Study on Orthogonal and Symmetric Five-fingered Pneumatic Robot Hand

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***Abstract*—To improve the operation and the flexibility of the robot hand, in this paper we presented a new type pneumatic flexible robot hand based on the pneumatic artificial muscles and active flexible bending joints which developed in the previous research. The robot hand is imposed of five three-joint fingers; the middle finger is on the datum axis with the other four fingers orthogonal and symmetrical. The structure of the robot hand forms the dual-thumb oriented grasp model. Furthermore, we solved the large deformation and nonlinear problems of flexible joint perfectly in the posture model of the flexible robot hand, and then the mathematical equations on the four types of typical grasp posture are given respectively. Finally, both the simulation and the experiments were carried out to verify the mathematical model. The results show that the robot hand has good flexibility and compliance that can complete the operation well.**

***Index Terms*—Flexible joints, Five-fingered robot hand, Position and posture, grasp, Pneumatic artificial muscle**

I. INTRODUCTION

With the social development and scientific technology progresses, various types of robot hands are wildly used in industry, extractive industry, national defense, medical and service industry in recent years, and they have become an irreplaceable assistant to human[1,2]. Most robot hands applying advanced and matured technologies mainly utilize motor, hydraulic and pneumatic cylinder to actuate rigid joints, which make them depend entirely on the control technology to changes in movement agilely [3-5]. Both the driving device and joints body are large volume, less flexibility and more provision to the motion, yet this type of joints can be controlled convenient and accurately.

In order to improve the flexibility and compliance of the robot hand, many researchers have developed the PAM (Pneumatic Artificial Muscle) [6-9] to drive the joints, and various dexterous hands. They have deeply studied the structure, kinematics and dynamics on the robot hand and have made a definite progress so far [10, 11]. The flexibility of robot hand is improved a certain degree due to the flexibility of driver. Yet the joints of robot hand are still rigid. To achieve the flexibility, compliance and adjustability similar to humans and animals, the key is to improve the flexibility of joints of robot hand.

In this work we developed a five-fingered hand with three joints each finger based on the bidirectional active flexible bending joints that mimics a human hand, and it has good flexibility and inherent compliance.

II. STRUCTURE AND WORK OF FLEXIBLE ROBOT HAND

Flexibility and universality are two characteristics of robot hand we developed. All joints of robot hand are pneumatic and flexible which improve the flexibility of robot hand; the universality is implemented by the amount and distributing of fingers.

A Structure of Bidirectional Active Flexible Bending Joints

The flexible joint we developed is mainly composed of four elongation artificial muscles and flanges (see Fig.1), with two ends fixed on the flanges. It can axial elongate and bend two-dimensional two-way control in space simultaneously, and it has three degrees of freedom. Exactly, it has one degree of freedom and two degrees of maneuvering. It is only controlling one degree of freedom each moment. Through controlling the air pressure of the four artificial muscles, the joint can bend anti-stretch, abducent and adducent. For example, ensuring the air pressure of muscle① is equal to muscle② and more than muscle③ and muscle④ simultaneously, the joint can bend about Y-axis (see Fig.2). And the degree of bending is determined by the pressure differential controlled by the proportion valve. The bending of joint behaves like the nonlinear beam with large deformation which is

Manuscript received; revised; accepted.
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doi:10.4304/jcp.7.11.2726-2733

characterized by the elongation of axis and the bending angle of the end.

