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ANGLE MEASUREMENT AND CALIBRATION OF FORCE FEEDBACK DATAGLOVE

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ABSTRACT

With the development of virtual reality technology, portable force feedback dataglove plays an important role in virtual assembly and telepresence system. Angle measurement is a basic function of force feedback dataglove, in which the measurement accuracy and calibration are often considered as unsolved problems in previous research. For solving these problems, some work is conducted with an exoskeleton force feedback dataglove using pneumatic artificial muscles as actuators. First, a measurement model of the finger flexion angle based on the theory of four-bar-linkage motion stabilization is built. The effect of structure parameter of linkage on the angle measurement and force feedback is analyzed, which has provided a help for the choice of linkage parameters and improved the accuracy of measuring angle. Then a new calibration method, which is called the “four-posture calibration” based on standard block and genetic algorithm, is proposed. Taking index finger as an example, the process of calibration is introduced in detail. Experiment has shown that with the new calibration method more accurate results can be obtained than that in previous work.

KEY WORDS

Virtual reality, Force feedback, Dataglove, Calibration

INTRODUCTION

Virtual reality can be defined as the user’s real-time multimodal interaction with a computer-generated world, which provides a real-time immersive environment that integrated several new communication modalities, such as stereo graphics, three-dimensional sound, force or tactile feedback and even taste and smell, by means of hardware such as head mounted display, stereoglass, dataglove, etc. By providing these sensorial interactions, virtual reality makes the user feel immersed in the simulation or application of the virtual environment. Current applications of virtual reality include virtual assembly, teleoperations and robotic control, etc.

In recent years, haptic interface, especially the portal force feedback dataglove[1~4] has been attracting great attention. Dataglove, measuring directly or indirectly joint angles of human hand and driving a virtual hand, provides a real-time interaction between user and virtual environment in a natural manner. The quality of interaction is much dependent on the accuracy of angle measurement. However, human hands are different in sizes and shape and the glove wearing positions are often changed more or less with different persons or at different time. This will cause measurement errors. In order to decrease the measurement errors caused by the hand sizes and wearing positions, dataglove must be calibrated before use. The structure of dataglove and the calibration results have much affection on the accuracy of measurement.

For solving problems above-mentioned, some research work is conducted with an exoskeleton force feedback dataglove using pneumatic artificial muscles as actuators. The research work involves designing the whole structure of a dataglove, building a measurement model of the finger flexion angle, suggesting a new calibration method named the "four-posture calibration" and making necessary experiments.

FORCE FEEDBACK DATAGLOVE

The force feedback dataglove shown in Fig.1 can be used to measure the flexion angles of the thumb, index and middle fingers, and provide force feedback with every joint. The work principle of single joint is shown in Fig.2.

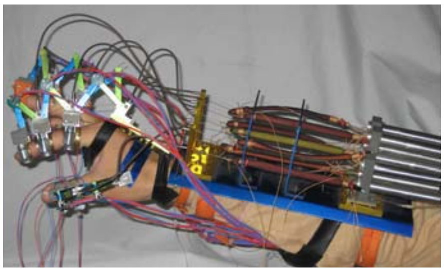


Figure 1 Force feedback dataglove

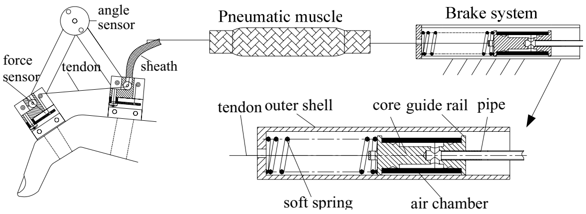


Figure 2 Work principle of single joint

The process can be described as follows. When a hand moves naturally, the angles of links are measured by the angle sensor and the flexion angles of joint are calculated according to the trigonometry of the links. The brake air chambers in deflation condition are not in contact with the outer pipe and only the smooth air chamber slider is in contact with the outer pipe. Therefore the friction is less. A rope drives pneumatic muscle to move with brake air chamber so as to compress the spring. When the hand moves from flexion to extension, the compressed spring makes the muscles and brake air chamber go to the original position. When virtual hand grasps the object in the virtual environment, the inflated air chamber is braked when contacting the outer pipe. Then, the pneumatic muscle is inflated according to the forces calculated from the virtual environment. The user thus feels the force feedback sensation. The force sensor could measure the value of force and provide the feedback control.

