Master-Slave Design and Control of Five-Finger Dexterous Hand Based on Tendon-Sheath Transmission

Shixuan Zhang\textsuperscript{1,2,3}, Zhigang Xu\textsuperscript{1,2}, Meng Yin\textsuperscript{1,2,3}, and Wanqi Wang\textsuperscript{4}

\textsuperscript{1}Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China
\textsuperscript{2}Institutes for Robotics and Intelligent Manufacturing, Chinese Academy of Sciences, Shenyang 110169, China
\textsuperscript{3}University of Chinese Academy of sciences, Beijing 100049, China
\textsuperscript{4}The Sixth Research Institute of China Electronics Corporation, Beijing 100049, China

Abstract. In order to make the dexterous hand more lightweight and anthropomorphic, a 19-joint anthropomorphic dexterous hand driven by the servo through the Tendon-Sheath transmission was designed. First, the configuration of the dexterous hand is determined with reference to the joints of the human hand, and the decoupling and driving of the joint motion are realized through the Tendon-Sheath transmission, and the joint mechanism and the driving integration are designed respectively. Then, based on the bending sensor and master-slave mapping algorithm, the grasping master-slave tracking control is realized. Finally, a dexterous hand prototype is built, joint motion experiments and grab control experiments are carried out. It can be seen from the experimental results that the designed dexterous hand has high movement flexibility, and the cooperation of each finger can realize the effective grasping of objects such as water bottles and apples. The experimental results show that it is feasible to apply the Tendon-Sheath transmission to the dexterous hand. Based on the master-slave control, the dexterous hand can grasp various objects.

1 Introduction

The dexterous hand is similar to the human hand in function, and can realize the grasping function similar to the human hand. Since its inception, it has been highly valued by research institutions in various countries[1]. The humanoid multi-finger dexterous hand can be used as an end effector in the industrial field, can also be used as a prosthetic limb for the disabled, and can also be used in the dangerous areas of space, deep sea, nuclear power plants, etc. to achieve precise operation, which has important social application value [2-3].

According to different driving methods, dexterous hands can be divided into motor drive, pneumatic drive, hydraulic drive and functional material drive. The representative of the pneumatic drive is the Shadow hand\textsuperscript{[4-5]}. Its driving part is integrated on the forearm, and the movement of the fingers is more like a human hand. However, the advantages of pneumatic air muscles are lower price and lower environmental requirements. The
disadvantages are poor rigidity and poor dynamic characteristics. Schulz S[6-7] applied hydraulic drives to humanoid robotic hands and developed smart hands that could be used as prostheses. The advantage of hydraulic drive is that the driving torque is large, the transmission efficiency is high, the response is sensitive, overload protection can be achieved, and the stability is good. Disadvantages are large volume, complicated pipelines, high sealing requirements, high manufacturing and maintenance costs, and easy to cause pollution to the environment. Functional material driving refers to the use of shape memory alloys, electroactive polymers and other new materials to drive finger joints. At present, shape memory alloys have been driven by Hitachi hands[8] and Engeberg[9]. Shape memory alloys change the size and length through temperature, the amount of deformation is difficult to control accurately, and the motion accuracy is poor. Its reliability, versatility and cost performance need to be improved.

The Tendon-Sheath transmission[10-12] uses a hollow sleeve to guide the movement path of the flexible cable, which is closer to the actual human movement, which can overcome the shortcomings of the existing flexible cable transmission mechanism and realize the transmission of long-distance movement and movement joints. The structure is simpler and lighter, the space is adaptable, and the design cost is low. The rear of the drive motor can make the multi-joint series system more lightweight and the structure is more compact.

This paper designs a five-finger dexterous hand with reference to human hand joints, proposes a scheme for rearing the motor through lasso transmission, and designs the joint and drive separately. The master-slave grasping is realized based on the bending sensor and master-slave mapping algorithm tracking control. We build a prototype to perform joint motion experiments, and conduct grab control experiments based on the designed master-slave mapping algorithm. The experimental results verify the feasibility of applying the Tendon-Sheath drive to the dexterous hand, and provide a new idea for the design of the dexterous hand.

