Research on Multi-point Continuous Electromyography Control Algorithm and Its System for Multi-Finger Dexterous Hand

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Abstract. As the application field of robots expands from industry to agriculture, medical rehabilitation and service industries, its working environment becomes dynamic and not good. The end effectors of robots also need to be more flexible to adapt to changing operating objects. Based on the existing research of our group, a multi-finger dexterous hand included two kinds of bending joints is designed which used human hand as the prototype and combined with the characteristics of human hand joint movement. The EMG signal is proposed as the control source to improve the diversity and flexibility of dexterous hand movement. In the link of EMG signal processing algorithm, EMG signal feature value of the independent and complete action is discretized to form a continuous characteristic parameter curve. And multi-point continuous myoelectric control which is used to characterize the action process can be realized. The real-time adjustment of the driving air pressure is realized by the control system. And the system can control the different action forms of multi-finger dexterous hand. Finally, the relative error of proposed control algorithm and its system was verified to be about 3.23% by the joint position control test.

1. Introduction
Since the 1990s, the technology and application of traditional industrial robots have become saturated [1]. With the emergence of bionics and the rapid development of robotics and artificial intelligence technology, the application field of robots has gradually extended from the industrial field to Extended to agriculture, medical rehabilitation, service and entertainment industries, etc. And the operating environment is always dynamic and not good [2]. Therefore, not only the end effector of the robot needs to be more flexible for various variable operating objects, but also more flexible control strategy and higher control precision are necessary for robot control system.

Whether it is an industrial robot or an agricultural robot, the end effector is an important execution component which contacts operating objects directly. The flexibility of its structure and control system is directly related to the overall robot's working effect. At present, the researcher generally adopts the scheme during the robot end effector designing: based on human hands, its function and structure are simulated to design the multi-joint, multi-finger and multi-degree of freedom dexterous hand [3]. In the aspect of robot control system, the traditional control strategy is based on the motor-driven manipulator, which is simple, easy to implement, and high control precision. These advantages make this control strategy widely used in traditional robots. However, the form of the motor-driven rigid structure also determines the shortcomings in terms of motion form and flexibility of traditional robots, which limits the robot to more complicated and precise work in the industrial and agricultural
production.

Aim at the limitations on traditional robots in structural design and control strategies, this paper replaces traditional rigid structure with flexible pneumatic actuator (shorted as: FPA). Based on FPA, a multi-finger dexterous hand prototype which used human hand structure as the prototype and combined with the characteristics of human hand joint movement is designed and produced. At the same time, the ElectroMyoGraph Signal (shorted as: EMG Signal) is introduced into the control strategy of the multi-finger dexterous hand. And the multi-finger dexterous hand is operated by the way of multi-point continuous control. On the basis of ensuring the control precision, the human hand motion is simulated for the movement form increasing of multi-finger dexterous hands in order to expand its application in industrial and agricultural.

2. Structure Design of Multi-finger Dexterous Hand

2.1 Pneumatic Flexible Bending Joint with Single-FPA

Pneumatic flexible actuator FPA [4,5] is proposed by the research group. And the axial deformation of the rubber tube in FPA is restrained by embedded steel wire in the inner wall of the rubber tube. Based on this, the pneumatic flexible bending joint with single FPA was designed. The structure is shown in Figure 1. The working principle of this bending joint is as follows: the compressed air enters the inner cavity through inflatable end of the FPA. And the continuous increase of the inner air pressure causes the expansion of the rubber tube of the FPA. However, the FPA can deform only in the axial direction because of the constraint of the embedded spring. Its specific performance is axial elongation. The FPA elongates in the axial direction, and pushes the rigid structure of the joint to rotate around its axis of rotation. Then the rigid structure will form an angle in order to bending the joint. Conversely, if the inner air pressure is reducing, bending joint will be restored due to the elastic force of the FPA rubber tube. According to the working principle of bending joint, the target angle can be obtained by adjusting the inner pressure value because of the correspondence between bending angle and inner air pressure.