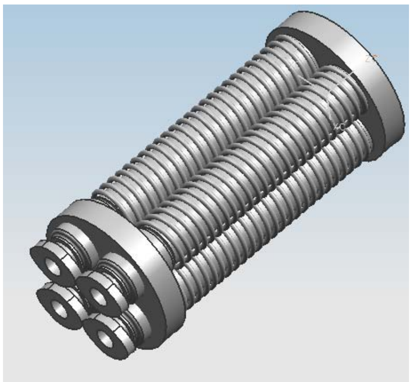


Figure 1. Structure of joint

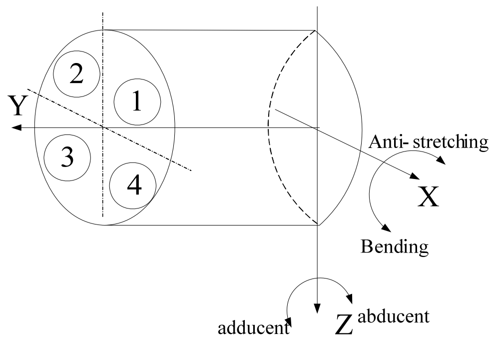


Figure 2. Movement pattern of joint

B. Structural Design on Finger of Robot Hand

The flexible finger is made of three pneumatic flexible joints connected in series, with the two ends of joint fixed on the wedge plate (see Fig.3).

The bending angle of one joint is no more than 35° under working pressure which due to the maximum bending angle of three flexible joints connected in series are 105°.We adopt the wedge plate whose wedge angle is 30° in this paper, thus the bending angle of the finger (θ_0) is 90° under free state, which lead to the bending range about x-axis (θ) to (90°-105°, 90°+105°), about z-axis (γ) to (-105°, 105°), respectively. The good flexibility of the finger creates significant compliance of the robot hand and satisfied the bionic requirements to grasp, pinch, clip, and scratch etc.

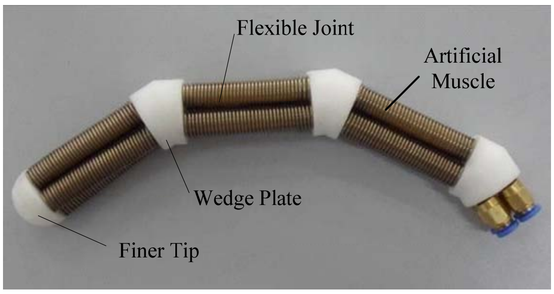


Figure 3. Structure of finger

C. Structural Design of Five-Fingered Flexible Robot Hand

The multi-fingered robot hand is composed of five fingers, and each finger is made of three bidirectional active flexible bending joints in series. The distribution of fingers is design as shown in Fig.4, the other four fingers are orthogonal and symmetrical except the middle finger, and the palm is axial symmetry along the middle finger. This distribution of fingers has good adaptability with the variety of object to grasp and it easy to achieve the geometry- closed and force-closed.

For convenience and computational efficiency, five fingers are just the same to each other. As shown in Fig.5, the robot hand has fifteen flexible joints, and three degrees of freedom for each joint,giving it 45 degrees of freedom under free condition. The geometry characteristic forms the dual-thumb oriented grasp model in which four fingers predominate, or the thumb oriented and the others to cooperate it.

Figure 4. Structure of dual-thumb robot hand

III ANALYSIS ON POSITION AND POSTURE OF ROBOT HAND

To make it clear and facilitate the analysis on the position and posture of robot hand, we define axis intersection coincide with the origin O of palm coordinate system $O_0X_0Y_0Z_0$ (see Fig.5). Let coordinate system $O_{ij}X_{ij}Y_{ij}Z_{ij}$ denote the local coordinate system of joints and fingers, where i(i=1,2,3,4,5) is the symbol of finger, and it denotes the thumb, index finger, middle finger, ring finger and little finger, respectively; and j(j=0,1,2,3,4,5,6) denotes the labels of the flexible joint and wedge as showed in Fig. 6. It depicts in Fig 6 that AB, CD and EF denote the proximal phalange, middle phalange and distal phalange, respectively.

The poses of the finger are calculated by the homogeneous coordinate transformation matrix in which the transformation of coordinates from the end to the other end of the joint varied with the difference of the bending condition of joints, and the others are invariable.

