Research on High Precision Attitude Measurement of Flexible Link Based on Low Cost Sensors

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Abstract. Flexible links are widely used in industrial robots and special robots due to their light weight, high load ratio and good maneuverability. Due to the flexibility of the connecting rod, the vibration and deformation of the manipulator will occur during the movement, which will affect the stability of the flexible arm. According to the theory of elastic deformation, the attitude of the whole flexible arm can be estimated by indirectly measuring the deformation of the flexible arm. In this paper, low-cost sensors such as encoder, strain sensor and angle sensor are used to measure the deformation of the flexible arm. Through theoretical analysis, the posture and end position of the flexible arm after deformation are obtained. The experimental system is built to verify the proposed method. The results show that the method is correct and effective. The measurement error is 6.5% in the experiment, which meets the measurement accuracy requirements of flexible arm control.

Keywords: flexible links, sensors, attitude measurement, vibration and deformation.

1. Introduction

Due to its light weight, large load ratio, fast movement speed, and low energy consumption, flexible manipulators have important applications in the fields of national defense, aerospace and modern industry, such as space station manipulator arms [1], nuclear reactor assembly and maintenance Robot arm [2] and intelligent pouring arm of concrete pump truck etc. [3].

However, when the flexible manipulator is working, the manipulator will inevitably vibrate and deform, which will seriously affect the work efficiency of the manipulator and the positioning accuracy of the end of the flexible arm [4-5]. Active control of the flexible manipulator is the main method to solve this problem. When performing deformation compensation control, it is first necessary to detect the posture of the flexible manipulator and position the end. At present, the measurement of the flexible arm mainly includes the measurement of the vibration of the flexible arm through the strain gauge [6] and the acceleration sensor [7], and the measurement of the deformation of the flexible arm with the optical fiber sensor [8], but the optical signal conditioning equipment is expensive and can be realized by using image recognition. The end is positioned [9], but it is more sensitive to ambient light.
This paper proposes a low-cost measurement method based on the fusion of orthogonal encoders, strain sensors, and attitude sensors to detect and position the end of a flexible manipulator.

The remaining structure of this paper is as follows: the second section introduces the attitude description of the flexible arm, the third section introduces the attitude measurement method of the flexible arm, the fourth chapter is the sensor data acquisition, the fifth chapter is the experimental verification and data analysis, and finally is the summary of the paper.

2. Description of flexible manipulator posture

Because the description of the posture measurement of the multi-degree-of-freedom flexible arm is complicated, this paper takes the two-degree-of-freedom flexible arm as an example in order to illustrate the proposed measurement method, but the measurement method can be extended to the detection of the posture of the multi-degree-of-freedom flexible arm.

The two-degree-of-freedom flexible manipulator is described in the inertial coordinate system \( \{0\} \) as shown in Figure 1. A float coordinate system is attached to each flexible arm, and the \( x \) axis of the float coordinate system sequentially passes through the start and end points of the flexible arm, and its origin coincides with the start point of the arm. Assuming that the angle between the \( x \) axis of coordinate system \( \{0\} \) and the coordinate system \( \{1\} \) is \( \theta_1 \), the angle between the \( x \) axis of coordinate system \( \{1\} \) and the coordinate system \( \{2\} \) is \( \theta_2 \), the straight line \( OC \) and \( OD \) are the tangent line of the arm 1 and the arm 2 at the starting point. The angles between the two tangents and the \( x \) axes of the two float coordinate systems are \( \alpha_1 \) and \( \alpha_2 \). Since the physical structure and other parameters of the flexible manipulator have been determined, only measurement \( \theta_1 \), \( \theta_2 \) and \( \alpha_1 \), \( \alpha_2 \) are needed, and from this, the vertical deformation of the end of the flexible arm under the action of gravity can be calculated.

3. The measurement principle of flexible arm attitude and end positions

The schematic diagram of the posture measurement of the flexible arm is shown in Figure 2. In the following coordinate system \( \{i\} \), \( i = 1, 2 \), the flexible arm \( \{i\} \) can be treated as a simply supported beam. According to the literature [10], the lateral displacement (deflection) \( y_p \) of the point \( P \) on the arm \( i \) from the origin \( x \) can be expressed as

\[
y_{p}(x,t) = \sum_{k=1}^{n} q_{ik}(t) \phi_{ik}(x)
\]

Where \( q_{ik}(t) \) is the \( k \) order modal coordinates of the arm \( i \), and \( \phi_{ik}(x) \) is the modal function of the corresponding modal coordinates, and \( \phi_{ik}(x) = \sin(k \pi x / L_i) \), in general, at \( k = 2 \), a higher approximation accuracy can be obtained, so
The tangent angle of the flexible arm at the starting point

\[
\alpha_1 = \frac{\partial y_{p1}}{\partial x}\bigg|_{x=0} = q_1\pi / L_1 + 2q_12\pi / L_1
\]

(3)