![Flexible pneumatic bending joint with Single-FPA](image)

1 coupling; 2 left end cover; 3 connecting rod; 4 rotating shaft; 5 rubber tube; 6 spring; 7 right end cover; 8 intake connector

**Figure 1.** Flexible pneumatic bending joint with Single-FPA.

Literature [6] established the static model and dynamic model of Flexible pneumatic bending joint with Single-FPA. The static and dynamic characteristics were analyzed. The following static model was proposed.

\[
\Delta L = \frac{(P - P_{\text{atm}})r_0}{2E(t_0 - (P - P_{\text{atm}}))r_0}L_0
\]

where, \( \Delta L \) is the elongation of the FPA rubber tube (mm); \( P \) is inner air pressure of the FPA (MPa); \( P_{\text{atm}} \) is atmospheric pressure (MPa); \( r_0 \) is the average radius of the FPA rubber tube, and the radius of the coil spring (mm); \( E \) is the elastic modulus of the FPA rubber tube (MPa); \( t_0 \) is the initial wall thickness of the FPA rubber tube (mm); \( L_0 \) is initial length of the FPA rubber tube (mm).
2.2 Pneumatic Flexible Bending Joint with Double-FPA

This pneumatic flexible bending joint consists of a T-shaped structure, two rotating structures and two symmetric FPAs, as shown in Figure 2. The two ends of the FPA are respectively fixed on the T-shaped structure and the rotating structure. They are connected by rotating shaft. The rotating structure moves in a circular motion relative to the rotating shaft. The working principle is: when inner cavity of the FPA is filled with compressed air, the FPA elongates. The FPA can only elongate on the rotating end because of the constraint of the fixed end and thereby push the rotating structure to rotate a certain angle around the rotating shaft. Then the left and right rotating structures can form an angle to accomplish the bending action of joint. When the inner pressure of the FPA reduces, the FPA returns to the original state gradually because of the influence of rubber elasticity and spring and thereby pulls the rotating structure back to the original position. Then the bending joint can return to the initial state.

Figure 2. Flexible pneumatic bending joint with Double-FPA.

| 1 T-shaped structure; 2 FPA; 3 rotating structure; 4 rotating shaft; 5 rotating structure; 6 FPA sealed end; 7 FPA intake end |

Literature [7] analyzed the static characteristics of Flexible pneumatic bending joint with Double-FPA. The following static model was proposed:

\[
\Delta P = P - P_{\text{atm}} = \frac{2Et_0}{r_0} \int_0^\pi \frac{H + r_0 \cdot (1 - \cos \phi)}{\pi r_0 (H + r_0)} \cdot \arcsin \left( \frac{a - b \cos \alpha}{\sqrt{a^2 + b^2 - 2ab \cos \alpha}} \right) d\phi
\]

\[
a = \frac{L}{\tan \alpha} + H + r_0 \cdot (1 - \cos \phi)
\]

\[
b = \frac{L}{\sin \alpha} + H + r_0 \cdot (1 - \cos \phi)
\]

(2)

Literature [8] analyzed the dynamic characteristics of Flexible pneumatic bending joint with Double-FPA. The following dynamic model was proposed:

\[
2(M_v - M_a) = J_a \frac{d^2 \alpha}{dt^2} + \mu \frac{d\alpha}{dt} + \frac{K}{dV_c/dt} \frac{dP}{dt}
\]

\[
\frac{dP}{dt} = \frac{KRTQ}{V_c} \frac{dV_c}{dt} - \frac{K}{dV_c/dt} \frac{dV_c}{dt} - \frac{(K - 1)F_a}{dV_c/dt} \frac{dL}{dt}
\]

\[
Q = c_1 c_2 \sqrt{T_c} \frac{AP}{\Phi(P_c/P_a)}
\]

\[
\frac{dV_c}{dt} = \pi (r_c^2 - \frac{T_c}{L_c})^2 \frac{dL_c}{dt}
\]

\[
\frac{dL}{dt} = \frac{(H + r_c + L_c \sin \alpha \cdot \alpha (1 + \cos \alpha))}{\sin^2 \alpha} \frac{d\alpha}{dt}
\]