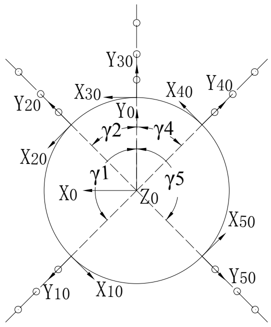


Figure 5. Palm coordinate system

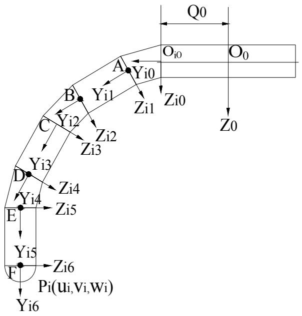


Figure 6. Coordinate of one finger

A Mathematical Model of Bending on Finger

In this paper, we establish the mathematical model on pose of the finger in the act of grasping. The coordinate origin of each flexible joint of robot hand can be represented in their local coordinate system by

$$D = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^T \quad (1)$$

According to the geometry of deformation of joint, as shown in Fig.7, the projection from the center of top cover of the flexible joint onto the bottom cover can be expressed as $(0, a_{ij}, b_{ij})$, and we have the following equations

$$a_{ij} = \frac{l_0 + \Delta l_{ij}}{\theta_{ij}} \sin\theta_{ij} \quad (2)$$

$$b_{ij} = \frac{l_0 + \Delta l_{ij}}{\theta_{ij}} (1 - \cos\theta_{ij}) \quad (3)$$

where l_0 is the active length of the flexible joint, Δl_{ij} is the elongation of the flexible joint and θ_{ij} is the bending angle about the x-axis.

Then, the transformation of coordinates from the end to the other end of the joint can be expressed as

$$ {}_{2}^{1}H_i^{zq} = {}_{4}^{3}H_i^{zq} = {}_{6}^{5}H_i^{zq} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_{ij} & -\sin\theta_{ij} & a_{ij} \\ 0 & \sin\theta_{ij} & \cos\theta_{ij} & b_{ij} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Where ${}_{j}^{j-1}H_i^{zq}$ denotes the transformation matrix from coordinate system *j* to coordinate system *j*-1 within the finger which is numbered *i*, and *j*=2, 4, 6; the superscript *zq* denotes the condition of bending of finger.

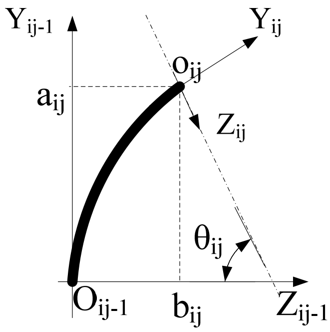


Figure 7. Bendingdeformation of joint

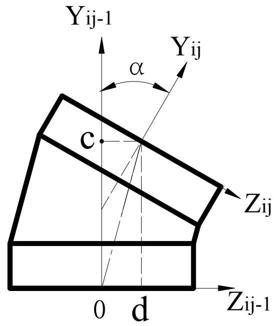


Figure 8. Structure of wedge plate

As shown in Fig.8, when the top center of the wedge plate project onto the undersurface, the point $(0, c, d)$ denotes the spot projection, where c and d is the corresponding Y and Z coordinates values. And they can be expressed as

$$c = t_0 \cos(\alpha / 2) \quad (5)$$

$$d = t_0 \sin(\alpha / 2) \quad (6)$$

where t_0 and α is the distance and angle between the two ends of the wedge plate, respectively.

And the transformation matrix when the center of top end project onto the undersurface of the wedge plate can be expressed as

$$ {}_{1}^{0}H_i = {}_{3}^{2}H_i = {}_{5}^{4}H_i = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & c \\ 0 & \sin\alpha & \cos\alpha & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

According to the geometric relations as shown in Fig.5, the homogeneous transformation matrix from $O_{i0}X_{i0}Y_{i0}Z_{i0}$ to $O_0X_0Y_0Z_0$ can be expressed as

$$ {}^{0}T_i = \begin{bmatrix} \cos\gamma_i & -\sin\gamma_i & 0 & Q_0\sin(-\gamma_i) \\ \sin\gamma_i & \cos\gamma_i & 0 & Q_0\cos(-\gamma_i) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

Where Q_0 is the radius of palm circle, γ_i is rotation angle from the finger coordinate system which is numbered *i* to the palm coordinate system. When adopt the structure of dual-thumb, we have the following equations: $\gamma_1 = -135^\circ$, $\gamma_2 = -45^\circ$, $\gamma_3 = 0$, $\gamma_4 = 45^\circ$, $\gamma_5 = 135^\circ$.