The measurement mechanism and force feedback of single joint are shown in Fig.3. The planar four-bar mechanism is composed of one active joint O_1 and three passive joints. The angle relation between linkages is unique, i.e., if one angle is known, the other angles can be solved according to the trigonometry. The four-bar mechanism consisting of finger phalanx and linkages is equal to the four-bar O_1ABC. The angle α between the linkage AB and BC is measured by a non-contact magnetoresistance sensor. The relation between the joint flexion angle θ and α is indicated in Eq. (1) according to the law of cosines.

$$\theta = \beta_1 + \beta_2 + \beta_3 - 180° \tag{1}$$

Where

$$\beta_2 = \arcsin(h_1 / \sqrt{h_1^2 + h_2^2}) \tag{2}$$

$$\beta_3 = \arcsin(h_3 / \sqrt{h_3^2 + h_4^2}) \tag{3}$$

$$\beta_1 = \arccos(\frac{h_1^2 + h_2^2 + h_3^2 + h_4^2 - (2l_1 \sin(\alpha/2))^2}{2\sqrt{h_1^2 + h_2^2}\sqrt{h_3^2 + h_4^2}}) \tag{4}$$

Where β_2 and β_3 are invariable and determined after the dataglove wearing, h_i (i = 1, 2, 3, 4) are the calibrating parameters.

The output force of pneumatic muscle exerts on the finger through the tendon-sheath system. The torque at finger joint is:

$$\tau_m = F_m \sqrt{h_1^2 + h_2^2}\sqrt{h_3^2 + h_4^2} \sin\beta_1 /(2l_1 \sin\frac{\alpha}{2}) \tag{5}$$

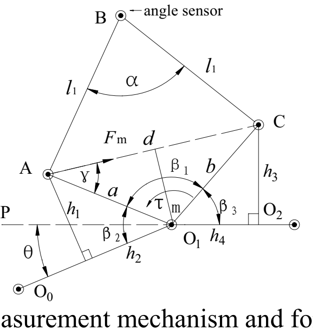


Figure 3 Measurement mechanism and force feedback of single joint

ANALYSIS OF STRUCTURE PARAMETER

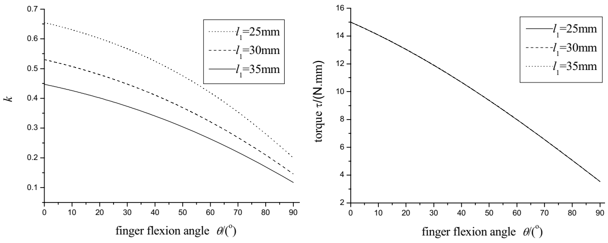
From Eq. (1), (5), it can be seen that the measurement of flexion angle and torque are related to the link length. The angle θ is calculated by the angle α according to the trigonometry. The angle range of finger flexion is definite. At the finger flexion range, the larger the variation of link angle is, the higher the measurement accuracy of α . Eq. (1) can be expressed as the following after derivation and simplification:

$$k = \left|\frac{d\alpha}{d\theta}\right| = \left|\frac{ab(\sin(\theta - \beta_2 - \beta_3))}{l_1^2 \sin\alpha}\right| \tag{6}$$

The coefficient k denotes the ration of θ to α in unit time. The bigger the coefficient k is, the larger the variation of α corresponding to the unit variation of θ . The force feedback of dataglove can be realized if the torque at the finger joint caused by contraction force of muscle is equal to the drive torque. When the output force of artificial muscle is definite, the longer the arm of force at the joint is, the bigger the torque and the heavier the grasping object. The effect of structure parameter can be analyzed using the torque at the joint caused by the unit force of muscle.

The structure parameters of four-bar mechanism include l_1, h_1, h_2, h_3, h_4 shown in Fig.3. Taking PIP joint of index finger as an example, the effect of linkage parameter on the coefficient k and the torque of unit contraction force is analyzed as follows.

The value of h_1, h_2, h_3, h_4 is 15,10,15,10mm respectively, and the value of l_1 is 25,30,35mm respectively. The coefficient k shown in Fig.4a) is decreased with the increase of l_1 . The torque is shown in Fig.4b). The variation of l_1 has no effect on the torque. In view of angle measurement, the length l_1 of link should be as small as possible.

