Design of Low-cost Tactile Force Sensor for 3D Force Scan

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Abstract—A new 3D tactile sensor was proposed for measuring tri-axial ground reaction force distribution. Pressure sensitive electric conductive rubber (PSECR) and smart pectinate circuits were used to design the pressure sensing cells in the 3D force sensor, making it possible to implement a low-cost, compact and light sensing matrix which is highly sensitive in measuring force distribution. Moreover, to address the application for measurements of human touch force, we adopted the elastic rubber as the sensor input component to realize a comfortable human-sensor interface. A compact electrical hardware system including amplifiers module, conditioning circuits and a micro-computer controller and wireless modules was developed to sample sensor outputs into personal computer for data processing. Calibration experiments were conducted, in which a smart 3-axial force sensor (Tec Gihan, Japan) was used as the verification measurement device.

Keyword: 3D tactile sensor, ground reaction force, conductive rubber.

I. INTRODUCTION

Force plates have been successfully devoted to measure force and moment for human dynamics analysis in various environments [1]-[2]. Because this method needs sizeable operation space and expensive signal processing devices, recently some wearable sensor systems were developed for applications in measurements of human reaction force. Pressure sensors were widely used to estimate the distributed vertical ground reaction forces [3], but the effects of shearing force or friction force were neglected. Some silicon sensors recently were developed to measure both vertical and shearing forces at the skin-object interface [4], but the force levels of these sensors are limited in the measurements of small forces (about 50N). As shown in Fig. 1, we are concentrating on applying and developing some wearable 3D force sensors to measure ground reaction force during human walking. In our prior study, we had made a multi-axial force sensor to measure 3-axial ground reaction forces and coordinates of center of pressure, when fixed under a specially designed shoe [5]. However, its hard interface and weight load for the foot affected human normal walking according to our experimental study. A sensor matrix will be constructed to perform 3D force scan, which also can be integrated into a flexible material, so this force sensor system can measure 3D ground reaction force with a comfortable interface for the human body. A new design of low-cost tactile force sensor for 3D force scan is presented in this paper.
II. MATERIALS AND METHODS

A. Sensing Material

Pressure sensing cell of the 3D force sensor was designed using pressure sensitive electric conductive rubber (PSECR) which has been used for measuring pressure force distribution. PSECR has been developed for the sheet-switch of the electronic circuits, and has a unique property in that it conducts electric current only when compressed, and acts as an insulator when the pressure is released. The material properties of PSECR are given in Table I.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>gray-black</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>1.86 MPa</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>220 %</td>
</tr>
<tr>
<td>100% modulus</td>
<td>0.86 MPa</td>
</tr>
<tr>
<td>Tear resistance</td>
<td>7 kN/m</td>
</tr>
<tr>
<td>Hardness in Durometer</td>
<td>50</td>
</tr>
</tbody>
</table>

B. Structure of Sensor

As shown in Fig. 2, the pressure sensing cell in the developed sensor is composed of a PSECR film and a pectinate circuit in fan shape. When pressure force is applied on the surface of PSECR film, the change of resistivity of pectinate circuit is transformed to corresponding voltage output using an operation amplifier circuit. We designed the 3D tactile force by combining four pressing sensing cells (see Fig. 3), and a decouple algorithm was given to calculate 3-axial force from pressure force \( P_i \) measurement the voltage outputs \( V_i \) of sensing cells.

Pressure force measured using the sensing cell can be obtained from \( P_i = S_i \cdot V_i \) for each measurement point. As shown in Fig. 3, all the four sensing cells can detect pressure force introduced by vertical force \( F_z \), while sensing cell I and III were also used to measure pressure force produced by positive and negative shearing force \( F_x \) respectively, and in the same way, sensing cell II and IV were designed to transduce y-direction shearing force \( F_y \). In order to explain the calculation of 3-axial force, here we give two hypotheses: the sensing cell has a high lever degree of linearity in its measuring range; vertical pressure \( F_z \) is evenly distributed on the four sensing cells. When three-directional force is applied on the sensor designed by four sensing cells, pressure force \( P_i \) can be calculated form below equations.