(3)
2.3 Design of Overall Layout Plan and Structure
In order to assemble and improve structure facilitate easily, modular concept is adopted during the design of the multi-finger dexterous hand. And the basic structure of each finger is identical, but the size is different. Based on the motion characteristics of human knuckle, two kinds of pneumatic flexible bending joint with different structural principles and independently driven are used. Where, pneumatic flexible bending joint with Single-FPA is the bending joint I, and the double FPA pneumatic flexible bending joint with Double-FPA is the bending joint II. Bionics optimization strategy is adopted, meanwhile the layout and proportion of the human hand are referred [9,10] for overall layout scheme and structural parameters of the multi-finger dexterous hand. Considering the space occupied by the joint position sensor, the multi-finger dexterous hand prototype is designed based on the dimension when the human hand is completely opened. And the axis of middle finger is the axis of the whole structure. The main structural parameters are shown in Table 1. The pneumatic flexible actuator FPA is self-made by our research group. And the rest of the multi-finger dexterous hand is produced by rapid prototyping technology which is named laser selective sintering forming technology [11]. And the material is nylon material (PA12). The strength and toughness of nylon is good enough to meet the needs of practical applications of dexterous hands. Photo of Multi-finger dexterous hand (without sensor and air tube) is shown in Figure 3.

| Parameter name                          | Parameter value | Parameter name                      | Parameter value |
|-----------------------------------------|-----------------|-------------------------------------|-----------------|
| Length of middle finger bending joint I | 50              | Length of little finger bending joint I | 40              |
| Length of index finger bending joint I  | 50              | Length of thumb finger bending joint I | 35              |
| Length of ring finger bending joint I   | 50              | Length of thumb finger bending joint II | 30              |

![Table 1. Structural parameters of mechanical hand(mm).](image)

Figure 3. Photo of Multi-finger dexterous hand (without sensor and air tube).

3. Control Strategy of Dexterous Hand Based on sEMG

3.1 Basic Control Principle of Multi-point Continuous
With the in-depth study of the correspondence between EMG signals and body movements, the gradual improvement of myoelectric control theory and control strategies and the continuous improvement of the overall structure of external equipment, the traditional myoelectric control strategy can no longer meet the practical application requirements: not only the recognition ability of
body movement intention and different action modes is required, but also the ability to simulate the habits and patterns of human body movement during the entire movement process is required. Then the omnidirectional simulation of the motion process and the motion mode can be realized.

Based on the traditional myoelectric control theory, the multi-point continuous myoelectric control method for an independent and complete action process is proposed in this paper. And its core idea is simulating continuous variation feature of action with a certain set of characteristic parameters of EMG signal. And based on the existing EMG signal research foundation, it is impossible to establish an accurate mathematical model between the signal characteristics and the action state. So the specific expression of the corresponding relationship cannot be obtained. But, if the number of used to express the same action is sufficiently large, it can be considered that the characteristic parameter curve formed by these features is approximated to a continuous characteristic parameter curve, which can be used to simulate the changing characteristics of the body movement. The key step of the multi-point continuous myoelectric control method is to obtain an approximate characteristic parameter curve by EMG signal analysis and processing algorithm according to the needs of practical applications.

3.2 Control algorithm based on EMG signal

The relationship between the change process of EMG signal and the state of body movement were studied in literature [12] and [13]. The EMG signal generated by body action continuous movement is converted into a continuous characteristic parameter curve. And the consistency between characteristic parameter curve and the action process characterized by EMG signal was verifies by comparison between characteristic parameter curve and original EMG signal. The original EMG signal including 2000 sampling points can be used to reconstruct into a characteristic parameter curve containing only 16 feature points by the characteristic parameter curve extraction algorithm proposed in [12] and [13]. And the curve can be used for joint motion control of multi-finger dexterous hands. The direct drive volume of multi-finger dexterous hand is the output air pressure of electric proportional valve. And there is certain correspondence between the output air pressure of the electric proportional valve and its input voltage. Therefore, the characteristic parameter curve needs to correspond to the input voltage of the electric proportional valve. Then the myoelectric control of multi-finger dexterous hand can be realized.

