Design of a decoupled calibration device for six-axis heavy force sensor based on the orthogonal parallel mechanism

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Abstract. Six-axis heavy force sensors are widely used in heavy manipulator, but the development of the six-axis heavy force sensor is seriously restricted by the technology of calibration. In order to reduce the positioning error for movement of the sensor or the force source, we employ an orthogonal parallel mechanism as the loading part of the calibration device for six-axis heavy force sensor. The decoupling character is deduced by the force mapping matrix. The calibration device is designed including force source, frame and fixture. The loading mode of the six-axis heavy force is described. The pose error of the calibration device is analyzed. The calibration device can apply the six-axis heavy force simultaneously without moving the sensor or force source.

1. Introduction

Six-axis heavy force sensor is widely used in the heavy industry field. The spatial arbitrary six-axis heavy force including the three-dimensional orthogonal forces and three-dimensional orthogonal moments can be measured by the sensor [1,2]. However, the calibration device for common six-axis force cannot bear heavy force. For the calibration device of six-axis heavy force sensor, the six-axis heavy force is applied by changing the position of the sensor or the force source, which will influence the calibration accuracy seriously for the positioning error.

In recent years, some results of calibration device have been achieved by scholars. Kim [2] has developed a six-axis force calibration loading station. The calibration device is not suitable to calibration of the six-axis heavy force. Wang [3] has designed a calibration device with weight loading. The calibration device cannot endure heavy force, and the friction will increase the error. Huang[4] has developed a new air floatation type six-axis force/torque calibration platform. The compound forces and compound moments along coordinate axes X,Y,Z are obtained from measuring the changes of pressure difference in every group air nozzle pressure cavity, which is not suitable for the calibration of six-axis heavy force sensor. In summary, problems in different calibration device of six-axis force sensor can be summarized as follow: 1) The calibration device cannot endure the heavy force. 2) The sensor or the force source should be moved for loading in different direction. The six-axis force cannot be applied simultaneously 3) The applied six-axis force from the calibration device is coupled, which will affect the calibration accuracy.

In this paper, an orthogonal parallel mechanism is used to achieve the loading of six-axis heavy force simultaneously. The decoupling character of the mechanism is proven by the force mapping matrix. The specific structure of the calibration device including the force source, frame and fixture is designed. A calibration device applied the six-axis heavy force simultaneously without moving the sensor or force source is proposed.
2. of the orthogonal parallel mechanism

Jin[5] proposed a 2-2-2-SPS(2-2-2-spherical hinge-prismatic joint-spherical hinge) orthogonal parallel mechanism, which is shown in figure 1. The six SPS branches of the parallel mechanism are divided into three groups. The three groups of branches and the stage are connected with three groups of spherical hinges, which are denoted as $b_i (i = 1,2,\cdots,6)$. The lines connecting of each group spherical hinges are perpendicular to each other. And the distance of the two spherical hinges in one group is $d$. The width of the stage is denoted as $c$. The distribution characteristics of the spherical hinges on the base are similar with these on the stage, which is denoted as $B_i (i = 1,2,\cdots,6)$. If the three groups of branches are perpendicular with the three surfaces of the stage, the parallel mechanism is in the orthogonal state. The length of the branch in the orthogonal state is $l$.

Figure 1. The model of the orthogonal parallel mechanism

If the 2-2-2-SPS orthogonal parallel mechanism is used as the calibration device of six-axis heavy force sensor, the relationship between the force of six branches and the force of output should be analyzed. Then the relationship between the force acted on the center of the stage and the force of the six bars can be derived as [5]

$$f_1S_1 + f_2S_2 + f_3S_3 + f_4S_4 + f_5S_5 + f_6S_6 = F + \epsilon \in M$$

where, $f_i$ is the force value along the $i$ rod, $S_i$ is the unit line vector, $F$ is the force vector acted on the moving platform; $M$ is the torque acted on the moving platform.

The equation (1) can be simplified into a matrix form,

$$F = [G_f^T] f$$

where, $F = [F_1,F_2,F_3,M_x,M_y,M_z]^T$, $f = [f_1,f_2,f_3,f_4,f_5,f_6]^T$, $[G_f^T]$ is the force mapping matrix.

