ABSTRACT: The three-dimensional (3-D) flexible tactile arrays sensor is a kind of sensor with high-precision, high-resolution and high-speed response which can measure tactile information as human skin perception for robotic to access environmental information. It’s critical to study the calibration apparatus and its method of the 3-D flexible tactile sensor arrays. This paper proposes the principal of the 3-D flexible tactile sensor arrays and designs a novel calibration apparatus and the calibration method for it. It can be used not only for calibration experiment but also for the design experiment of the sensor arrays with different array size, different precision and different range. The calibration experiment result indicates that the calibration apparatus meets the precision requirement and promotes the use of such sensors.

Keywords: 3-D flexible tactile sensor arrays, calibration apparatus, calibration method

1 INTRODUCTION

With the deepening of robotic exploration in the world, three dimensional (3-D) flexible tactile sensor arrays have become a hot research for robot skin and an essential tool for robotic to access environmental information, which is a kind of sensor with high-precision, high-resolution and high-speed response, and can measure tactile sensor information as human skin perception[1]. However, because of the nonlinearity of flexible sensing microstructure, there is a large output error with this kind of sensor. In addition, characteristics of different parts of the 3-D flexible tactile sensor arrays are non-uniformity due to the non-identity of production process. Because of the nonlinearity and hysteresis of the sensing microstructure, now the studies of 3-D flexible tactile sensor arrays based on conductive rubber are focused on the structure design and decoupling algorithm of the sensor, assuming that the sensor characteristic is ideal linear with a highly simplify sensor model [2-3].

Because of the problems exist in 3-D flexible tactile sensor arrays, the sensor must be calibrated before measurement [4]. Lack of calibration apparatus has make great difficulties in widely use of the 3-D flexible tactile sensor arrays. The existing platforms such as calibration apparatus made by Hefei Institute of Intelligent Machines which can be used as calibration apparatus for independent rigid 3-D force / torque sensor [5], can’t calibrate 3-D flexible tactile sensor arrays. A mechanical calibration apparatus for sensor arrays and its working method proposed by document[6] can be used as a calibration apparatus for one-dimensional tactile sensor arrays, but it cannot be used for the 3-D tactile sensor arrays. There is a lack of calibration apparatus and the calibration method for the large-scale 3-D flexible array tactile sensor based on flexible sensitive materials. It is necessary to study the calibration apparatus and the calibration method for the sensors of this kind. The calibration results will directly affect the measurement accuracy and promote the use of such sensors.

2 THE PRINCIPLE OF 3-D FLEXIBLE TACTILE SENSOR ARRAYS

Pressure sensitive conductive rubber is a new type composite material of electrically conductive, which is
an ideal flexible tactile sensor material with soft viscoelastic with adjustable mechanical and electrical properties. Reference [7] proposed a novel structure of 3-D flexible array tactile sensor arrays based on pressure-sensitive conductive rubber. The conductive rubber is filled into a pre-arranged multi-arrays structure by injection molding method, which solve the problems of the flexibility and the multi-dimensional information achievement existed in multi-dimensional tactile sensor arrays.

The internal structure of 3-D flexible tactile sensor arrays is shown in Figure 1, where ordered micro-structure units are connected by wires. When the external force is applied onto the micro-structural unit, three columns of the micro-structure unit will deform and the applied external force can be decomposed into three different directions (x, y and z). According to the piezoresistive effects of conductive rubber and the measured resistance matrix of three cylindrical conductive rubbers by sampling circuit, the force size $F_i$ can be obtained, where $i$ is x, y or z.

![Figure 1. Schematic diagram of the flexible 3-D tactile sensor arrays.](image)

As shown in Figure 2, the gantry is located on the base by bolting, where the X-axis moving mechanism in horizontal direction connected to the Y-axis moving mechanism in horizontal direction, 3 is the X-axis moving mechanism in horizontal direction, 4 is the Y-axis moving mechanism in horizontal direction, 5 is the sensor mounting platform, 6 is the Z-axis moving mechanism in vertical direction, 7 is the horizontal rotating mechanism of loading head, 8 is the vertical rotating mechanism of loading head, 9 is 3-D force loading head and 10 is the measured sensor.

![Figure 2. Calibration apparatus of the flexible 3-D tactile sensor arrays.](image)

The 3-D force can be resolved by calibration resistance matrix as a superposition of three directions and the input and output characteristic of sensor agree with the actual calibration results.