In summary, Diagram of multi-point continuous myoelectric control algorithm is proposed which is shown in Figure 4.

**Figure 4.** Diagram of multi-point continuous myoelectric control algorithm.

The corresponding relationship between joint bending angle of the multi-finger dexterous hand and the output air pressure of the electric proportional valve is determined by the characteristics of the bending joint which is proposed in literature [6-8]. The mapping relations between output air pressure and input voltage of electrical proportional valve is determined by its characteristics, and independent of external devices or algorithms. So, the logic of multi-point continuous myoelectric control algorithm proposed in this paper is shown in Figure 5.
The specific implementation steps are as follows:

**Step 1:** The characteristic parameter values obtained after the and processing of the EMG signal are normalized. And the maximum bending angle required by the multi-finger dexterous hand is determined according to actual needs. Then the normalized characteristic parameter curve is processed by amplitude corresponding algorithm in order to obtain bending angle curve of joint;

\[ \theta_{\text{joint}} = f \cdot \Delta \theta \]  

Where, \( \theta_{\text{joint}} \) is the joint bending angle of the multi-finger dexterous hand, \( f \) is the normalized characteristic parameter value, \( \Delta \theta \) is the difference between the maximum and the minimum bending angle required by the multi-finger dexterous hand (the minimum bending angle is usually 0 °)

**Step 2:** Based on the relationship between air pressure and angle of the bending joint I \([6]\), the bending angle of the joint I is converted into output air pressure of electric proportional valve:

\[ \Delta P_i = \frac{2Et_1(A\pi - L_i)}{Ar_i}, \quad A = \frac{\theta_i}{2} \left( L_i \sin \theta_i + 2H_i \right) \]  

Where, \( \Delta P_i \) is output air pressure of electric proportional valve corresponding to the curved joint I. \( \theta_i \) is bending angle of joint I. \( t_i \) is initial wall thickness of FPA in joint I. \( L_i \) is Initial length. \( r_i \) is average radius. \( E \) is elastic modulus of rubber tube. \( H_i \) is vertical distance between the centerline of rubber tube and the centerline of joint axis.

**Step 3:** Based on the relationship between the air pressure of joint II and the rotation angle of one-sided \([7]\) (The calculation formula is simplified in order to be consistent with the analysis of joint I. The elongation of FPA center line is took as the average elongation). And because the bending angle \( \theta_2 \) is sum of the rotation angles of respective rotating sides driven by the two FPAs, the relationship between the bending angle of joint II and the output air pressure of electric proportional valve can be got:

\[ \Delta P_2 = \frac{2Et_2(B\theta_2 - 4L_2)}{Br_2\theta_2}, \quad B = \frac{2\sqrt{1 - \cos \theta_2 + \sin(\theta_2)}}{1 - \cos \theta_2} + 2E_z + 2r_z \]  

Where, \( \Delta P_2 \) is output air pressure of electric proportional valve corresponding to bending joint II. \( \theta_2 \) is bending angle of joint II. \( t_i \) is initial wall thickness of FPA in joint II. \( L_2 \) is its Initial length. \( r_i \) is average radius. \( E \) is elastic modulus of rubber tube. \( H_2 \) is vertical distance between the FPA center line and bending part of joint.

**Step 4:** According to the electrical proportional valve manual of ITV0050-3BS, the linear ratio between output air pressure and input voltage is 0.09. Combined with the relationship (5) and (6) between the pressure and angle of joint I and II, the relationship between characteristic value of EMG signal and input voltage can be got:

\[
\begin{align*}
V_{i1} &= \frac{200Et_1(A\pi - L_i)}{9Ar_i}, \quad A = \frac{\theta_i}{2} \left( L_i \sin \theta_i + 2H_i \right) \\
V_{i2} &= \frac{200Et_2(B\theta_2 - 4L_2)}{Br_2\theta_2}, \quad B = \frac{2\sqrt{1 - \cos \theta_2 + \sin(\theta_2)}}{1 - \cos \theta_2} + 2E_z + 2r_z
\end{align*}
\]

Where, \( V_{i1} \) and \( V_{i2} \) are input voltages of driving valve of joint I and the joint II respectively.

