Structure Design and Research of Dextroous Finger based on the SMA Driver

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Abstract. Because of its light weight, high power density, simple structure, continuous and soft movement, no noise in operation, no pollution to the environment and so on, the SMA (shape memory alloy) driver widely is used in dexterous hands. However, due to the requirement of the length of the drive wire, the driver can not be integrated into the palm of the hand. The SMA differential actuator with smaller structure size is designed to integrate the finger driver into the palm of the hand. The kinematic analysis of the single joint of the finger was carried out and the relationship between the driving current and the joint angle was obtained and the simulation analysis was carried out by using Matlab/Simulink. Finally, a driver experimental platform is built to verify the accuracy of the mathematical model of finger joints.

1. Introduction

As the end effector of a robot, dexterous hand has attracted the attention of researchers because of its importance and particularity. The commonly used dexterous hand drives have electromagnetic servo motors, such as the Robonaut [1] hand developed by the NASA and HIT/DLR-II hands developed by HIT and DLR; pneumatic drive, such as the Shadow dexterous hand developed by the UK Shadow Robot company [2]; hydraulic actuators, such as hydraulic actuated dexterous hand developed by Germany [3]. However, because of the low power-weight ratio, the driver must be installed in a position far away from the driving point, and when the motor runs at high speed, it needs reducing gear to reduce speed, which makes the whole system complex. Most of the typical dexterous hands at home and abroad use this kind of driver. These dexterous hands have their own advantages, but there are still shortcomings such as large volume, complex mechanism, difficult control and lack of flexibility. Similarly, in some areas with limited operating space, the driving device based on the principle of traditional motor and hydraulic pressure is difficult to meet the requirements of precision operation. More and more tasks need small size, simple structure and flexible driving device. In recent years, a variety of new functional materials have appeared, which provide a variety of new solutions to reduce the drive volume. The shape memory alloy (SMA) driver is one of them.

SMA driver is a new type of driver, which integrates sensing, control, energy conversion and actuation. By using the unique shape memory effect of SMA (Shape Memory Effect, SME) [4] and a certain deflection device, the dual range reversible actuating element can be formed, and the mechanical and electrical energy conversion can be realized by specific control means. The SMA driver has the advantages of light weight, high power density, simple structure, easy to form a micro drive, continuous soft movement, no noise, no pollution to the environment and so on [5].
2. Structure Design of Dexterous Finger based on the SMA Driver

2.1. Structure Design of Dexterous Finger
As shown in Figure 1, the length of the knuckle of the SMA driven dexterous fingers is $L_2$, $L_3$ and $L_4$ respectively, and there is a distance($L_1$) between the pendulum joint and the pitching joint of the base joint(MP). The size of the dexterous hand is designed according to the anthropomorphic standard. The length of each knuckle is approximately 2:1.35:1. Based on the measurement of human hand, the length of each finger joint is $L_2=45\text{mm}$, $L_3=30\text{mm}$, $L_4=20\text{mm}$, and $L_1=9\text{mm}$. So the total length of the whole finger mechanism is $L=104\text{mm}$.

![Figure 1. Finger appearance](image)

In this paper, the distal interphalangeal joint (DIP) and the proximal interphalangeal joint (PIP) are coupled by 1:1, similar to human fingers. Compared with the four bar linkage, the "∞" type coupling has the advantages of fixed transmission ratio, small friction and small volume.

The wire rope is wound around R3 guide wheel of DIP joint and R4 guide wheel of PIP joint to couple the two joints.

![Figure 2. "∞" type coupling mechanism](image)

The base joints of dexterous fingers have two degrees of freedom. According to whether the motion of two degrees of freedom is coupled, the MP joints with two degrees of freedom can be divided into two forms: independent motion and coupled motion.

Because the SMA driver needs to cool the SMA during the working process, there is a stagnation between the positive and negative motion of the driver. If the coupling motion scheme is adopted, the movement of the base joints will not be coherent enough, and at the same time, the control difficulty of the SMA drive will be increased. Therefore, the decoupling scheme is illustrated (as shown in Figure 3).

![Figure 3. Structure of base joint](image)

2.2. Design of SMA Driver
SMA drives are divided into two types according to their driving displacement: differential driver and bias-type driver. Because the pulling force of the bias-type driver during the reset process is only
related to the spring deformation and is not controlled, the motion of the bias-type SMA driver is not completely controllable. In contrast, the pulling force of the differential SMA driver during the reset process is determined by SMA, so the reset process is completely controllable. To improve the dexterity of dexterous hand, the differential SMA driver is chosen.

In order to integrate five fingers into one palm, the winding mode shown in Figure 5 is used when designing the driver.

