The design and applications of F/T sensor based on Stewart platform

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Abstract—A force/torque sensor based on Stewart platform is established and an effective dimension design way, the model of solution space, which relates the performance criteria and the dimensional parameters of the sensor structures is presented. Some applications of the F/T sensor are introduced.

Keywords: F/T sensor, design, applications

I. Introduction

Force/torque (F/T) sensors have widely been used in measuring inertia force [1], monitoring forces of variable directions and intensity [2] and as a component of force feedback controller [3]. Many kinds of F/T sensors have been presented [4-12]. Kerr [13] presented a Stewart platform transducer force sensor. Nguyen [14] and Ferraresi [15] analyzed the Stewart platform force sensor. The importance of the performance criteria for evaluation of the force sensors attracts attentions of many researchers. Uchiyama proposed an index for the evaluation of a structural isotropy of the force sensors [16] and studied a systematic design procedure to minimize a performance index for the forces sensors [9]. Bayo [10] investigated the criteria of condition number, stiffness and strain gauge sensitivity of the sensors. Diddens [1] used a three-dimensional finite-element model to optimize the strain-gauge positions of the sensor.

A force/torque sensor based on Stewart platform is established and an effective way, the model of solution space, relating the performance criteria and the dimensional parameters of the sensor structures is presented.

II. Sensor structure

As shown in Fig.1, the force/torque sensor based on the Stewart platform. The upper platform and the lower platform is connected with six same limbs, each of them includes two elastic spherical pair and a rigid link. The strain gages are attached in the links. The structure should be symmetric and there are four determinative parameters 1R, 2R, 3R and ABθ.

By analyzing the mechanism, the equations for performance criteria can be found."

$$\lambda_\rho = \frac{R_2^2 - h^2}{2h^2}$$

$$\lambda_\theta = \frac{R_2^2 h^2}{2R_1^2}$$

$$\lambda_{\alpha_1} = \frac{R_3^2}{R_4^2}$$

$$\lambda_{\alpha_2} = \frac{1}{4h_4}$$

$$\lambda_{\alpha_3} = \frac{1}{4R_1^4 R_2^4 \sin^2 \theta_{ab} 2}$$

Where $\lambda_\rho$, $\lambda_\theta$, $\lambda_{\alpha_1}$ and $\lambda_{\alpha_2}$ is the singularity vector of the force matrix, the torque matrix, the position deformation matrix and the orientation deformation matrix respectively. The parameters $c_1$, $c_2$ and $h$ are the functions of four determinative parameters $R_1$, $R_2$, $R_3$ and $|\theta_{ab}|$.

III. The model of the solution space for the sensor mechanism

The four parameters of the mechanism have the relationship below.

$$\theta_{ab} = |\theta_A - \theta_B| (0 < \theta_{ab} < 120^\circ)$$

$$\theta_A = \angle A_A A_1$$

$$\theta_B = \angle B_B B_1$$

$$\theta_{ab} = \angle A_B A_1 = \angle A_1 A_2$$

$$\theta_{ab} = \angle B_B B_1 = \angle B_1 B_2$$

$$180^\circ - \theta_A = \angle A_2 A_3$$

$$180^\circ - \theta_B = \angle B_2 B_3$$
Let
\[ L = \frac{R_1 + R_2 + R_3}{3} \quad (3) \]
\[ r_i = \frac{R_i}{L} \quad (i = 1, 2, 3) \quad (4) \]

Where \( R_i \) is the length of link \( i \), \( r_i \) is the normalized nondimensional length of link \( i \), and \( L \) is the average length of the mechanism. The sum of the normalized lengths is
\[ r_1 + r_2 + r_3 = 3 \quad (5) \]

From the conditions to assemble the mechanism, the inequations must be satisfied.
\[
\begin{align*}
0 < r_1 < 1.5 \\
0 < r_2 < 1.5 \\
0 < \psi < r_3 < 3
\end{align*}
\]
\[
\psi = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \frac{\theta_{AB}}{2}}
\]

A physical model of the solution space for the sensor mechanism can be constructed as shown in Fig.2, which is the rhombus ABCD. Fig.3 shows the planar closed configuration of the solution space. Within the model, the relationship between the criteria and the parameters of the sensor mechanism can be investigated.

IV. Dimensional design

The sensor measures the forces and torques from the deformation of the links. The three performance indexes sensitivity, force/torque isotropy and stiffness are very important for the sensor. The dimensional design of the sensor is carried out based on these indexes.

The definition of the force/torque sensitivity is
\[
\rho_F = \frac{F_{\text{max}}}{\sqrt{\lambda_{F_{\text{max}}}}} = \sqrt{\frac{F_{\text{max}}}{\lambda_{F_{\text{max}}}}}
\]

From the conditions to assemble the mechanism, the inequations must be satisfied.
\[
\begin{align*}
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These indexes can be plotted within the model of the solution space shown in Fig.3. Fig.4-Fig.6 are the atlases of the three indexes with the precondition \( |\theta_{AB}| = 10^\circ \).
More performance atlases should be plotted by changing the value of $|\theta_{ab}|$. From the figures, an important conclusion for the dimensional design can be drawn as when $r_1 \approx r_2$ and $r_3$ reaches the minimum value, which means the three linear parameters locate near the vertex D in the Fig.3, the sensor mechanism have optimum performances. Another conclusion is when $|\theta_{ab}|$ is bigger, the values of $r_1, r_2, r_3$ will be limited. By the performance atlases, the four parameters can be easily selected.

V. Applications

Some kinds of sensors have been designed by the method and have been applied in several areas. Fig.7 is the sensor designed by the method. The sensor is as small as the fingertip and can be used as the last end of finger.

Fig.7 Small size F/T sensor

Fig.8 shows another F/t sensor based on a decoupled structure and designed by the model of solution space.

Fig.8 Structure decoupled F/T sensor

Shown in Fig.9 is the 6-dimensional mouse based on the F/T sensor. The sensor measures the force and torque applied on it and changes them into electrical signals to drive the mechanism in virtual environment accomplish corresponding motions. The mouse is a good controller having widely applications. The micromanipulator shown in Fig.10 can accomplish tasks in the order of micron even nano magnitude. The macro/micro manipulator shown in Fig.11 is designed to cut chromosome. Both of them should be controlled by the mouse.

The mouse can also be used as controller to drive macro manipulator. Shown in Fig.12 is a novel type 5-DOF 4-PUS&1-PU*U parallel CNC machine. Under the 6-D mouse, the mechanism can accomplish the 5-DOF motions smoothly.

Fig.9 6-D mouse

Fig.10 Micro manipulator

Fig.11 The prototype for macro/micro parallel manipulator for chromosome cutting and cloning

Fig.12 Novel type 5-DOF parallel CNC machine
VI. Conclusion

In this paper, the optimal design process based on the performance atlases within the model of the solution space for the sensor based on Stewart mechanism was established. The atlases show the relationships between the performance indexes and the dimensional parameters, the parameters can be easily decided. The sensor designed has many applications and some of them were shown in the paper.

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References