4. Data Analysis of Multi-Point Electromyography Control Experiment
4.1 Experimental Platform Construction
The pneumatic experimental platform of multi-point continuous myoelectric control system proposed in this paper mainly includes industrial computer, motion control board, and necessary pneumatic components such as air compressor, electric proportional valve and filter pressure reducing valve. The control system based on the above pneumatic experimental platform mainly includes functional modules such as data acquisition and joint control.

The data acquisition module consists of the Trigno Wireless System with its EMGworks software (shown in Figure 6) produced by DELSYS, USA, and 5DT knuckle data collection gloves (shown in Figure 7). The above system can complete collecting task of EMG signal and bending angle of human joint respectively.

4.2 Acquisition Experiment of sEMG signal
Considering the advantages of atraumatic acquisition of sEMG signals and the similarity of action classification between sEMG signals and iEMG signals, the sEMG signal was chosen as the control source for multi-point myoelectric control. In addition to the sEMG signal, it is necessary to acquire bending angle of finger joint simultaneously for comparing the processing result of sEMG signal with bending angle of finger joint to verify the processing effect of sEMG signal. The control effect of the multi-point myoelectric control scheme proposed in this paper and its practical feasibility can be proved by comparing results of multi-finger dexterous hand control experiment with bending angle of
finger joint

According to the experimental platform built in Section 4.1, sEMG signal and joint movement signal must be acquired simultaneously because of the correspondence between them. Therefore, start time of acquisition experiment is controlled by synchronous flip-flop. And the possible delay time between the two acquisition systems is minimized in order to eliminate signal disturbances or control errors caused by out-of-synchronization. The sampling time of each set of experiment is 100s. And finger moves continuously according to “bending-recovery-bending”. The time of each “bending-recovery” is about 5s. There are sEMG signal for 20 times movement in each set of data. The acquisition experiment is shown in Figure 9, and some of the collected data is shown in Figure 10.

![Figure 9. Photo of acquisition experiment.](image)

![Figure 10. Result of acquisition experiment.](image)

4.3 Experiment and Analysis of Joint Bending Angle Control Experiment

The bending joint parameters used in the experiment are shown in Table 2. And the FPA positional parameters of joint II are different on different fingers (thumb is 12 mm, small finger is 10 mm, and the rest three fingers are 15 mm).

| Parameter              | Bending joint I | Bending joint II |
|------------------------|-----------------|------------------|
| Initial wall thickness t/mm | 1.0             | 1.0              |
| Initial length L/mm     | 15.0            | 15.0             |
| Average radius r/mm     | 4.0             | 4.0              |
| Positional parameter H/mm | 15              | 12/15/10         |
| Elastic modulus E/MPa    | 2.0             | 2.0              |
The experimental steps are as follows: after the control signal curve of multi-finger dexterous hand was got, the corresponding FPA lumen was inflatable by electric proportional valve controlled by the joint proportional control system. In order to eliminate the influence of the viscosity of rubber on bending angle of joint, it would be stabilized for 1~2s after each pressurization. Then the actual bending angle of joint is recorded. During the experiment, the sample that failed to be identified was excluded which means that the control accuracy of control system was discussed based on the successful recognition of the movement finger. Because the control method of the five fingers of multi-finger dexterous hand is exactly the same, the single-finger is taken as an example to analyze the control precision of multi-point continuous myoelectric control system.

After obtaining the characteristic parameter curve of original signal, the bending process control precision experiment is carried out for the 16 feature points and the angle change characteristic of movement process characterized by the above feature points. The results are shown in Table 3.

