A Multifunctional Approach for Flexion Angular Measurement

Wei QUAN* and Katsunori SHIDA*

The paper presents a novel approach for flexion angle measurement based on the multifunctional technology, which is different from previous works with respect of its ability of measuring obliquity and bending direction simultaneously with a single structure. A flexible tube is utilized to imitate the status of skin on the elbow whose length varies with different gesture. Its flexible and compact character permits the biomechanical application and easy substitutability ability. Two angular parameters are converted to the linear movements of three iron wires, which are measured using inductive principle. We herein discuss the sensing structure, its geometric analysis, and the reconstructed equations. The estimated results of the built prototype prove the feasibility of the proposed approach.

Key Words: multifunctional, flexion angle, biomechanical application, direction, obliquity

1. Introduction

An approach with flexible characteristic is highly recommended to measure the angular position of flexion, which contains the structures such as human extremity, whose two segments is connected by an arthrosis as elbow and knee, or the robot arm with two separated motors to set direction and obliquity simultaneously. The flexion angular position is always used to describe the gesture of extremity of human, which can be measured directly by sensing angles using electromechanical body sensors or calculating angles by computer in vision-based sensing system. Internal sensor as rotary encoder are designed to test the robot relative angular parameters\(^1\),\(^2\). But it needs to be mounted inside of the joint and its invasive character limits the application in biomechanical angular position. Lementec, J.C\(^3\) reports an approach for recognition of arm gestures using multiple orientation sensors. Miniaturized accelerometers also can be used to track the gesture of human\(^4\). They can provide data at a high sampling frequency and give good results but the cost is high and the user is forced to wear a somewhat cumbersome device. Vision-based system is another popular method for obtaining the flexion position. Single or multiple cameras acquire video stream that is processed and gestures are mapped into temporal signatures of changes in video frames\(^5\). Another well known vision-based system is that by viewing a number of strategically placed dots on the human body, people can easily perceive the position, movement and other aspects of bodies\(^6\),\(^7\). The major advantage of optical system is the lack of wires and a tether. But they are expensive, cumbersome and having requirement to the environment. As a result, it is not easy to be applied in common life. A flexible and non-invasive approach with a simple structure and low cost is required for easily utilizing in measurement of extremity gesture and assistant for therapy.

Based on multifunctional technology which is developed in recent years\(^8\),\(^9\), a novel approach for flexion angular measurement is proposed in this paper, which is different from previous works in the following respects. First, instead of combining several individual sensors together as common sense, a single structure is proposed with the ability of estimating both obliquity and bending direction simultaneously. Direction can be measured with the scale ranging from 0° to 360° while the scale of obliquity depends on the requirement, the maximum of which can reach to 180°. The prototype proposed in this study is possible to measure obliquity ranging from 0° to 90°. Second, the selection of a hollow flexible tube as main body characters the non-invasive advantage. It gives good alternative ability for application and results the ability for biomechanical application. Third, the result has a good linearity in obliquity measurement and sinusoidal characteristic in direction estimating. As a result, a simple data processing can be obtained. Fourth, the selection of inductance principle provides the robust character environment change. Finally, its simple and compact structure causes a lower cost than previous techniques.

As to this approach, the tube can be fixed on the testing object as convenient with no limit. For example, directly ring the tube over the object or fix its two ends outside

* Department of Advanced System Control Engineering, Graduate School of Saga University, 1 Honjo-machi, Saga (Received July 3, 2006) (Revised December 11, 2006)
2. Working Principle and Configuration

As we know, human skin covers outside of bones in order to protect tissues such as muscle and blood vessel. Besides the flexibility of skin itself, the skin on the elbow and knee has many wrinkles. Arm bending causes the extending of wrinkles and skin, whose surface length change depends on the bending magnitude and its direction. Based on this principle, a flexible tube with wrinkles are selected for imitating the skin on the elbow, whose radius of section keeps its value in the movement of tube. Its wrinkles extend with bending and by analyzing the generatrix changing, two angular information is able to be calculated. In order to obtain a simple data processing and a single structure, the multifunctional principle is used to instruct this design.

2.1 Multifunctional Sensing Approach

Multifunctional sensing approach, which has been developed in the last decade, is used to instruct the design of sensor. It is different from integrated and compound sensors whereas the former one uses the same structure to realize multiple functions or measure several parameters, while the latter two employ individual sensor for each function or measurement. As shown in Fig. 2, \( X_1 \) and \( X_2 \) are the two quantities being measured, \( Y_1 \) and \( Y_2 \) are the outputs, while \( X'_1 \) and \( X'_2 \) are the estimating results. In conventional works, two sensors with the characters as \( Y_1 = f_1(X_1) \) and \( Y_2 = f_2(X_2) \) are combined for measurement. Although data processing of this way is simple, fixing of two separated sensors and their corresponding measuring setups may cause a complicated structure. As to multifunctional sensing, each output is the fusion of two measurands, which are \( Y_1 = f_1(X_1, X_2) \) and \( Y_2 = f_2(X_1, X_2) \). Comparing to conventional works, the structure may be compact, but the data processing for reconstructing two measurands is needed. By well designing of the sensing structure, a simple data processing can be obtained.

