A Six-dimension Parallel Force Sensor for Human Dynamics Analysis

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Abstract—In this paper, parallel support principle of force sensor is discussed, and a six-dimension parallel force sensor is presented for human dynamics analysis. The force sensor with parallel support mechanism was designed to measure six-axis reaction forces during human walking. Finite element method was adopted to optimize mechanism dimension of the force sensor. Sensitivity of force sensor was improved by distributing strain gages on the maximum strain positions. A three-direction drag mechanism was designed for calibrating load cells in the parallel force sensor, and method of least-squares was used to calculate calibration coefficients.

Keywords—parallel force sensor; finite element method; human dynamics

I. INTRODUCTION

It is important to identify motions of certain parts of human body in a number of application fields, e.g. hand-gesture analysis, gait analysis, and muscle tension analysis. Tracking and interpreting human motions have been a key problem, especially in the biomechanics and robotic system with haptic interface. In daily life, human dynamics analysis is becoming important, for example, the gait analysis of pregnant woman can illustrate the different body dynamic conditions that ankle joint moment and hip joint moment are much larger than non-pregnant women. Based on dynamic analysis data, the assistant and rehabilitative devices are developed for pregnant woman or patients [1].

The integration of three-dimension motion measurement with multi-camera system and ground reaction measurement with force plates has been successfully devoted to tracking human body parts and performing dynamics analysis of their physical behaviors in a complex environment [2][3]. However this method needs sizeable work space and high-speed graphic signal processing devices, therefore it is inefficient in real time controls and is expensive for daily product development. Moreover, human body is composed by many highly flexible segments, and the up body motion of human is especially complicated for accuracy calculation.

In this research, a six-dimension force sensor is developed to measure reaction forces in human dynamics analysis. The traditional and commercial sensor usually adopts serial load cells structure, so each load cell should be strong enough to stand the loads originating from non-measurement directions. However, in the case of reaction forces during human walking, the gravity direction forces may be over 1000N, and the friction forces are only about 50N. The large landing impact and rotational forces of human moving make it difficult to find traditional or commercial sensors for such application. The force sensors with parallel support mechanism developed by Nishiwaki [4] can be used to measure the reaction force during human walking, and control humanoid robots' Zero Moment Point (ZMP). This sensor is, however, a little ambitious in its claim that the sensor prototype can be universally used in experiments with humanoid robot and humans, because its weight of 700g and height of 35mm are not appropriate to reduce the disturbance of human walking. In this paper, parallel support principle is introduced in section 2, and a parallel force sensor is presented and analyzed in section 3.

II. PARALLEL SUPPORT PRINCIPLE

A. Parallel-mechanism Force Sensor

Figure 1 shows the measurement theory of the two kinds of support mechanisms. The sensor with serial structure should be strong enough for each load cell to stand loads coming from non-measurement directions [5]. To stand large pressure force and rotational moment, parallel support mechanism is used to distribute the reaction forces to many different support points. In each support point, only translational forces are measure by load cells. The interference of different direction forces can be neglected, because the relationship of measurement load cell and input force is one-to-one.

The sensor with parallel support mechanism can detect moments in three directions, through measuring translational forces in three directions on each support point. As shown in Fig. 2, the sensor is mainly composed of four parts: top plane, bottom plane, load cell and balls. When the forces including...
moments are applied on down plane, keeping mechanisms on the down plane transfer the forces to four support balls, then through the contacting actions between balls and load cells, three-axis translational forces on each support point are measured by load cell. The strain gages on load cells are the sensing components.

B. Load Cell

Load cell is design to measure the translational force by using strain gauges, and on each support point, three load cells are used to measure three-direction translational forces.

Three load cells are put on three support points respectively, and measure three-direction translational forces, each load cell uses strain gauges to detect the translational force. Fig. 3 shows that ball of each support point is used to transfer three-direction translational forces to load cell by point contacting with load cell. The contacting moment between ball and load cell is not included, because the point contact of ball only transfer translational force. In order to decrease effect of friction, as show in Fig. 4, high hard balls (SUJ Hardened high carbonchrome steel, surface hardness HRC 62-67) and hardened tool steel (SKD11 HRC 65) are used on the contacting points.

III. SIX-DIMENSION FORCE SENSOR

A. Finite Eelement Analysis

Finite element method was adopted to optimize the dimension of strain beam. As shown in Fig. 5, the solid model of the beam measuring Y- and Z- direction force was constructed by using Pro/E, and imported to ANSYS to perform the static analysis of beam. The resistant strain gauges are distributed on the position with maximum strain according to the FEA result. Figure 6 is the one of the graph result of FEA by using ANSYS.

Finite element method was adopted to optimize the mechanism dimension of strain beams, and improve the sensitivity of force sensor.