2 Mechanical design

2.1 Design of five-finger dexterous hand and joint layout

The scheme of the system is shown in Figure 1. The mechanical system is composed of a smart hand and drive integration. The system adopts a bionic design, and the joint arrangement refers to the configuration of the human hand. The dexterous hand is composed of the palm and five fingers. The index finger, middle finger, ring finger and little finger have four degrees of freedom, the thumb has three degrees of freedom, and the dexterous hand has nineteen degrees of freedom.
The finger is installed on the palm, and the bottom of the palm is connected with the driver integration. The joint is separated by a Tendon-Sheath transmission method. The two ends of the lasso are connected to the joint and the drive module respectively. The drive module is installed in the drive integrated box. The lasso is routed in the palm and fingers with a length allowing for movement.

The layout of the dexterous hand joint is shown in Figure 1. The index finger, middle finger, ring finger, and little finger all contain four joints, namely the base joint, the near finger joint, the middle finger joint, and the distal finger joint. The thumb contains three joints, namely the base joint, the near joint and the distal joint. The base joint is the lateral swing joint, and the remaining joints are all flexion joints. The five base joints are driven by a double lasso mechanism. In order to simplify the structure and reduce the number of lasso, the other joints are driven by a single lasso mechanism.

2.2 Tendon-Sheath transmission

The transmission adopts a double lasso transmission mechanism, which is mainly composed of a casing, a flexible cable and a pretension device, as shown in Figure 2. The transmission process of the double lasso is: when the driving wheel rotates clockwise, the flexible cable in the sleeve a will follow the right movement, and the flexible cable in the sleeve b will follow the left movement, thus driving the driven wheel to rotate clockwise; When the driving wheel rotates counterclockwise, the flexible cable in the sleeve a will move to the left, and the flexible cable in the sleeve b will move to the right, thereby driving the driven wheel to rotate counterclockwise. When the system is at rest, the pulling force on the flexible cable in sleeve a can counteract the clockwise torque received by the driven wheel, and the pulling force on the flexible cable in sleeve b can counteract the counterclockwise torque received from the driven wheel.
3 Control strategy

3.1 Gesture feature capture

In order to use the master-slave control method to control the five-finger smart hand, a bending sensor will be installed on the human hand to feedback the finger bending angle, and the mapping relationship between the bending angle and the smart hand will be established, and the master-slave hand control will be realized according to this mapping relationship. The bending sensor is composed of a variable resistance. Different bending angles will change the resistance value of the sensor. The bending angle can be judged according to the change of the resistance value of the sensor.

As shown in Figure 3, the two ends of the sensor are fixed to the fingertip and the finger root, respectively, \( o_b-x_b y_b z_b \) is the coordinate of the sensor finger root, and \( o_f-x_f y_f z_f \) is the coordinate of the sensor finger tip. When the finger is fully extended, as shown in Figure 3(c), the resistance of the bending sensor is the smallest at this time; when the finger is bent the most, as shown in Figure 3(a), the resistance of the bending sensor is the largest at this time; between the sides, as shown in Figure 3(b), the resistance of the bending sensor is at an intermediate value.
In order to conveniently compare the changing rules of different finger bending features, a linear function is used to normalize the original input to the [0, 90°] range. The specific conversion is shown as:

\[ y_i = 90^\circ \times \frac{x_i - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \]  (1)

In the formula, \( x_i \) and \( y_i \) are the values before and after conversion, respectively, \( x_{\text{max}} \) and \( x_{\text{min}} \) are the maximum and minimum values of the collected data, \( i = 1, 2, \cdots, 5 \) respectively correspond to the thumb, index finger, middle finger, ring finger and little finger.

In order to obtain the output value of the sensor more accurately, considering the response time characteristics of the sensor and the experimental error, multiple sets of experiments are used to calibrate the normalized output, the number of calibration groups is \( j \), the maximum is 10, and the average value is obtained after multiple experiments as valid data for the experiment.

\[ x_{\text{min}} = \frac{1}{10} \sum_{j=1}^{10} x^j_{\text{min}}, \quad x_{\text{max}} = \frac{1}{10} \sum_{j=1}^{10} x^j_{\text{max}} \]  (2)