Based on this principle, a structure is designed with the same three sensing elements in order to obtain a simple data processing.

2.2 Configuration of Prototype

A prototype based on proposed approach is built for testing its performance, as shown in Fig. 3. The main part is a flexible tube with wrinkles as shown in Fig. 3(a).
One important character of the chosen tube is that its radius of section keeps the same value with bending. The radius of tube for building the prototype is 12mm with length of 220mm. Three iron wires with radius of 0.75mm and length of 170mm are fixed on one end of tube with 120° interval of each other by a fixing ring. Three rigid solenoids with radius about 1mm and length about 100mm are fixed on the other end of tube corresponding to the position of iron wires. 15 small rings are attached on the surface of tube and compose three tracks for restricting the iron wires to move smoothly on the tube surface in a fixed orbit. The free ends of iron wires are injected into three solenoids throughout the restricting rings and their initial positions are the middle of solenoids. Iron wires act as cores of solenoids for increasing their self-inductances, and each pair of them composes a sensing element. Bending of tube causes different length changes of three chosen generatrices and drives the wires to move up and down in the solenoids, which lead to the change of self-inductances. The technology for inductance measurement has been mature, and the design of circuit part is not concerned in this study. Three self-inductances L1, L2 and L3 of solenoids are measured by LCR meter (ZM2355, NF. Corp) as outputs of the approach. In order to prove the feasibility of this approach and obtain the characters of outputs, some sample points need to be measured as database. A device with direction scale and obliquity scale used for setting required positions is proposed as shown in Fig. 3(b).

2.3 Working Coordinate System and Geometric Analysis

Fig. 4 shows the coordinate system for geometric analysis of the prototype, in which two angular parameters are defined to describe the relative position of two ends of tube. The definitions of original direction 0°, obliquity 0°, direction φ and obliquity θ are illustrated in the coordinate system, respectively. Obliquity is defined as the supplementary of the angle included between normal vectors of two end sections. The two ends of the tube are supported by the rigid solenoids and fixing ring, and the middle part of tube bends, which causes the length changes of generatrices. Three generatrices with 120° interval on the surface of tube are selected for describing tube gesture. P1P'1, P2P'2 and P3P'3 are their curve lengths of the bending part.

The bending radius of the tube is not a constant, which changes gradually with obliquity. The definite integral is selected to calculate the lengths of P1P'1, P2P'2 and P3P'3. Fig. 4(a) shows a section view of the tube. C(θx) is the bending central point of the tube central axis which is not a constant position. Three lines bend around the same axis vertical to OC as shown in Fig. 4(a). The change of direction results in the variety of three radii of selected lines, which leads to different length changes of generatrices. We can obtain following equations:

\[
\begin{align*}
      r_1(\theta_x) &= r(\theta_x) - a \cdot \cos(\phi + 90°) \\
      r_2(\theta_x) &= r(\theta_x) - a \cdot \cos(\phi + 210°) \\
      r_3(\theta_x) &= r(\theta_x) - a \cdot \cos(\phi - 30°)
\end{align*}
\]

where \(r(\theta_x)\) is the bending radius of the tube central axis whose value can be affected by obliquity and working condition, for example, the extending or compression of tube. \(r_1(\theta_x), r_2(\theta_x)\) and \(r_3(\theta_x)\) are the bending radii of three chosen lines. a is the radius of tube section as a constant. As we know, the length of arc is the product of central angle and radius. As shown in Fig. 4(b), the central angle is equal to obliquity. The lengths of \(P_1P'_1, P_2P'_2\) and \(P_3P'_3\) with their symbols of \(d_1, d_2\) and \(d_3\) can be expressed with variables \(\psi\) and \(\phi\) as below:
2.4 Inductance Principle for Measurement

If the length of solenoid is much greater than its radius, the magnetic field can be considered as average distributing. Self-inductance is direct proportional to the core length inside of it, which can be expressed as

\[
L = L_0 + k \cdot l_c \quad (k = \frac{4\pi N^2 r_c^2}{l^2} (\mu_r - 1) \cdot 10^{-7})
\]

\[
= L'_0 + k \cdot \Delta l_c
\]

(3)

\[l_c: \text{the length of the core in solenoid} \]

\[\Delta l_c: \text{the length change of core in solenoid}. \]

\[L_0: \text{the self-inductance of solenoid without core} \]

\[L'_0: \text{the self-inductance of solenoid with core at its initial position}. \]

\[k: \text{a constant decided by solenoid scale and characters of iron core.} \]

\[\mu_r: \text{relative permeability of the core.} \]

\[r_c: \text{the radius of the iron core.} \]

\[N: \text{the number of turns.} \]

\[l: \text{the length of solenoid.} \]