\[
P_1 = S_1 \cdot V_1 = t_1 F_{+x} + F_z / 4
\]

\[
P_3 = S_3 \cdot V_3 = t_3 F_{-x} + F_z / 4
\]

\[
P_2 = S_2 \cdot V_2 = t_2 F_{+y} + F_z / 4
\]

\[
P_4 = S_4 \cdot V_4 = t_4 F_{-y} + F_z / 4
\]
\[
F_x = \left( S_1 / t_1 \right) \cdot V_1 - \left( S_3 / t_3 \right) \cdot V_3
\] (5)

\[
F_y = \left( S_2 / t_2 \right) \cdot V_2 - \left( S_4 / t_4 \right) \cdot V_4
\] (6)

\[
F_z = S_1 \cdot V_1 + S_2 \cdot V_2 + S_3 \cdot V_3 + S_4 \cdot V_4 - t_i \cdot \left( |F_x| + |F_y| \right)
\] (7)

where \( t_i \) is equal to \( t_i (i = 1, 2, 3, \text{and} 4) \), and \( |F_x| = (F_{-x} + F_{+x}), |F_y| = (F_{-y} + F_{+y}) \). When \( (S_i / t_i) \) is defined as one parameter \( S_{ti} \), we can rewrite (5), (6) and (7) as below equations for the sensor calibration.

\[
F_x = S_{t1} \cdot V_1 - S_{t3} \cdot V_3
\] (8)

\[
F_y = S_{t2} \cdot V_2 - S_{t4} \cdot V_4
\] (9)

\[
F_z = t_i \cdot \left( |S_{t1}\cdot V_1| + |S_{t2}\cdot V_2| + |S_{t3}\cdot V_3| + |S_{t4}\cdot V_4| - |F_x| - |F_y| \right)
\] (10)

C. Calibration of Sensor

To calibrate and characterize the 3D tactile force, a testing experimental system composed of a smart 3-axial force sensor USL06-H5-500N-C (Tec Gihan, Japan) and a 3D stage (Micro mill) was constructed to provide 3-axial reference force (see Fig. 4). In the first step, we need obtain calibration coefficients for two shearing directions referred as x- and y-axis. As shown in Fig. 5 and Fig. 6, when the two sensor systems worked in the synchronized mode, a group of results including four sensing cells’ voltage output signals and two-axial reference force measured by smart 3-axial force sensor, were obtained from a calibration experiment to estimate calibration coefficients composed of \( S_{t1}, S_{t2}, S_{t3}, \text{and} S_{t4} \). We finished multiple regression analysis of the sampled sensor data using a statistical software of SPSS 11.0J. The results of the multiple regression analysis are shown in table II, and the column \( S_{ti} \) of calibration coefficients were used for the next step calibration experiment for vertical force of z-axial force.

![Fig. 4: Calibration experimental system.](image)

![Fig. 5: Experimental results of sensor calibration.](image)


![Fig. 6: Experimental results of sensor calibration.](image)

### Table II Results of the multiple regression analysis

<table>
<thead>
<tr>
<th>Sensing cells</th>
<th>Unstandardized</th>
<th>Standardized</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sti</td>
<td>Std. Error</td>
<td>Beta</td>
</tr>
<tr>
<td>I</td>
<td>2.99</td>
<td>0.04</td>
<td>-0.66</td>
</tr>
<tr>
<td>II</td>
<td>6.30</td>
<td>0.19</td>
<td>-2.65</td>
</tr>
<tr>
<td>III</td>
<td>3.75</td>
<td>0.02</td>
<td>1.22</td>
</tr>
<tr>
<td>IV</td>
<td>5.36</td>
<td>0.24</td>
<td>1.75</td>
</tr>
</tbody>
</table>

By substituting the results of the first step for shearing direction calibration to (10), a linear regression analysis was used for obtaining the calibration coefficient (ti), and calculating z-axial force. Fig. 7 presents the graphs of the data, which imported into the linear regression analysis in SPSS. The results of the linear regression analysis show low standard error of 0.09 for ti=79.3.

### III. RESULTS

In order to evaluate the precision of the sensor, 3D measurement tests have been performed using the preliminary calibration system composed of a 3-axial force sensor and a 3D stage. As shown in Fig. 8, when the reference sensor and the developed sensor worked in the synchronized mode, three-axial outputs of the sensor were compared with three-directional reference loads, and the correlation coefficients for the vertical force (z-axis) and two-axial shearing force (x- and y-axis) are 0.92, 0.98 and 0.93 respectively. In the measurement experiment the percent error of x-, y- and z-axial outputs are 1.2%, 2.0%, and 4.5% respectively.

![Graph showing results of sensor calibration](image)

**Fig. 7: Experimental results of sensor calibration.**

(a): Z-axial vertical reference load. (b): Output signals of four pressure sensing cells.

IV. CONCLUSION

Pressure sensitive electric conductive rubber (PSECR) and smart pectinate circuits were used to design the pressure sensing cells in the 3D force sensor, making it possible to implement a low-cost, compact and light sensing matrix which is highly sensitive in measuring force distribution. We constructed a testing experimental system using a 3-axial force sensor to measure reference load, and the calibration experiment of the developed sensor was completed through the application of arbitrary forces with known magnitude and direction. The verification experiment results indicate that the sensor can measure three-axial forces with high precision.

### REFERENCES