### 3.2 Master-slave mapping algorithm

A single finger can only feedback one signal, but the actual finger control requires three joint angle signals. As shown in Figure 4, the master-slave mapping needs to be introduced to solve the joint angle. Here, the \( j \) joint bending angle of the finger \( i \) is obtained by the weight coefficient:

\[ \theta^j_i = k^j_i \times y_i \]  (3)

\[ \begin{cases} k^j_i = \tilde{k}^j_i, & y_i \leq y'_i \\ k^j_i = \tilde{k}^j_i, & y_i > y'_i \end{cases} \]  (4)

where \( \theta^j_i \) is the \( j \) joint motion angle of the finger \( i \), and \( k^j_i \) is the weight coefficient that converts the normalized value to the joint bending angle, where \( i = 1, 2, \cdots, 5 \) is the finger label, \( j = 1, 2, 3 \) are the joint labels corresponding to the near finger joint, middle finger joint.
and distal finger joint. When the fingers move, the distal and middle finger joints move first, and the near finger joints move last. In order to make the dexterous-hand move in the same law, $y_i'$ is defined as the critical value. When $y_i$ is in different ranges, $k'_i$ selects different values.

After the experiment, select the conversion coefficient $k_i$ matrix of each finger joint to obtain the human hand joint angle $\theta_i$ matrix, as shown in the following:

$$k_i = \begin{bmatrix}
    k_1^1 & k_1^2 & k_1^3 & k_1^4 & k_1^5 & k_1^3 \\
    k_2^1 & k_2^2 & k_2^3 & k_2^4 & k_2^5 & k_2^3 \\
    k_3^1 & k_3^2 & k_3^3 & k_3^4 & k_3^5 & k_3^3 \\
    k_4^1 & k_4^2 & k_4^3 & k_4^4 & k_4^5 & k_4^3 \\
    k_5^1 & k_5^2 & k_5^3 & k_5^4 & k_5^5 & k_5^3 \\
\end{bmatrix}$$

$$\theta_i = \begin{bmatrix}
    \theta_1^1 & \theta_1^2 & \theta_1^3 \\
    \theta_2^1 & \theta_2^2 & \theta_2^3 \\
    \theta_3^1 & \theta_3^2 & \theta_3^3 \\
    \theta_4^1 & \theta_4^2 & \theta_4^3 \\
    \theta_5^1 & \theta_5^2 & \theta_5^3 \\
\end{bmatrix}$$

$k_i^2 = 0$ is the virtual thumb middle finger joint of the dexterous hand.

The inconsistency between the size of the human hand and the robot’s dexterous hand will cause the dexterous hand to have a motion error, resulting in difficulty in mapping the master-slave fingertip motion space. Aiming at the problem of inconsistent master-slave hand size, introduce the ratio of master-slave finger joint:

$$\hat{\theta}_i = m_i \times \theta_i$$

Among them, $m_i$ is the size scale factor.

During the bending process, the value of $y_i$ cannot be expressed as a simple ratio with dynamic changes. Here we use the least square method to set the $y_i$ dependence dynamically.

$$\hat{y}_i = f(\hat{\theta}_i) = a(\hat{\theta}_i)^2 + b\hat{\theta}_i + c$$

The values of $a$, $b$, and $c$ are determined by the minimization function:

$$J = \min \sum_i \sum_j (f(\hat{\theta}_i) - \hat{y}_i)^2$$

Then:
\[ \dot{\theta}_i = m_i \times k_i \times \hat{y}_i \] (10)

4 Prototype and experiment

4.1 Prototype

The dexterous hand prototype test platform constructed in this paper is shown in Figure 5. The dexterous hand structure is made by 3D printing of nylon material, and the drive motor is a LX-16A serial bus servo with a reducer (maximum output torque 19.5kg.cm). The control system of the dexterous hand uses NI-cRIO-9067 as the lower computer. The control program is first written by Labview on the upper computer, and then downloaded to the lower computer running the real-time system through the Can interface for execution. The finger bending signal is measured by the Flex-4.5 bending sensor and input to the NI-9205 module. The joint angle feedback signal is measured by the potentiometer and then input to the NI-9205 module. The motion control signal is output by the NI-9264 module to the motor driver. The resistance of the bending sensor changes from 60kΩ to 110kΩ, and the frequency of real-time feedback and data monitoring is set to 1kHz.