By (2), \(\Delta l_c\) of three solenoids can be expressed as below:

\[
\begin{align*}
\Delta l_{c1} &= d_0 + a \cdot \theta \cdot \cos(\phi + 90^\circ) - \int_0^\theta r(\theta_x) d\theta_x \\
\Delta l_{c2} &= d_0 + a \cdot \theta \cdot \cos(\phi + 210^\circ) - \int_0^\theta r(\theta_x) d\theta_x \\
\Delta l_{c3} &= d_0 + a \cdot \theta \cdot \cos(\phi - 30^\circ) - \int_0^\theta r(\theta_x) d\theta_x
\end{align*}
\]

(4)

\[\Delta l_{c1}, \Delta l_{c2} \text{ and } \Delta l_{c3} \text{ are the length changes of core in solenoids.} \]

\(d_0\) is the initial length of the curve part when \(\theta = 0^\circ\). As a result, using (3) and (4), three inductances can be calculated as

\[
\begin{align*}
L_1 &= k \cdot a \cdot \theta \cdot \cos(\phi + 90^\circ) + f(\theta, r) + \delta L \\
L_2 &= k \cdot a \cdot \theta \cdot \cos(\phi + 210^\circ) + f(\theta, r) + \delta L \\
L_3 &= k \cdot a \cdot \theta \cdot \cos(\phi - 30^\circ) + f(\theta, r) + \delta L \\
(f(\theta, r) &= L'_0 + k \cdot d_0 - k \cdot \int_0^\theta r(\theta_x) d\theta_x)
\end{align*}
\]

(5)

\(\delta L\) is the inductance change caused by environment change or measurement circuit, which is the same value to three inductances. By subtracting each equation in (5), except \(\phi\) and \(\theta\), the integral part containing \(r\) and \(\delta L\) can be eliminated.

\[
\begin{align*}
L_1 - L_2 &= k \cdot a \cdot \theta \cdot (\cos(\phi + 90^\circ) - \cos(\phi + 210^\circ)) \\
L_1 - L_3 &= k \cdot a \cdot \theta \cdot (\cos(\phi + 210^\circ) - \cos(\phi - 30^\circ))
\end{align*}
\]

(6)

2.5 Process of Scale Design

Step 1: Decide the suitable radius of the tube based on requirement and the fixing way.

Step 2: Calculate the length of solenoid. By (2), the maximum length difference of generatrix caused by bending is

\[
\Delta d = 2 \cdot \theta_0 \cdot a
\]

\(\theta_0\) is the measuring scale of requirement, and \(\Delta d\) is the minimum value for designing the length of solenoid. In order to obtain good linearity at the edge and considering the existing of extending of tube, the real length should be longer than \(\Delta d\).

Step 3: Compose all parts and fix on measured object.

3. Characteristic Experiment of Prototype

3.1 Experimental Method

In order to prove the feasibility of this approach, three inductances of the prototype are measured at the sample points whose \(\phi\) steps by \(30^\circ\) with ranging from \(0^\circ\) to \(330^\circ\), and for each \(\phi\), obliquity \(\theta\) steps by \(10^\circ\) with ranging from \(0^\circ\) to \(90^\circ\). Consequently, the data list as \(L_x(\phi, \theta)\), whose \(x = 1, 2, 3; \phi = m \cdot 30^\circ, m = 0, 1, \ldots 11; \theta = n \cdot 10^\circ, n = 0, 1, \ldots 9\) can be obtained. At these points, \(L_1, L_2\) and \(L_3\) are measured in sequence by the LCR meter with working frequency of 10kHz. The experiment is carried out four times and the average value is calculated for obtaining the characters of outputs.

Fig. 5 shows the surface composed by sample points with \(L_1, L_2\) and \(L_3\) as their coordinate values, respectively. The center point of the surface is the initial position where \(\phi = 0^\circ\) and \(\theta = 0^\circ\). The longitudinal radial line indicates the inductances changing with obliquity at

![Fig. 5 Experimental results at sample surface](image-url)
a fixed direction, while the latitudinal loop line indicates the inductances changing with direction at a fixed obliquity. Each point on this surface has a unique set of inductances as its coordinate value, which corresponds to a unique space direction.