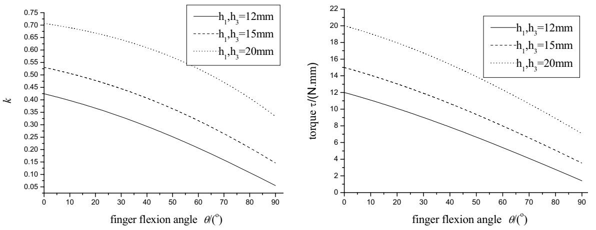


a) Coefficient k b) Torque

Figure 4 Effect of l_1

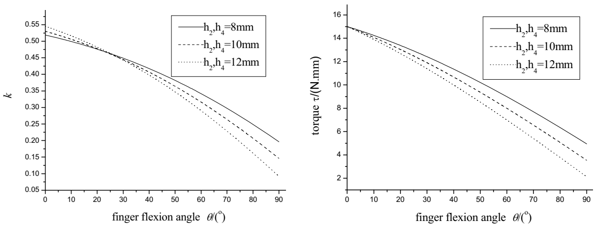
The value of h_2, h_4, l_1 is 10, 10, 30mm respectively, and the values of h_1, h_3 are 12, 15, 20mm respectively. The coefficient k shown in Fig.5a) is increased with the increase of h_1, h_3 . The torque is shown in Fig.5b). The torque is increased with the increase of h_1, h_3 . From the analysis above, the length h_1, h_3 of link should be as big as possible.

The value of h_1, h_3, l_1 is 15, 15, 30mm respectively, and the values of h_2, h_4 are 8, 10, 12mm respectively. The coefficient k shown in Fig.6a) is increased with as the increase of h_2, h_4 . The torque is shown in Fig.6b). The torque is decreased with the increase of h_2, h_4 . From the analysis above, the length h_2, h_4 of link should be as small as possible, but the variation of h_2, h_4 has less effect on the coefficient k and torque.



a) Coefficient k b) Torque

Figure 5 Effect of h_1, h_3



a) Coefficient k b) Torque

Figure 6 Effect of h_2, h_4

From the analysis above, it can be seen that the length l_1 only has effect on the angle measurement and its value should be as small as possible. However the value of h_1, h_3 should be as big as possible. In view of decreasing the whole weight, the values of every link parameter should be as small as possible. In the meantime, every parameter should meet the constraint condition as follows:

1. When the finger flexion angle is 0°, the sum of l_1 should be greater than the sum of h_2 and h_4 , that is:

$$2l_1 > h_2 + h_4 \tag{7}$$

2. When the finger flexion angle is 90°, the following condition should be met:

$$2l_1 > \sqrt{(h_1 + h_4)^2 + (h_2 + h_3)^2} \tag{8}$$

3. When the finger flexion angle is 90°, the distance from O_1 to AC should be greater than 0. That is:

$$\sqrt{h_1^{\ 2} + h_2^{\ 2}} + \sqrt{h_3^{\ 2} + h_4^{\ 2}} > \sqrt{(h_1 + h_4)^2 + (h_2 + h_3)^2} \tag{9}$$

And

$$h_1 > h_2 \quad \text{or} \quad h_3 > h_4 \tag{10}$$

Because the diameter of finger and the length of finger phalange are different and their values are not easy to measure accurately, the values of structure parameter

h_1, h_2, h_3, h_4 are only approximately estimated and determined through calibration after wearing the dataglove. The values l_1 at DIP, PIP, MP joint of index and middle finger are 25, 30 and 35mm respectively. The values l_1 at DIP, PIP joint of thumb finger are 25, 35mm respectively. The distance from point A or C to the surface of finger is 17mm.

CALIBRATION OF DATAGLOVE

Calibration method

Calibration is the initialization of angle measurement, which is indispensable before using the dataglove. The lengths of the linkage AB and BC are known. The mapping relation between θ and α can be calculated as long as the values of h_1, h_2, h_3, h_4 are known. The hand size of a person varies and therefore the relative position of the glove with respect to the hand varies with each wearing. The size and geometry of a hand and the relative position of the glove with respect to the hand together determine the values of h_1, h_2, h_3, h_4. Dataglove should be calibrated to obtain the real values of h_1, h_2, h_3, h_4 before use.

For the exoskeleton dataglove, the two-posture calibration method[3,5] is adopted in the previous research which supposed that the value of h_2 is equal to the value of h_4 or that the values of h_1, h_3 are known. But it is difficult to ensure the complete equality of the value of h_2 and h_4 and measure the length of h_1, h_3 accurately. This causes a bigger calibration error and then affects the measurement accuracy of finger flexion angle.