B Homogeneous Transformation of Anti- stretch

According to the geometry of anti- stretch of joint, as shown in Fig.9, the transformation of coordinates from the end to the other end of the joint can be expressed as

$$ {}^1_2H_i^{fs} = {}^3_4H_i^{fs} = {}^5_6H_i^{fs} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(-\theta_{ij}) & -\sin(-\theta_{ij}) & a_{ij} \\ 0 & \sin(-\theta_{ij}) & \cos(-\theta_{ij}) & -b_{ij} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9) $$

Where the superscript *fs* denotes the condition of anti-stretch of finger

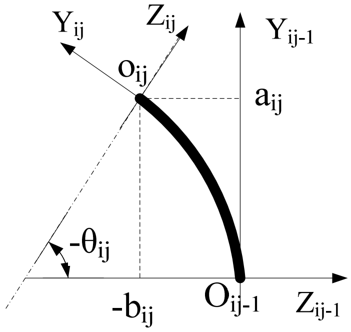


Figure 9. Anti-stretch deformation of joint

C Homogeneous Transformation of Adducent

According to the geometry of adducent of joint, the transformation of coordinates from the end to the other end of the joint can be expressed as

$$ {}^1_2H_i^{ns} = {}^3_4H_i^{ns} = {}^5_6H_i^{ns} = \begin{bmatrix} \cos(-\theta_{ij}) & -\sin(-\theta_{ij}) & 0 & b_{ij} \\ \sin(-\theta_{ij}) & \cos(-\theta_{ij}) & 0 & a_{ij} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10) $$

Where the superscript *ns* denotes the condition of adducent of finger

D Homogeneous Transformation of Abducent

According to the geometry of abducent of joint, the transformation of coordinates from the end to the other end of the joint can be expressed as

$$ {}^1_2H_i^{wz} = {}^3_4H_i^{wz} = {}^5_6H_i^{wz} = \begin{bmatrix} \cos\theta_{ij} & -\sin\theta_{ij} & 0 & -b_{ij} \\ \sin\theta_{ij} & \cos\theta_{ij} & 0 & a_{ij} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11) $$

Where the superscript *wz* denotes the condition of abducent of finger

E Alysis on Coordinates of Feature Points of Finger

According to the finger's local coordinate system, we get the position of six points (*A, B, C, D, E* and *F*) in palm coordinate system through transformation matrix; furthermore, the lines between the points descript the position of the finger (see Fig.6).

The coordinates of point *A* is the origin of coordinate system ($O_{i1}X_{i1}Y_{i1}Z_{i1}$) transform to palm coordinate system ($O_0X_0Y_0Z_0$), that is

$$ \begin{bmatrix} x_{Ai} & y_{Ai} & z_{Ai} & 1 \end{bmatrix}^T = {}^0T_i\,{}^0_1H_i D \quad (12) $$

The coordinates of point B is the origin of coordinate system ($O_{i2}X_{i2}Y_{i2}Z_{12}$) transform to palm coordinate system ($O_0X_0Y_0Z_0$), that is

$$ \begin{bmatrix} x_{Bi} & y_{Bi} & z_{Bi} & 1 \end{bmatrix}^T = {}^0T_i\,{}^0_1H_i\,{}^1_2H_i^m D \quad (13) $$

Where *m* denotes the deformation of joint, and $m = zw, fs, wz, ns$.