Tangent angle of the flexible arm at the end

\[
\alpha_2 = \frac{\partial y_{p2}}{\partial x}\bigg|_{x=L_1} = q_2\pi / L_2 + 2q_22\pi / L_2
\]

(4)

In the actual signal acquisition process, an encoder is installed at the starting point of each flexible arm, and an attitude sensor is installed at the end point. If the measured angles of the two encoders are \(\hat{\theta}_1\) and \(\hat{\theta}_2\), and the measured angles of the two attitude angle sensors are \(\hat{\gamma}_1\) and \(\hat{\gamma}_2\), then it can be seen from Figure 2:

\[
\hat{\theta}_1 = \theta_1 + \alpha_1 = \theta_1 + q_1\pi / L_1 + 2q_12\pi / L_1
\]

(7)

\[
\hat{\gamma}_1 = \theta_1 + \beta_1 = \theta_1 - q_1\pi / L_1 + 2q_12\pi / L_1
\]

(9)

\[
\hat{\theta}_2 = \theta_2 + \alpha_2 = \theta_2 + q_2\pi / L_2 + 2q_22\pi / L_2
\]

(8)

\[
\hat{\gamma}_2 = \theta_2 + \beta_2 = \theta_2 + \theta_2 - q_1\pi / L_2 + 2q_22\pi / L_2
\]

(10)

Fig. 3 Stress diagram of flexible arm  
Fig. 4 Schematic diagram of encoder circuit connection and pulse acquisition

When the flexible arm is in equilibrium with the force, the state is shown in Figure 3. According to force balance and torque balance

\[
F_{r0} = (m_1 + m_2 + M_1 + M_2)g
\]

(11)

\[
\tau_i = [(M_1 + m_1/2 + M_2 + m_2)L_1 \cos(\theta_i) + (M_2 + m_2/2)L_2 \cos(\theta_i + \theta_2)]g
\]

(12)

According to the section method, the bending moment of the arm at the strain gauge 1 can be calculation as

\[
M_{s1} = \int_{l_1} F_{s1} dL \cos \left( \frac{\partial y_{s1}}{\partial x} \bigg|_{s_1} + \theta_i \right) - \tau_i = \int_{l_1} F_{s1} dL \cos \left( \frac{\pi d_1}{L_1} \cos \left( \frac{\pi d_1}{L_1} \right) + q_1 \frac{2\pi d_1}{L_1} \cos \left( \frac{2\pi d_1}{L_1} \right) + \theta_i \right) - \tau_i
\]

\[
= (M_1 + m_1 + M_2 + m_2)d_1 \cos \left( \frac{\pi d_1}{L_1} \cos \left( \frac{\pi d_1}{L_1} \right) + q_1 \frac{2\pi d_1}{L_1} \cos \left( \frac{2\pi d_1}{L_1} \right) + \theta_i \right) + \frac{pg(d_1^3 - 4L_1d_1^2 + 3L_1^2d_1)}{6L_1}
\]

(13)
The actual strain value $\hat{\varepsilon}_1$ of the surface of arm 1 at this section ($x = d_1$) can be measured by a strain gauge, and there is

$$\hat{\varepsilon}_1 = \frac{b_1 M_{11}}{2E_1 I_1}$$  (14)

The same is true in strain gauge 2

$$M_{22} = (M_2 + m_2)d_2 \cos(q_{21} \frac{\pi}{L_2} \cos(\frac{\pi d_2}{L_2}) + q_{22} \frac{2\pi}{L_2} \cos(\frac{2\pi d_2}{L_2}) + \theta_1 + \theta_2)g$$

$$-[(M_2 + m_2/2)L_2 \cos(\theta_1 + \theta_2)]g + \rho g(d_2, L_2 - \frac{1}{2}d_2^2)$$

$$\hat{\varepsilon}_2 = \frac{b_2 M_{22}}{2E_2 I_2}$$  (16)

The unknown quantity can be solved by formula (7)-formula (16) $\theta_1, \theta_2, \alpha_1, \alpha_2$.

Thus, the posture angle of the flexible arm $\theta_1, \theta_2, \alpha_1, \alpha_2, \beta_1, \beta_2$ can be known. At the same time, the height of the end of the flexible arm in the vertical direction

$$h = L_2 \sin(\theta_i) + L_2 \sin(\theta_i + \theta_j)$$  (17)

The relative deformation of the rigid arm in the vertical direction is

$$\Delta h = L_2 [\sin(\theta_i + \alpha_i) - \sin(\theta_j)] + L_2 [\sin(\theta_i + \theta_j + \alpha_j) - \sin(\theta_i + \theta_j)]$$  (18)

So far, the entire posture of the flexible arm has been detected by the encoder, attitude sensor and strain gauge combined with the small deformation theory of flexible arm (AMM), and the deformation of the end of the flexible arm under the action of gravity is also calculated. The deformation compensation control at the end of the flexible arm provides the measurement basis.