In order to decrease the calibration error, the dataglove is calibrated using the four postures of hand, which is constrained by the standard block in Fig.7 with four known angles (0°,30°,60°,90°). Then set the finger joint to the known positions respectively, relate the sensor values to those known positions and get four group angles (θ, α). Thus the parameters h_1, h_2, h_3, h_4 are calibrated by the above four group angles.

Eq. (1) can be expressed as the following equation group including the above four group angles. For *i* = 1, 2, 3 and 4

$$h_1^2 + h_2^2 + h_3^2 + h_4^2 + 2\cos\theta_i(h_2h_4 - h_1h_3) + 2\sin\theta_i(h_1h_4 + h_2h_3) = (2l_1\sin(\alpha_i/2))^2 \quad (11)$$

The solution of the nonlinear equation group (11) can be converted into an optimization problem and solved by the genetic algorithms. Simulation and experiment results demonstrate that more accurate calibration parameters and smaller calibration errors [6] can be obtained by the calibration method based on the genetic algorithms.

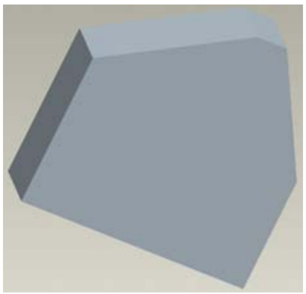


Figure 7 Standard block

Calibration process

Because there is the same structure with the index and middle finger, in this paper it is reasonable to take index and thumb finger as an example for introducing the calibration process and results. Moreover only the calibration of PIP joint of index finger is introduced in detail since the calibration process for every joint is the same. In order to clearly illustrate the calibration process, in Fig.8 only one finger is demonstrated wearing the exoskeleton dataglove. The calibration process of wearing the whole dataglove is identical.

When wearing the dataglove, firstly, the index finger should stretch and put on the side of the standard block shown in Fig.8a). Write down the angle α corresponding to the joint flexion angle θ when it equals to 0 degree. Then bend the joint to the other angle of standard block in turn and write down the angle α respectively shown in Fig.8b), c), d). In this case for Fig.8, the four group angles(θ, α)are (0°,34.43°),(30°,58.34°),(60°, 81.04°), (90°,100.01°).

After obtaining the above four group angles, the next step is to measure the values of every parameter with ruler approximately. The upper and lower limits of parameters are determined according to the measuring values, which are as follows:

$$20 < h_1 < 30; 5 < h_2 < 12; 20 < h_3 < 30; 7 < h_4 < 15 \quad (12)$$

Besides the Eq. (7) ~ (10), the constraint conditions should also include the following conditions according to the wearing position.

$$h_1 < h_3 \,\&\, h_2 < h_4 \quad (13)$$

Solved by the genetic algorithms, the calibration results of PIP joint are shown in Table 1. E_{max} is the maximum error between the finger flexion angle calculated through calibration results and the angle of standard block.

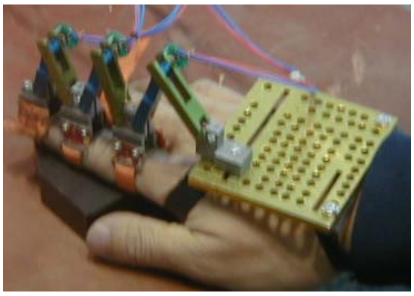
The four group angles(θ, α) of MP joint for index finger are (0°, 60.08°), (30°, 85.41°), (60°, 109.3°), (90°, 128.4°) respectively. Because the value h_3 of PIP joint has been obtained by calculation, the upper and lower limit of h_1 for MP joint can be reduced. The upper and lower limit of other parameter is determined according to the values measured using ruler. They are as follows:

$$24.99 < h_1 < 26; 20 < h_2 < 25; 25 < h_3 < 30; 10 < h_4 < 16 \quad (14)$$

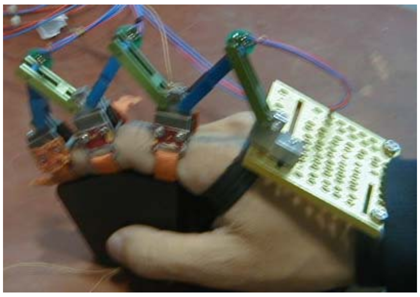
The constraint conditions should include the following conditions according to the wearing position.

$$h_1 < h_3 \,\&\, h_4 < h_2 \quad (15)$$

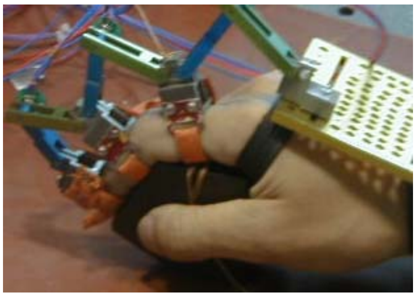
The calibration parameters of MP joint are shown in Table 1.