### 3 AUTOMATIC CALIBRATION APPARATUS OF 3-D FLEXIBLE TACTILE SENSOR ARRAY

The schematic diagram of calibration apparatus [9] for 3-D flexible tactile sensor array is shown in Figure 2, in which, 1 is the base, 2 is the gantry, 3 is the X-axis moving mechanism in horizontal direction, 4 is the Y-axis moving mechanism in horizontal direction, 3 is the X-axis moving mechanism in horizontal direction, 4 is the Y-axis moving mechanism in horizontal direction, 5 is the sensor mounting platform, 6 is the Z-axis moving mechanism in vertical direction, 7 is the horizontal rotating mechanism of loading head, 8 is the vertical rotating mechanism of loading head, 9 is 3-D force loading head and 10 is the measured sensor.
ing mechanism in horizontal direction. The 3-D coordinate system is established at the center of the horizontal beam of gantry.

At the same time the Z-axis moving mechanism in vertical direction is set in the middle of the gantry with the horizontal rotary loading mechanism connected below it, and the vertical rotary loading mechanism with 3-D force loading head is connected in sequence. The axis of the vertical rotary loading mechanism located in the base plane coplanar with the horizontal rotary loading mechanism axis, which is perpendicular to the surface of the horizontal rotary loading mechanism. The 3-D XYZ axis movement mechanism and the vertical / horizontal rotary loading mechanism were driven by subdivision drive motor to ensure the high accuracy of the calibration apparatus.

The 3-D force loading head is constitutes of a mounting arm, standard force sensor, conical nozzle and pure shear loading arm, where the mounting arm, a standard force sensor and the conical nozzle is coaxially installed with force loading head in proper order by the fixing jig. When a pure shear force is loaded, the specially configured loading mechanism is shown in Figure 3, in which 3-1 is the installation arm, 3-2 is the standard force sensor, 3-3 is the tapered mouth, and 3-4 is the pure shear loading arm. Otherwise the pure shear loading arm with a thin adhesive at the bottom surface can be bolted to the conical nozzle of the loading arm when pure shear force is loaded, and the pure shear loading arm can be dismantled after calibration.

![Figure 3. Schematic diagram of loading head.](image)

The measured 3-D flexible tactile sensor arrays are connected to the sensor mounting platform by the viscose with moderate adhesion, which can be removed after calibration without damage to the sensor. Zero-hole for zero calibration is set at the side of the sensor mounting platform for device zero adjustment of calibration. The XYZ-axis grating ruler, XYZ-axis direction moving mechanism and horizontal/vertical rotating mechanism are set to be zero coordinate of calibration by zeroing operation.

4 THE PRINCIPAL OF CALIBRATION DEVICE

4.1 3-D force loading

Under the control of calibration procedure different loading head is chosen according different loading. The 3-D force loading head is chosen for pure shear force loading with the conical nozzle gesture of the loading head adjusted by the direction of 3-D forces. As shown in Figure 4, the calibration procedure calculates the size and direction of the 3-D force loading $F_{\text{total}}$ and controls the horizontal and vertical rotation mechanism to adjust the angle of the loading head to the 3-D joint direction [10]. The 3-D force loading head rotates in the vertical plane XOZ with angle $\beta$ to Y-axis driven by vertical rotary stepper motor-driven, and rotates in the horizontal plane with angle $\alpha$ to X-axis driven by horizontal rotary stepper motor-driven, where angle $\alpha$ and $\beta$ can be calculated as follows:

$$F_{\text{total}} = \sqrt{(F_x^2 + F_y^2 + F_z^2)}$$  \hspace{1cm} (4)

$$\alpha = \arctan \frac{F_x}{\sqrt{F_y^2 + F_z^2}}$$  \hspace{1cm} (5)

$$\beta = \arctan \frac{F_x}{F_y}$$  \hspace{1cm} (6)

![Figure 4. Schematic diagram of the 3-D force angle.](image)

When angle $\alpha$ and $\beta$ is positive, the 3-D force loading head rotates in the clockwise direction, on the contrary the 3-D force loading head rotates in anti-clockwise direction. The angle of the 3-D force loading head is adjusted in the closed-loop control of horizontal and vertical angle encoder until its direction consistent with the 3-D force.

After the angle adjustment of the 3-D force loading head, the calibration procedure solves the 3-D XYZ coordinate position of loading endpoint for conical nozzle by the measurement of the XYZ axis grating ruler, the horizontal and vertical angle encoder. By comparing the positions between the loading endpoint and the point to be calibration on the flexible tactile sensor array surface, the XYZ-axis movement mechanisms adjust the loading endpoint to coincide the two coordinate positions under the closed-loop control of XYZ-axis grating ruler, the horizontal and vertical angle encoder.