Substituting the hinge point coordinate into equation (2), the matrix $[G_f^T]$ can also be expressed as,

$$[G_f^T] = \begin{bmatrix}
    b_1 - B_1 & b_2 - B_2 & \cdots & b_6 - B_6 \\
    \|b_1 - B_1\| & \|b_2 - B_2\| & \cdots & \|b_6 - B_6\| \\
    B_1 \times b_1 & B_2 \times b_2 & \cdots & B_6 \times b_6 \\
    \|b_1 - B_1\| & \|b_2 - B_2\| & \cdots & \|b_6 - B_6\|
\end{bmatrix}$$

In the initial orthogonal state of the mechanism, the center of stage is used as the coordinate origin. The coordinate of the six spherical hinge on the frame can be denoted as $B_i = [(c/2+l),d/2,0]^T$, $B_1 = [(c/2+l),d/2,0]^T$, $B_2 = [0,-(c/2+l),d/2]^T$, $B_3 = [d/2,0,-(c/2+l)]^T$, $B_4 = [-d/2,0,-(c/2+l)]^T$. And the coordinate of the six spherical hinge on the stage can be denoted as $b_i = [-c/2,d/2,0]^T$, $b_1 = [-c/2,d/2,0]^T$, $b_2 = [0,-c/2,d/2]^T$, $b_3 = [d/2,0,-c/2]^T$, $b_4 = [-d/2,0,-c/2]^T$. Then the force mapping matrix $[G_f^T]$ can be obtained as follow,
Substituting equation (4) into equation (2), the relationship between the force $f$ along the six rods and the force $F$ on the stage can be expressed as

$$
\begin{bmatrix}
G_f
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 \\
0 & 0 & -d/2 & d/2 & 0 & 0 \\
0 & 0 & 0 & 0 & -d/2 & d/2 \\
-d/2 & d/2 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

(4)

where, $f_i (i = 1, \cdots, 6)$ is the force of each rod, $F_i (i = x, y, z)$ is the force on the stage, $M_i (i = x, y, z)$ is the torque on the stage.

Equation (5) can be simplified as the following,

$$
\begin{align*}
F_x &= f_1 + f_2 \\
F_y &= f_3 + f_4 \\
F_z &= f_5 + f_6 \\
M_x &= (f_6 - f_5)d/2 \\
M_y &= (f_4 - f_3)d/2 \\
M_z &= (f_5 - f_6)d/2
\end{align*}
$$

(6)

According to equation (6), $F_i (i = x, y, z)$ and $M_i (i = x, y, z)$ determined by the force along or around the direction of them. And the force on other directions cannot influence them. Then the output force of parallel mechanism is in decoupling state on the initial position.

3. Design of the decoupled six-axis heavy force calibration device

Electric cylinder or hydraulic cylinder can be used as the driving source of each branch. If electric cylinder or hydraulic cylinder with large rated load is selected, the calibration device can be used to calibrate the six-axis force sensor with large measurement range. In order to position and clamp of the sensor accurately, we design fixtures for fixing the bottom and top of the calibrated sensors separately. Three-jaw chuck is selected as fixture to fix the lower end of sensor because of its advantages of automatic centering and clamping. The wedge expansion fixture is used on the stage to fix the upper
part of the sensor. The wedge-shaped expansion mechanism is shown in the figure 2. The relative horizontal displacement of the two wedge-shaped blocks can be achieved by screwing the screw. The increasing of the vertical dimension of the expansion mechanism leads to the upper plate of the sensor clamped by the wedge-shaped expansion mechanism. Then the assembly structure including the framework, fixture and electric cylinder is shown in figure 3.

![Figure 3. Assembly drawing of calibration device](image)

4. Conclusions
A novel decoupled calibration device for six-axis heavy force sensor based on the orthogonal parallel mechanism is proposed. The decoupling character is proven by the force mapping matrix. The specific structure of the calibration device including the force source, frame and fixture is designed. The calibration principle of the machine is proposed. The fixture for the upper end and the lower end of the six-axis force sensor is designed. The Force analysis shows that all the design meet the requirement.

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References
[1] D. Diddens, D. Reynaerts and H.V. Brussel 1995 Sens. Actuators, A 46 225-232
[2] G.S. Kim 2001 Meas. Sci. Technol. 12 1445-1455
[3] Z.J. Wang, J.T. Yao and Y.D. Xu 2012 Mech. Mach. Theory. 57 84-94
[4] B. Huang, X. Yu and H. Ying 2010 Chin. J. Sci. Instrum. 31 2003-2009
[5] Z.L. Jin, F. Gao 2002 Chin. J. Mech. Eng. 15 298-302