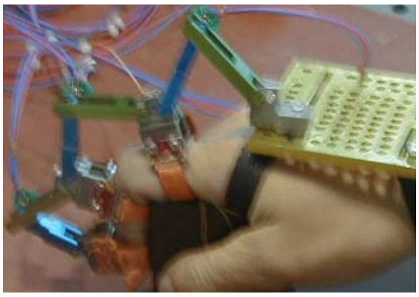
a) 0°



b) 30°



c) 60°



d) 90°

Figure 8 Calibration of PIP joint for index finger

The range of flexion angle for DIP joint (0~70°) is smaller than that for PIP and MP joint and unable to bend to 90°. The angles of DIP joint are not accurate when the finger bends to the standard block. In the research of Lee [7], it is demonstrated that the relation of flexion angle between PIP and DIP joint is described in following formula:

$$\theta_{DIP} = 0.46 \times \theta_{PIP} + 0.083 \times \theta_{PIP}^2 \quad (16)$$

The flexion angle θ of DIP joint can be calculated by the flexion angle of PIP joint according to Eq. (16) and the corresponding link angles α are written down. The upper and lower limit of h_3 for DIP joint can be determined according to that of h_1 for PIP joint. The constraint conditions should include the condition $h_1 < h_3$. The calibration parameters of DIP joint are shown in Table 1.

After finishing the calibration, the length of MP and PIP phalange can be obtained. The distance between the two axes of base is 10mm. The length of MP Phalange, 42.96mm, is the sum of h_4 for PIP joint, h_2 for MP joint and the base length. The length of PIP Phalange, 24.2mm, is the sum of h_4 for DIP joint, h_2 for PIP joint and the base length. The variation of the ratio of every phalange's length to the metacarpal's length is only 1-2%. The length of DIP phalange, 16.72mm, can be calculated according to the length of MP and PIP phalange and the ratio [8]. The accurate value of every phalange is obtained through calibration, so the driving torque can be calculated by the flexion angle and the values of each phalange [9].

Table 1 Calibration results

	h_1	h_2	h_3	h_4	E_{max}(°)
DIP joint of index finger	20.0002	7.1250	22.2694	7.1270	0.6
PIP joint of index finger	22.4364	7.0564	24.9915	10.5156	0.3
MP joint of index finger	24.9985	22.4404	28.6205	11.9180	1

The calibration process of DIP and PIP joint for thumb finger is almost the same to that of index finger. The range of flexion angle for DIP and PIP is 0~75 or 90°. The four-posture calibration is adopted if the finger can bend to 90°. If the finger can't bend to 90°, the three-posture (0°, 30° and 60°) calibration is adopted, but the error would be increased. The maximum error is less than 1.5°, which is a satisfied accuracy to the application of virtual reality (e.g., for telerobotics, virtual assembly).

When the finger bends to the angle of standard block, in order to prevent the difference between the actual flexion angle of finger and standard angle, the method of averaging the multi-measurement values is adopted to decrease the errors.

CONCLUSIONS

Focus on the problems in the measurement accuracy and calibration, an exoskeleton force feedback dataglove is developed using pneumatic artificial muscles as actuators and some theoretical and experimental work are conducted with the dataglove. First, a measurement model of the finger flexion angle based on the theory of four-bar-linkage motion stabilization is built. The effect of structure parameter of linkage on the angle measurement and force feedback is analyzed, which has provided a help for the choice of linkage parameters and improved the accuracy of measuring angle. Then a new calibration method, which is called the "four-posture calibration" based on standard block and genetic algorithm, is proposed. Taking index finger as an example, the process of calibration is introduced in detail. Experiment has shown that with the new calibration method more accurate results can be obtained than that in previous work. In addition, the actual size of each phalange can be obtained as appendix, which can solve the calculation of driving torque of dataglove.

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