B. Mechanism of the Parallel Force Sensor

A wearable force sensor was developed to measure three-direction reaction force and three-direction moment during human walking. In this paper, X-, Y-, and Z- directions represent leftward, forward, and upward direction respectively, and Mx, My, and Mz represent three-direction moments. The mass of the six-dimension sensor is about 300g, and its length, width and height are 170mm, 105mm and 26.5mm respectively.
Figure 7 shows the prototype of the wearable force sensor, in which the measurement beam is made of ultra hard duralumin, and eight groups of resistant strain gages are used to construct the 12 load cells. In order to make the mechanism more compact, as shown in Figure 8, hybrid measurement beam is adopted for Y, and Z direction load cell. This design also can decrease the number of strain gauges and amplifier modules. The full rated force sets for this sensor are specified to be $F_x=F_y=20$ kgf, $F_z=100$ kgf, and $M_x=M_y=M_z=100$ Nm.

C. **Calculation of Six-dimension Force**

Figure 9 shows a simplified graph of six-axis measurement sensor. Assume six-dimension force calculation point as the center of ball center’s plain. Force for positive direction of $F_x$ is measured as $F_{x1}+F_{x2}$, and negative direction as $F_{x3}+F_{x4}$. Therefore, $F_x$ can be defined as follows:

\[
F_x = F_{x1} + F_{x2} - F_{x3} - F_{x4} \quad (1)
\]

$F_x$ and $F_z$ can be calculated in (2) and (3) by using the same method.

\[
F_y = F_{y1} + F_{y4} - F_{y2} - F_{y3} \quad (2)
\]

\[
F_z = F_{z1} + F_{z4} + F_{z2} + F_{z3} \quad (3)
\]
Define $L$ as the distance of support point along Y-axis direction, and $W$ as the distance of support point along X-axis direction. Then rotation moments on center point can be calculated by using the output value of load cell. $M_x$, $M_y$ and $M_z$ are calculated as follows:

$$M_x = (F_{z2} + F_{z3} - F_{z1} - F_{z4})L / 2$$  

(4)

$$M_y = (F_{z3} + F_{z4} - F_{z1} - F_{z2})W / 2$$  

(5)

$$M_z = (F_{x1} + F_{x3} - F_{x2} - F_{x4})L / 2 + (F_{y1} + F_{y3} - F_{y2} - F_{y4})W / 2$$  

(6)

D. Strain Gage Signal Amplifier and Recorder

In the experiment of the six-dimension sensor, strain measurement device EDX-1500A of Kyowa Electronic Instruments Co is used to amplify and record dynamic signals of strain gage in each load cell.

IV. CALIBRATION OF FORCE SENSOR

A. Calibration Mechanism

A three-direction drag mechanism was designed to calibrate the load cells in the parallel force sensor, as show in Fig. 10. The load cell can be separately calibrated by using this mechanism, because the parallel sensor is designed to make six-axis forces decouple, and interference among different axes is decreased by the parallel support mechanism, which just measure translational forces in three directions.

B. Calibration of Force Sensor

Referenced forces were applied on every load cell, and outputs of load cells were recorded by strain measuring device (KYOWA EDX-1500A). Method of least square was used to calculate calibration coefficient in MATLAB. The calibration graphs of X-, Y- and Z-axes are shown in Fig. 11, Fig. 12 and Fig. 13 respectively. In the calibration graphs, the vertical axis is input forces of load cells, and the horizontal axis is output of load cells.

![Fig. 10 Calibration mechanism of six-axis force](image)

![Fig. 11 X-direction calibrations](image)

![Fig. 12 Y-direction calibrations](image)

![Fig. 13 Z-direction calibrations](image)
As show in table I, X-, Y- and Z-directions forces calibration matrices are defined as \([C_{x1}, C_{x2}], [C_{y1}, C_{y2}, C_{y3}, C_{y4}], [C_{z1}, C_{z2}, C_{z3}, C_{z4}]\) respectively.

<table>
<thead>
<tr>
<th>Calibration Coefficient</th>
<th>X(*10^-3)</th>
<th>Y(*10^-3)</th>
<th>Z(*10^-3)</th>
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<tbody>
<tr>
<td>Cx1</td>
<td>2.8</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Cx2</td>
<td>2.8</td>
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<td>2.4</td>
</tr>
<tr>
<td>Cy1</td>
<td>2.8</td>
<td>2.7</td>
<td>2.4</td>
</tr>
<tr>
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<td>7.0</td>
<td>6.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Cy3</td>
<td>6.2</td>
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<td>Cz1</td>
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<tr>
<td>Cz2</td>
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<tr>
<td>Cz4</td>
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</table>

V. CONCLUSION

In this research, a six-dimension parallel force sensor was developed to measure three-direction reaction forces and three-direction moments in human dynamics analysis. The calibration experiments were made to calculate calibration coefficient and test linear property of the sensor. This sensor with parallel mechanism can stand impact force and large rotational moment. Finite element method was adopted to optimize the mechanism dimension, and improve the sensitivity of force sensor by distributing strain gages on the maximum strain positions.

In human dynamics analysis, the single contacting plane force sensor can produce disturbance during human walking, so a second designed sensor with double contacting planes is to be designed to let toe joint freely move, and decrease disturbance in human walking.

REFERENCES