**Table 3. Comparison of bending angle.**

| Feature Parameters | Target angle (°) | Actual angle (°) | Deviation angle (°) | Relative error |
|--------------------|------------------|------------------|--------------------|---------------|
| 1                  | 4.0              | 3.9              | 0.1                | 2.50%         |
| 2                  | 5.5              | 5.3              | 0.2                | 3.64%         |
| 3                  | 9.4              | 9.2              | 0.2                | 2.13%         |
| 4                  | 19.6             | 19.1             | 0.5                | 2.55%         |
| 5                  | 51.7             | 49.9             | 1.8                | 3.48%         |
| 6                  | 72.6             | 70.1             | 2.5                | 3.44%         |
| 7                  | 74.5             | 72.8             | 1.7                | 2.88%         |
| 8                  | 80.1             | 76.8             | 3.3                | 4.12%         |
| 9                  | 59.1             | 58.0             | 1.1                | 1.86%         |
| 10                 | 41.1             | 40.3             | 0.8                | 1.95%         |
| 11                 | 29.9             | 29.0             | 0.9                | 3.01%         |
| 12                 | 15.8             | 15.3             | 0.5                | 3.16%         |
| 13                 | 9.2              | 9.1              | 0.1                | 1.09%         |
| 14                 | 2.9              | 2.7              | 0.2                | 6.90%         |
| 15                 | 6.0              | 5.8              | 0.2                | 3.33%         |
| 16                 | 6.4              | 6.0              | 0.4                | 6.25%         |
| **average value**  |                  |                  |                    | **3.23%**     |

According to the data in Table 3, there is a certain error between the actual bending angle of each feature point and its target angle. The joint control error is between 2.13% and 4.12% during rising phase of bending angle (feature points 1-8). During falling phase (feature points 9-14), the relative error of feature point is between 1.09% and 3.16% except point 14. The relative error of feature point 14 is 6.9%. Relative to the rising phase, the relative error of falling phase has dropped by about 1%. The relative errors are 3.33% and 6.25% during end phase (feature points 15 and 16). So, the average relative error of control system is approximately 3.23%. Comparison of actual bending angle and target angle is shown in Figure 11. Changing trend of relative error is shown in Figure 12.

Overall, two large errors (6.9% and 6.25%) appear at feature points 14 and feature points 16, both of which appear in the posterior segment of joint bending movement. The reason may be as follows: when inner cavity pressure of FPA rises, its pressure will greater than the resilience of rubber tube. Then rubber tube elongates and pushes joint to bend. When inner cavity pressure of FPA decreases, its pressure will lower than the resilience of rubber tube. So rubber tube gradually recovers its original length and pulls the joint back to original state. During posterior segment of joint bending movement, inner cavity air pressure of FPA has dropped to a lower value, and the increase of error between bending angle and target angle may be caused by the sudden increase of rubber tube rebound speed. In addition, during deflation phase of FPA, increase of error can also be caused by fluctuation in the air
pressure drop rate and some other reasons. If two large errors are excluded, the average relative error of control system is approximately 2.75%.

![Figure 11. Comparison of actual bending angle and target angle.](image1)

![Figure 12. Changing trend of relative error.](image2)

5. Conclusion

(1) Based on the joint behavior and size structure of human finger joint, the multi-finger dexterous hand is designed as the robot end effector by using the pneumatic flexible actuator FPA as driving core and combining two different structures of bending joints.

(2) EMG signal was introduced into the control strategy of multi-finger dexterous hand. And the moving process can be characterized by approximate continuous characteristic parameter curve composed of multiple feature points. At last, multi-point continuous electromyography control algorithm is proposed to make the hand achieve different moving modes of robot.

(3) Based on the multi-point continuous myoelectric control strategy, multi-finger dexterous hand control system was designed. The control precision of multi-finger dexterous hand control system was tested through joint position control experiment (relative error is about 3.23%). And the feasibility and control effect of the proposed multi-point continuous myoelectric control method are verified.

Conflict of interest
The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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