3.2 Calculation of Coefficient $k_0$

In (6), the value of $k \cdot a$ is the only coefficient for estimating $\phi$ and $\theta$. We suppose $k_0$ is equal to $k \cdot a$, which is decided by the scale of prototype. In this approach, instead of calculating in theory, $k_0$ is obtained by the experimental results of sample points for convenience and as well as for accuracy.

$$k_0 = \frac{1}{n} \left( \sum \frac{L_1 - L_2}{L_1 - L_3} \right) \left( \frac{n}{\theta} \cdot \cos(\phi + 90^\circ) - \cos(\phi - 210^\circ) \right) + \frac{1}{\theta} \cdot \cos(\phi + 90^\circ) - \cos(\phi - 30^\circ)$$

Fig. 6 gives the experimental results of $L_1 - L_2$ and $L_1 - L_3$, whose value has a sinusoidal relation with direction with a fixed obliquity. The only difference between them is the 120° phase. Direction can be calculated by (9), which eliminates obliquity and $k_0$ by dividing each equation of (6).

$$\frac{L_1 - L_2}{L_1 - L_3} = m = \frac{\cos(\phi + 90^\circ) - \cos(\phi + 210^\circ)}{\cos(\phi + 90^\circ) - \cos(\phi - 30^\circ)}$$

$$\phi' = \frac{1 + m}{\sqrt{3} (1 - m)} \Rightarrow$$

$$\phi = \begin{cases} 
150^\circ & (L_1 = L_3, L_2 = \max(L_1, L_2, L_3)) \\
330^\circ & (L_1 = L_3, L_2 = \min(L_1, L_2, L_3)) \\
\phi' + 2\pi & (L_2 = \max(L_1, L_2, L_3), \phi' > 0) \\
\phi' + \pi & (\text{else}) \\
\phi' + 2\pi & (L_2 = \min(L_1, L_2, L_3), \phi' < 0) 
\end{cases}$$

Estimation of direction is independent of the scale of prototype. Fig. 7 shows the estimated direction at the sample points, the maximum error of which is approximately 2°. The average error obtained by the estimated results of all points is 0.69°.

3.4 Estimation of Obliquity

Fig. 8 shows the experimental results of $L_1 - L_2$ and $L_1 - L_3$, whose value has a linear relation with obliquity at a fixed direction. The slope of each straight line is the function of direction as demonstrated in (10).

$$L_1 - L_2 = k_1 \cdot \theta \quad L_1 - L_3 = k_2 \cdot \theta$$

$$k_1 = k_0 \cdot (\cos(\phi + 90^\circ) - \cos(\phi + 210^\circ))$$

$$k_2 = k_0 \cdot (\cos(\phi + 90^\circ) - \cos(\phi - 30^\circ))$$

$$\theta = \left( \frac{(L_1 - L_2) \cdot |k_1| + (L_1 - L_3) \cdot |k_2|}{k_1} \right) \ast \frac{1}{|k_1| + |k_2|}$$

For the reason that the bending direction causes a corresponding sensitivity of obliquity, the final result of obliquity is the weighted mean of obliquities calculated by $L_1 - L_2$ and $L_1 - L_3$, the weighted values of which are determined by estimated direction.

Fig. 9 shows the estimated obliquity obtained by (10), the maximum error of which is approximately 3°. The average error obtained by the estimated results of all points is 1.39°.
4. Discussion

The response of measuring system to different angle parameters is quite satisfactory. In terms of measurement accuracy, the experiment was carried out four times and the average value was calculated for obtaining the characters of outputs. The relative error of inductance measurement was found less than 0.2%. The estimated errors of the prototype we built were approximately 2° in direction and 3° in obliquity comparing to the setting parameters. Systematic errors are due to several factors, such as

1) the slight distortion of the section of tube changes the bending radius of each sensing elements.
2) the gaps between moving wires and the solenoids causes a drift of inductance value.
3) The error of experimental setup for setting corresponding positions is about 1°, which will surely affect the accuracy of estimated results.

Improving the technological manufacture level and the accuracy of the experimental apparatus for obtaining the characteristic of the device will surely reduce the error.

This approach is a passive measurement. According to (3), without considering the distortion of section of tube, the curve lengths of bending part of tube can be calculated by \( \phi \), \( \theta \) and integral of bending radius \( r \). The hysteresis of tube causes the changing of \( r \) during the hysteresis time. Because the part of integral of bending radius \( r \) is eliminated in data processing as shown in (6), the hysteresis of tube gives little affection to the estimated results. As a result, the dynamic characteristic mainly depends on the circuit for data collection and processing.

5. Conclusion

A novel multifunctional approach for estimating flexion angular parameters, which contains direction and obliquity information, is proposed in this study. Based on the principle of imitating the skin of human, a structure with its main body as a tube is designed. Its flexible and non-invasive characters give the possibility of applying in biomechanical field. Two kinds of angular parameters are converted to three inductances outputs. The data processing method eliminates the affections of different bending radius, environment change and so on. Errors of the prototype are approximately 2° in direction and 3° in obliquity comparing to setting position.

As a result, the proposed multifunctional approach can realize the aim of flexion angular measurement in a fast, simultaneously, non-invasive and low cost way.

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