Similarly, the coordinates of point *C*, *D*, *E* and *F* can be expressed as follow

$$ \begin{bmatrix} x_{Ci} & y_{Ci} & z_{Ci} & 1 \end{bmatrix}^T = {}^0T_i\,{}^0_1H_i\,{}^1_2H_i^m\,{}^2_3H_i D \quad (14) $$

$$ \begin{bmatrix} x_{Di} & y_{Di} & z_{Di} & 1 \end{bmatrix}^T = {}^0T_i\,{}^0_1H_i\,{}^1_2H_i^m\,{}^2_3H_i\,{}^3_4H_i^m D \quad (15) $$

$$ \begin{bmatrix} x_{Ei} & y_{Ei} & z_{Ei} & 1 \end{bmatrix}^T = {}^0T_i\,{}^0_1H_i\,{}^1_2H_i^m\,{}^2_3H_i\,{}^3_4H_i^m\,{}^4_5H_i D \quad (16) $$

$$ \begin{bmatrix} x_{Fi} & y_{Fi} & z_{Fi} & 1 \end{bmatrix}^T = {}^0T_i\,{}^0_1H_i\,{}^1_2H_i^m\,{}^2_3H_i\,{}^3_4H_i^m\,{}^4_5H_i\,{}^5_6H_i^m D \quad (17) $$

Ⅳ SIMULATIONS ON POSITION AND POSTURE OF FINGER

A Pose Analysis on Bending

In order to simplify verbose process of calculation, all flexible joints of robot hand are parallel controlled when robot hand grasp the object. We make sure the air pressure $P_{ij3} = P_{ij4} = 0$, and then adjust the values of $P_{ij1} = P_{ij2} = P$, simultaneously.

We obtain the coordinates of typical control points (B, D and F) and related points (A, C and E) using Matlab. Fig.10 shows the trajectory and the pose of the finger. According the coordinates of each finger within palm coordinate system, as shown in Fig.11, we get the limits of posture of finger when the air pressure is 0.35*MPa*. It illustrates that the simulation results is consistent with the theoretical model.

Bending grasp can manipulate the sphere, box, triangle object and other arbitrary shape objects effectively using one to five fingers. It is obvious that the bending grasping is the main effective work mode of the robot hand.