![Structure diagram of SMA driver](image)

**Figure 4. Structure diagram of SMA driver**

3. Kinematic analysis of single joint of finger

3.1. The basic governing equation for SMA

The basic governing equation for SMA, in its general form, is:

\[
\dot{\sigma} = E \varepsilon + \Omega \xi + \theta T \quad (2.1)
\]

Where \(\sigma\) is stress, \(\varepsilon\) is Strain, \(\xi\) is Volumetric fraction of martensite in the SMA, \(T\) is Temperature, \(E\) is Young’s modulus, \(\Omega\) is Phase transformation tensor, \(\theta\) is Thermoelastic tensor.

The phase transformation tensor \(\Omega\) and Young’s modulus \(E\) are both a function of the percentage martensite \(\xi\) in the material and are

\[
E(\xi) = E_A + \xi (E_M - E_A) \quad (2.2)
\]

Where \(E_A\) is Austenite Young’s Modulus, \(E_M\) is Martensite Young’s Modulus.

\[
\Omega(\xi) = -\varepsilon_{\ell} E(\xi) \quad (2.3)
\]

Where \(\varepsilon_{\ell}\) is the residual strain, the maximum strain that can be recovered through the phase transformation.

Heating phase, the relationship between temperature \(T\), stress \(\sigma\) and Volumetric fraction of martensite \(\xi\) is

\[
\xi = \frac{\xi_M}{2} \left\{ \cos[a_A(T - A_s) + b_A \sigma] + 1 \right\} \quad (2.4)
\]

cooling phase:

\[
\xi = \frac{1 - \xi_A}{2} \left\{ \cos[a_M(T - M_f) + b_M \sigma] + \frac{1 + \xi_A}{2} \right\} \quad (2.5)
\]

3.2. Thermodynamic model

The SMA heat transfer model is given by the following equation:

\[
m c_p \frac{dT}{dt} = i^2 R - h A (T - T_{amb}) \quad (2.6)
\]

Where \(i\) is current, \(R\) is resistance, \(m\) is mass, \(A\) is cooling surface area, \(T_{amb}\) is ambient temperature, \(h\) is heat convection coefficient

3.3. Mechanical model of single joint of finger

The joint angle position of the dexterous fingers designed in this paper is directly determined by the deformation of the SMA wires. Therefore, the angle displacement of each joint can be controlled by controlling the strain of SMA wire. The relationship between SMA filament length \(L\) and joint rotation angle is as follows:

\[
\Delta L = R \Delta \theta \quad (2.7)
\]

Where \(R\) is Radius of a steel wheel.
\[ \Delta \varepsilon = \frac{R \Delta \theta}{L_0} \] (2.8)

By analyzing the force of finger joint, the relationship between SMA wire stress and strain and finger joint motion parameters can be established. The force analysis of finger joints can be divided into statics and dynamics. This article only analyzes the dynamic model of the finger joints. The finger joints perform the action through the role of SMA wire. One side of the SMA wire (1) is heated and contracted to generate driving force, while the other side SMA wire (2) is stretched, and the finger joint movement is driven. The kinetic model is as follows:

\[ \dot{\theta} = F_1 R - F_2 R - \tau_f \] (2.9)

Where \( F_1 \) is force in tendon1, \( F_2 \) is force in tendon2, \( m \) is mass of the finger, \( l \) is distance of the center of mass with respect to the joint center location, \( \tau_f \) is frictional moment at the joint.

4. Simulation of single joint of finger

In order to simplify the simulation, only the MCP joint of the finger was used for simulation purposes. Combined with the mathematical model defined above, matlab/simulink is used to complete the simulation of finger joints. The parameters in the model can be changed to optimize the joint kinematics model in the simulation process. The simulation model is shown in Figure 5.

![Figure 5. simulation model of single joint of finger](image)

The relevant geometric parameters of the finger are obtained from the established CAD model. In this topic, SMA wire was purchased from the Institute of Metals of the Chinese Academy of Sciences, and some of the parameters were provided by it. The other relevant parameters were borrowed from literature, are shown in Table 1.

In addition, a maximum deformation of 8% to 5% is recommended for SMA wires.

| DESCRIPTION                              | PARAMETER VALUE | COMPANY          |
|------------------------------------------|-----------------|------------------|
| Austenite start temperature              | \( A_s \)       | 40 °C            |
| Austenite finish temperature             | \( A_f \)       | 85 °C            |
| Martensite start temperature             | \( M_s \)       | 45 °C            |
| Martensite finish temperature            | \( M_f \)       | 20 °C            |
| Martensite curve fitting parameter       | \( C_e \)       | 150 MPa          |
| Austenite curve fitting parameter        | \( C_A \)       | 10.3 MPa/°C      |
| Wire diameter                            | \( D \)          | 0.5 mm           |
| Specific heat of wire                    | \( c_p \)       | 460 J/(kg ⋅ °C) |
| Resistance per unit length               | \( R \)          | 4 Ω              |
| Ambient Temperature                      | \( T_0 \)       | 25 °C            |
| Heat convection coefficient              | \( h \)          | 70 W/(m² ⋅ °C)   |
| Initial wire length                      | \( L \)          | 258 mm           |
| Density                                  | \( \rho \)       | 6.5 g/cm³        |
| Martensite curve fitting parameter       | \( C_m \)       | 10.3 MPa/°C      |
| Austenite curve fitting parameter        | \( C_A \)       | 10.3 MPa/°C      |
Different driving currents are input to the model, and the temperature curve of the SMA wire is calculated by Matlab/Simulink. The result is shown in Figure 6. The parameter values used in the calculation are shown in Table 1. The driving current is set at 0.5 A, 1A, 1.5A and 2A respectively. From the figure, it can be seen that when the SMA wire is energized and heated, the SMA rapidly warms up, and then the rate of increase decreases and gradually reaches the maximum temperature value. At this time, the electric heat and heat dissipation of the SMA wire are dynamically balanced.