![Figure 5. Experimental prototype of the dexterous hand.](image)

4.2 Crawl control experiment

The bending sensor installed on the five fingers of the human hand is used as an input signal, as shown in Table 1, and the parameters related to gesture recognition are calibrated after many experiments. Through the manual control of the dexterous hand, grab the mineral water bottle and the apple separately for experiment. As shown in Figure 6, Figure 6(a) is the action diagram of the smart hand grabbing the mineral water bottle, and Figure 6(b) is the action diagram of the smart hand grabbing the apple.

![Figure 6. Experiments of grab control.](image)
Table 1. Parameters of gesture recognition.

<table>
<thead>
<tr>
<th>Finger</th>
<th>$x_{max}(v)$</th>
<th>$x_{min}(v)$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thumb</td>
<td>3.89</td>
<td>1.23</td>
<td>1.52</td>
</tr>
<tr>
<td>Index finger</td>
<td>4.83</td>
<td>1.19</td>
<td>1.54</td>
</tr>
<tr>
<td>Middle finger</td>
<td>4.77</td>
<td>1.17</td>
<td>1.49</td>
</tr>
<tr>
<td>Ring finger</td>
<td>4.62</td>
<td>1.20</td>
<td>1.50</td>
</tr>
<tr>
<td>Little finger</td>
<td>4.45</td>
<td>1.18</td>
<td>1.45</td>
</tr>
</tbody>
</table>

The joints of the fingers of the dexterous hand are controlled by the human hand through the master-slave mapping algorithm, and the relevant parameters of the master-slave mapping are calibrated after multiple experiments as shown in Table 2. The experimental correlation curve is shown in Figure 7, (a) is the curve of the posture feedback of each finger of the human hand based on the bending sensor; (b) is the curve of the angle change of the near and far joints of the thumb; (c) is the angle curve of the index finger near finger joint, middle finger joint and distal finger joint, and (d), (e), (f) are the angle curve of the middle finger’s, the ring finger’s, the little finger’s.

Table 2. Master-slave mapping related parameters.

<table>
<thead>
<tr>
<th>Finger</th>
<th>$\tilde{k}_1$</th>
<th>$\tilde{k}_2$</th>
<th>$\tilde{k}_3$</th>
<th>$\hat{k}_1$</th>
<th>$\hat{k}_2$</th>
<th>$\hat{k}_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thumb</td>
<td>0.89</td>
<td>0</td>
<td>1.23</td>
<td>1.17</td>
<td>0</td>
<td>1.25</td>
</tr>
<tr>
<td>Index finger</td>
<td>0.73</td>
<td>1.05</td>
<td>1.20</td>
<td>1.15</td>
<td>1.07</td>
<td>1.21</td>
</tr>
<tr>
<td>Middle finger</td>
<td>0.78</td>
<td>0.98</td>
<td>1.21</td>
<td>1.18</td>
<td>0.99</td>
<td>1.18</td>
</tr>
<tr>
<td>Ring finger</td>
<td>0.63</td>
<td>0.97</td>
<td>1.18</td>
<td>1.13</td>
<td>0.98</td>
<td>1.23</td>
</tr>
<tr>
<td>Little finger</td>
<td>0.81</td>
<td>1.08</td>
<td>1.12</td>
<td>1.10</td>
<td>1.10</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Figure 7. Curves of the grab experiments.
5 Conclusion

The article applies the Tendon-Sheath transmission to the dexterous hand, and proposes a 19-DOF anthropomorphic light dexterous hand behind the motor. The configuration of the dexterous hand is determined with reference to the configuration of the human hand, and the drive module and finger joints are designed. In order to control the dexterous hand to complete the grabbing task, the master-slave mapping algorithm is studied based on the bending sensor, then the master-slave tracking control of the grabbing is realized. The dexterous hand prototype was built and the joint motion experiment was conducted to verify the movement flexibility of the designed dexterous hand. Based on the bending sensor, the grab experiment was conducted to verify the effectiveness of the master-slave mapping control algorithm. The experimental results show that it is feasible to design smart hands based on Tendon-Sheath transmission, and the research content has certain theoretical value and practical significance for the technical development and social application of anthropomorphic multi-joint smart hands.

References