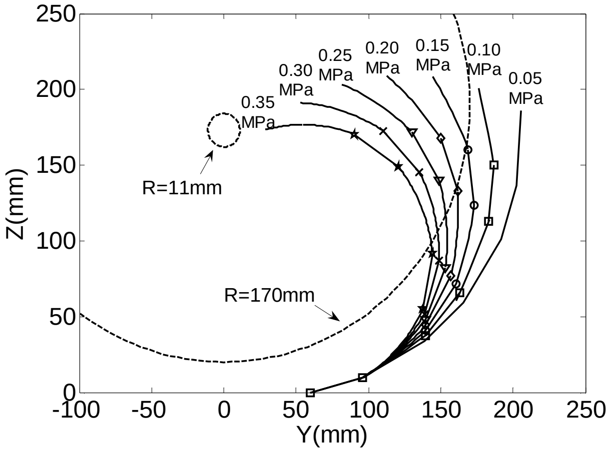


Figure 10. Finger trajectory when bending

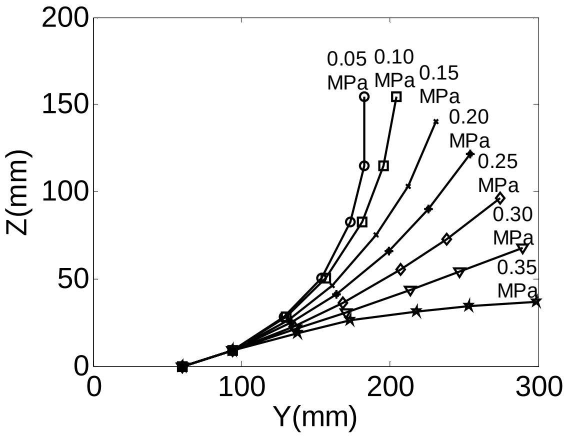


Figure 12. Finger trajectory when anti-stretch

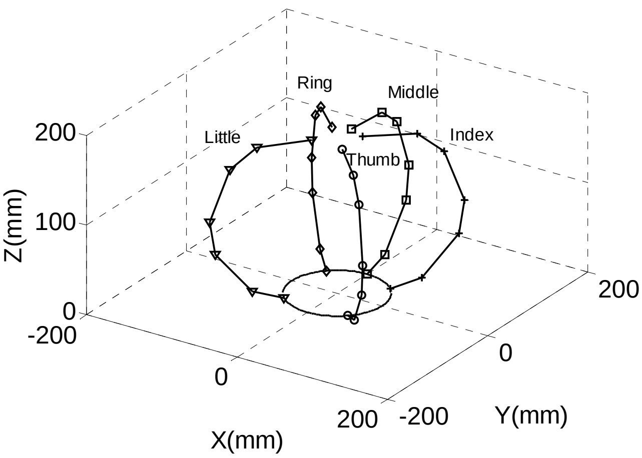


Figure 11. Pose of robot hand when bending grasp

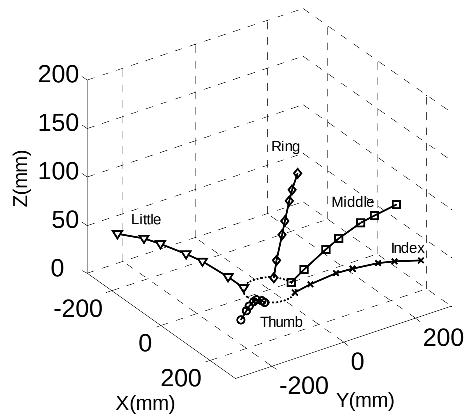


Figure 13. Pose of robot hand when anti-stretch

B Pose Analysis onAnti- stretch

The joints of each finger are supplied air pressure according to the anti-stretch mode. Ensuring the air pressure $P_{ij1} = P_{ij2} = 0$, and then adjust the pressure $P_{ij3} = P_{ij4} = P$. As showed in Fig.12, the fingers of robot hand stretch gradually with the increase of the air pressure. And when the air pressure increases to 0.35*Mpa*, the fingers stretch nearly horizontally. For large dish-shaped object, the anti-stetch of fingers in initial stage of grasp can expand the capture range effectively (see Fig.13).In addition, in conjunction with the bending grasp, the robot hand can flip and fiddle through increasing the anti-stretch speed.

C Pose Analysis on Clamping with Two Fingers

The robot hand can clamp the objects of sheet through the index finger abducing and the middle finger adducting when the other fingers in free condition or bending for avoiding collision. As shown in Fig.14, when the air pressure of these two fingers reaches 0.35*MPa*, the index finger and the middle finger do not only contact but also cross each other greatly. It illustrates that the robot hand have higher capacity to clamp the objects of plate nearly zero-thickness tightly.

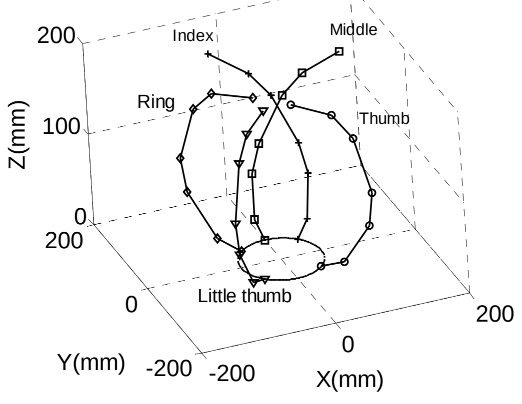


Figure 14. Pose of clamp with index and middle finger

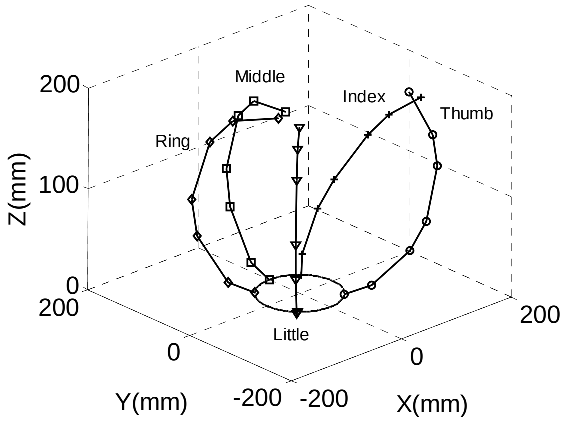


Figure 15. Pose of clamp with thumb and index finger

It depicts in Fig.15 that the thumb and the index finger cross lightly at 0.35*MPa*, when the thumb abducent and the index finger adducent. That is to say, it is difficult for robot hand to clamp the thin plate although these two fingers can contact the object. However, it can clamp the thicker sheet because of the larger span between these two fingers.