![Figure 6. Temperature change curve of different current](image)

As shown in Fig. 6, the maximum temperature of SMA wire varies with the input current. When the driving current is set at 0.5 A, 1A, 1.5A and 2A, the final temperature of SMA wire is 36.6℃, 71.6℃, 129.8℃, 211.3℃. When the current is 1.5A and 2A, the maximum temperature of SMA wire exceeds the end temperature of austenite transformation, resulting in complete phase transformation of SMA wire, that is, SMA wire has the largest amount of deformation. From Figure 7, we can see that with the increase of driving current, the rate of temperature rise is also increasing, so the response speed of the SMA driver can be adjusted by adjusting the driving current in the actual application.

In order to avoid the influence of high temperature on the service life of SMA wires, the current is set to fixed value 1.5A and the current in the simulation model is also set to 1.5A. The simulation results are shown in Figure 7.

![Figure 7. Response curve of single joint](image)

When the current is connected, the temperature of the SMA wire increases gradually. When the temperature reaches the starting temperature of the austenite phase transition (55℃), the electrified SMA wire begins to shrink and the joint begins to rotate. When the temperature reaches the end of the austenite phase transition temperature (80℃), the contraction of SMA wire stops, and the bending action is completed and the maximum bending angle is 93.8 degrees, which verifies the feasibility of the driving. In the process, another SMA is equivalent to the offset spring. The reverse process is the opposite. The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.
5. Performance experiment of drive

5.1. Introduction of experimental platform
In order to complete the above test content, the experimental platform shown in FIG. 8 was built. The hardware facilities of the laboratory bench include: SMA differential actuators, fixed clamps, thermocouples, tension sensors, photoelectric displacement sensors, and DC power supplies.

According to equation (2.9), when the driver reaches the maximum output displacement, the finger joint is in a static state ($\theta = 0$), therefore the maximum output displacement of the driver is independent of the moment of inertia of the finger. So the maximum output displacement obtained in this experiment is basically the same as the output displacement of the actual driverFootnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

5.2. Analysis of experimental results
Based on the above simulation analysis, the pre-stretching amount of the SMA wire of the two drivers was set to 4% and the energizing current was 1.5A. One of the SMA wires was heated to the end temperature of the austenite phase transformation before the experiment was started, and then the SMA wire is cooled to room temperature and the position at this time was taken as the starting position. At the beginning of the experiment, a constant current of 1.5 A was connected to another SMA wire and the change of drive stroke and driving force during the electrifying process were observed and recorded. Finally, the output displacement of the driver is converted to the joint angle equivalent, and the contrast diagram between the experiment and the simulation is obtained, as shown in Figure 9.

As can be seen from the figure, the actual maximum output displacement of the driver is basically the same as the simulation result, and the change trend is generally consistent with the simulation model, so the simulation model can closely reflect the actual driving effect of the SMA wire. At the
same time, it proves that the length of the SMA wire can meet the stroke requirements of the driving finger joint.

![Figure 10. The relation curve of current and displacement](image)

In order to explore the possibility of controlling the position of the driver by current, this experiment also measured the output displacement of the driver when the input current is between 0.5~1.5A. The curve of the input current and output displacement is shown in Figure 10.

Experiments show that when the input current exceeds a certain threshold, the driver can act. It can be seen from the diagram that when the driving current is between 0.8 and 1.2A, the output displacement of the driver is approximately linear with the driving current, therefore, the output displacement of the SMA driver can be controlled by controlling the input current. This provides the basis for finger joint position control.

6. Conclusion
In this paper, a modular dexterous finger based on the SMA wire driver is designed according to the size and characteristics of an adult hand. The SMA differential driver is designed to have a small size and integrate the driver of the finger into the palm of the hand. The relationship between the driving current and the joint angle is obtained by the kinematic analysis of the single joint (base joint pitching) of the finger, and the simulation analysis is carried out by using Matlab/Simulink. Finally, the experiment platform of the driver is built. The output displacement curve of the driver when the input current is 1.5A and the maximum output displacement curve corresponding to the different input current are obtained. This proves the correctness of the simulation model to a certain extent.

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