4. Sensor data acquisition

According to the principle of flexible arm attitude detection proposed above, the following further collects and processes the data of each sensor. Here, LabVIEW data acquisition software and cRIO-9035 data acquisition equipment are used for data acquisition.

The NI-9423 module in the acquisition device can be configured as a quadrature encoder function, which directly reads the high-speed pulse number of the quadrature encoder and converts it into an angle value. The E6B2-CWZ6C type encoder is used in the experiment, the collector is open-circuit output, and a pull-up resistor needs to be connected. The circuit connection diagram is shown in Figure 4. Select JY-901 as the attitude sensor, connect cRIO-9035 through RS485 to USB, and collect data according to Modbus-RTU protocol. The data acquisition program block diagram is shown in Figure 5.

Strain gauges are attached to the upper and lower sides of each flexible arm to detect the strain on the surface of the arm. As shown in Figure 6, a Wheatstone half-bridge circuit is used, and the NI-9203 module is used to collect analog voltage signals after conditioning by a dynamic strain gauge.
The data acquisition schematic diagram of the entire sensing system is shown in Figure 7. Finally, all the collected data are fused and processed, and the posture and end deformation of the flexible arm are calculated by formulas (7) to (16).

5. Experimental verification and effect analysis

The experimental device as shown in Figure 8 was built to verify the proposed flexible arm attitude detection and end positioning method.

At the beginning of the experiment, the flexible arm was kept horizontal, and then the positions of the two flexible arms were changed every 15°. After the flexible arm was deformed and stopped, the values of the three sensors were read, and the posture angle and end of the flexible arm were calculated by solving the equations. In the end, the deformation amount in the vertical direction is compared with the scale table. The parameters of the flexible arm device during the experiment are shown in Table 1, and the readings and calculated values of each sensor are shown in Table 2.

Table 1. Parameters of manipulator in experiment

|   | Length | width | thickness | density | elastic modulus | end mass |
|---|--------|-------|-----------|---------|-----------------|---------|
| Link1 | 445 | 30 | 4 | 7800 | 206GPa | 2.94 |
| Link2 | 435 | 30 | 3 | 7800 | 206GPa | 0.34 |

In Table 1, the unit of length is meter (/m), the unit of density is kilogram per cubic meter (/kg/m^3), and the unit of mass is kilogram (/kg).

Table 2. Readings and calculated values of each sensor in the experiment

| measured value | \( \hat{\theta}_1 \) | \( \hat{\theta}_2 \) | \( \hat{\gamma}_1 \) | \( \hat{\gamma}_2 \) | \( \hat{e}_1 \) | \( \hat{e}_2 \) | calculated value | \( \bar{\theta}_1 \) | \( \bar{\theta}_2 \) | \( \bar{\alpha}_1 \) | \( \bar{\alpha}_2 \) | \( \Delta h \) | altitude error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | -7.5 | -9.8 | 2075 | 118 | 1 | -6.3 | -23 | 6.2 | 4.12 | 0.085 | 7.2% |
| 2 | 15 | -15 | 9.5 | -6.9 | 2058 | 122 | 2 | 12.6 | -16.4 | 2.7 | 4.12 | 0.053 | 7.6% |
| 3 | 30 | -30 | 21.3 | -5.2 | 1932 | 121 | 3 | 24.2 | -28.5 | 5.9 | 4.14 | 0.075 | 4.3% |
| 4 | 45 | -45 | 35.5 | -7.8 | 1693 | 117 | 4 | 39.9 | -43.8 | 5.2 | 4.11 | 0.065 | 6.2% |
| 5 | 60 | -60 | 52.3 | -4.9 | 1276 | 117 | 5 | 55.2 | -59.3 | 4.9 | 4.13 | 0.051 | 6.7% |
| 6 | 75 | -75 | 68.7 | -2.8 | 793 | 118 | 6 | 67.3 | -71.3 | 7.8 | 4.14 | 0.049 | 6.5% |

In Table 2, the unit of length is meter (/m) and the unit of angle is degree (/°). It can be seen from the table that the maximum deformation of the arm end can reach 8.4cm, which is 9.5% relative to the entire arm length of 88cm, and its measurement error is about 7%. The theoretical value of the end position when the manipulator does not consider flexibility and when the flexibility is considered, the
result of the end position of the manipulator according to the measured and actual values is shown in Figure 9. It can be seen from the figure that after considering the flexibility, the position of the end of the robot arm is quite different from the rigidity. At the same time, it can be seen that the calculated value of the end of the flexible arm is relatively close to the actual value, indicating that the measurement method proposed in this article has higher accuracy.

6. Summary
According to the requirements of deformation compensation control at the end of the flexible manipulator, this paper proposes the use of rotary encoder, strain sensor, and attitude sensor fusion measurement method to detect and position the end of the flexible manipulator. The measurement principle and method are introduced and experimentally verified. The results show that the method can accurately detect the posture and end position of the flexible manipulator within the allowable error range, thereby providing a cost-effective posture detection method for the end deformation compensation control of the flexible manipulator.

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