D Pose Analysis on Clamping with Four Fingers

It illuminates in Fig.16 the manipulation of clamping with four fingers: the thumb and the ring finger abduce, the index finger and the little finger adduct. It is equivalent to two pairs clamping with two fingers. It is useful for columnar object. Meanwhile, the middle finger can bend to assist clamping or in free condition.

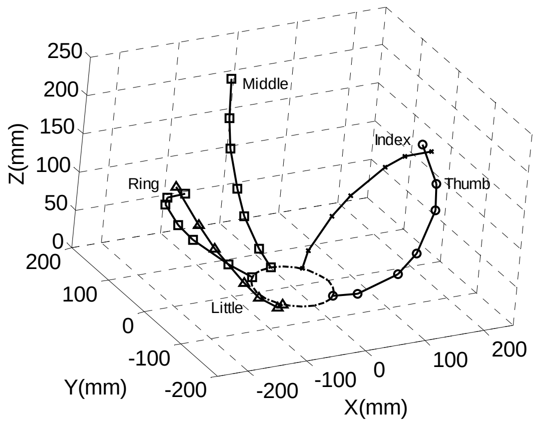


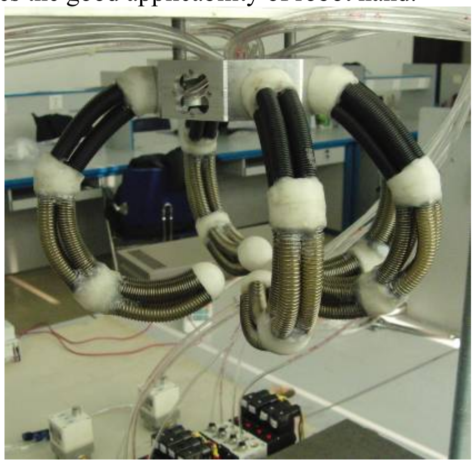
Figure 16. Pose of clamp with two pairs of fingers

V GRASPING EXPERIMENTAL ANALYSIS

Do a series of experiments to verify the function of robot hand and investigate the pose of fingers using the developed robot hand with the electric control system.

A Bending Grasp with Five Fingers

The robot hand is in free condition when the air pressure is zero. With the increase of the air pressure, the five fingers bend gradually to grasp the basketball (see Fig.17a, Fig.17b). It is shown in picture that the pose of fingers coincides with the simulation result. Fig.17c confirms the robot hand grasp the irregular objects. And it proves the good applicability of robot hand.



