joints. It needs only three motors which make real-time control of TH-1 Hand very easy. All motors, reducers and their driver circuit boards are housed into the hand.



(a) (b)

(c) (d) (e)

Fig. 14. TH-1 Hand and its grasping experiments

Fig. 14b, c, d, e separately show that TH-1 Hand grasps a cylinder, pinches a pencil, grasps a triangular prism and a cube. Experiments have proved that TH-1 Hand is able to stably grasp many ordinary objects, accords with the original design target totally.

IV. CONCLUSIONS

This paper develops a novel humanoid robot hand: TH-1 Hand, which can be installed in a humanoid robot arm, needs fewer drivers to make real-time control of the hand very easy. All the motors, reducers and their driver circuit boards are embedded into the hand. Its appearance, size and actions are similar to a human hand. It is easy to manufacture and maintain. It is capable of carrying out special actions like extending, making a fist and stably grasping ordinary objects with proper forces.

This paper develops a novel mechanical finger with control of grasping force. The finger makes a robot hand generated freely changeable grasping forces when the hand grasping different objects and the control precision of grasping force is very high. This mechanism is small, light, simple, reliable, and easy to produce. The finger can also be applied in many kinds of transmission styles.

This paper develops a novel under-actuated passive adaptive grasp finger. The finger makes a robot hand have fewer drivers, but more DOFs, and can realize passive adaptive grasp to objects with different shapes and sizes with the requirement of lower control precision. The finger has the advantages of simple, reliable, small, light and easy to produce.

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