a) Bending grasp with five fingers

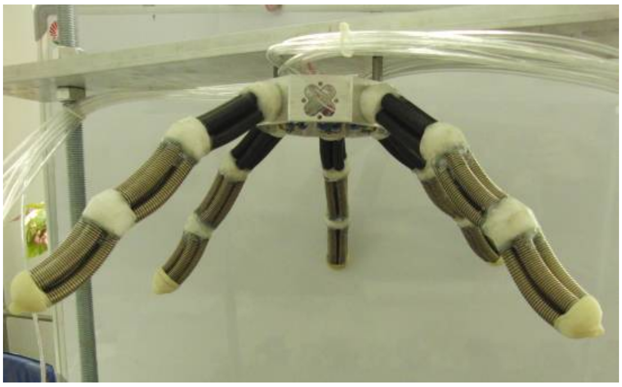
b) Grasp ball with five fingers bending

c) Grasp irregular objects with five fingers bending

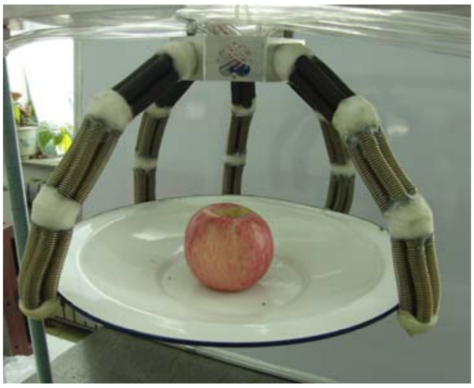
Figure 17. Experiments on bending grasp

B Anti-stretch Grasp with Five Fingers

Fig.18a shows the anti-stretch grasp with five fingers of robot hand when air pressure is 0.3*MPa*. Fig.18b presents the anti-stretch for large dish-shaped object. It illustrates the anti-stretch grasp can expand the work range of robot hand effectively.



a) Anti-stretch grasp with five fingers

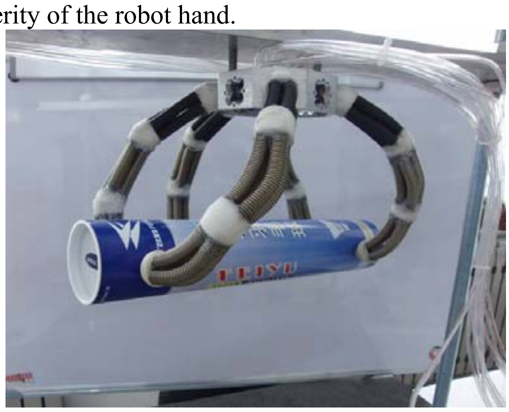


b) Anti-stretch for large dish-shaped object

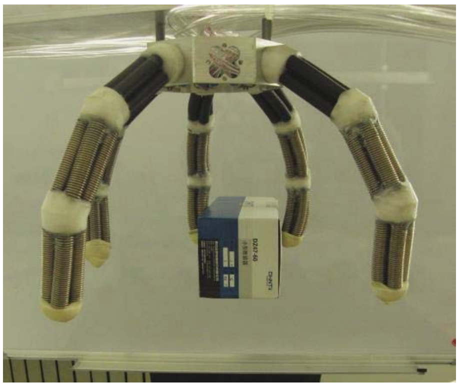
Figure 18. Experiments on anti-stretch grasp

C Clamping Objects

Fig.19 shows the clamping with four fingers and two fingers, respectively. And the experiments show the dexterity of the robot hand.



a) Clamp with two pairs of fingers



b) Clamp with two fingers

Figure 19. Experiments on clamp grasp

The experiments have good agreement with the simulation results, which verify the validity of the theoretical model. Furthermore, the gravity of the fingers is the main reason of error between the experiments and simulation results.

Ⅵ CONCLUSIONS

In this paper we have a deep research on the structure, function and the posture of the five-fingered pneumatic robot hand through the theoretical modeling, simulation and the experiments. And get some conclusions as following:

(1) The robot hand is mainly composed of the flexible bending joints with the five fingers reasonable layout which made the robot hand has good compliance to the object. Each joint of the robot hand can bend, anti-stretch, abducent, adduce and elongate which let the robot hand has good flexibility and easy to soft control.

(2) We studied the posture of the robot hand and introduced the large deformation non-linear variables of flexible joints to the transformation matrix using the parametric translational coordinates, and get the mathematical model of pose on fingers.

(3) The simulation was done to verify the validity of the theoretical model.

(4) We built the test system, and did the grasp experiments on the robot hand. The results show that the robot hand has good flexibility and strong and continuous adaptability, and can perfectly do the actions of grasp, clamp, flip and fiddle etc. The study of this paper provides a new way for the entire flexibility of the robot hand.

ACKNOWLEDGEMENT

Financial support for this research was provided by Office of Education, Jilin Province: Programs of Scientific and Technical Research from the 11th Five-Year Plan & Science and Technology Bureau, Plan for Scientific and Technology Development.

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