Then the 3-D force is applied onto the sensor surface by the Z-axis movement mechanism. In the closed-loop control of the standard force sensor, the
Z-axis stepper motor is adjusted until the standard force sensor gets the same force as required, and ultimately the 3-D force of specified size and direction is accurately loaded on the 3-D flexible tactile sensor arrays surface, which realizes a independent or combined 3-D force \((F_x, F_y, F_z)\) loading onto 3-D flexible tactile sensor arrays.

### 4.2 Pure shear force loading

Different with 3-D force calibration, when a pure shear force \((F_x, F_y, 0)\) is to be loaded, the z-axis force \(F_z\) is zero and \(\beta = 90^\circ\). The pure shear force loading arm is assembled at the end of the tapered nozzle by a bolt rear, and its bottom surface stuck on the sensor mounting platform with thin glue. The calibration procedure calculates the size and direction of the resultant force according to the size of the force \((F_x, F_y, 0)\), by the formula (7) - (8).

\[
F_{xy} = \sqrt{F_x^2 + F_y^2} \quad (7)
\]

\[
\theta = \arctg \frac{F_x}{F_y} \quad (8)
\]

In the closed-loop control of the horizontal and vertical angle encoder, the horizontal and vertical rotating mechanism adjust the pure shear force loading arm so that its axis is in the same direction of the resultant and its bottom surface is tangent to the surface of the sensor arrays. Then the calibration procedure adjusts the bottom surface center of the loading arm to coincide it with the calibration point on the flexible tactile sensor arrays surface as the same steps for the 3-D force loading and pasted a thin flexible adhesive on its bottom surface with the surface of 3-D tactile sensor array.

When the pure shear force is loaded, the calibration apparatus drives the X/Y axis stepper motor respectively in X/Y axis direction with drive torque at a ratio \(\frac{F_x}{F_y}\) to apply shear force in resolution motion direction onto the sensor. Under the loop control of standard force sensor, calibration apparatus applies an accurate pure shear force loading.

### 5 CALIBRATION SIMULATION

A sample of 3-D flexible tactile sensor arrays is selected for simulation, with a size of 10×10×1mm³ and a size of 1×1×1mm³ for micro-structure. The sample is pasted at the center of sensor mounting platform \((0,0,0)\). Comparing with the size, range, spatial resolution and material properties of the sample to be calibrated, calibration parameters such as the coordinates of each point to be marked, calibration path, the size and number of loading are calculated by the calibration procedure and set on the PC.

The initialization of calibration apparatus begins with horizontal and vertical alignment, which using gradienter for horizontal alignment of sensor mounting platform, horizontal beam of gantry and horizontal X/Y axis moving mechanism in a horizontal position, and at the same time using Cartesian rules for vertical alignment of gantry vertical beam and vertical Z-axis moving mechanism in a vertical position.

Next the return-to-zero command controls XYZ axis stepper motor, horizontal, vertical rotary stepper motor to coincide the conical nozzle with zero hole at the side of mounting platform, and the calibration program marks this 3-D coordinates as the zero point of XYZ-axis scale, XYZ-axis moving mechanism and horizontal/vertical rotation mechanism.

According to the sensor resolution, the calibration program calculates all microstructure to be calibrated, and selects a coordinate of loading point in sequential. In the closed-loop control of standard force sensor, an independent or combined 3-D force is loaded on the sensor and meanwhile the corresponding coordinates, force size and the output information of 3-D flexible array tactile sensor are recorded by the data acquisition device. Force in X, Y and Z direction is alternating loaded on sensor surface, where 0-300kPa in X, Y and Z direction, with an increments of 20kPa. And the program selected the microstructure to be calibrated point by point in sequence until all microstructures on the sensor surfaces are loaded. Further, the calibration apparatus changes the force to be loaded in sequence until all described forces loaded on all microstructures.

#### Table 1. The relative error of the 3-D force with different spreads.

<table>
<thead>
<tr>
<th>Spread</th>
<th>(\delta F_z)</th>
<th>(\delta F_x)</th>
<th>(\delta F_y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>3.13%</td>
<td>9.06%</td>
<td>15.63%</td>
</tr>
<tr>
<td>0.9</td>
<td>1.39%</td>
<td>1.63%</td>
<td>14.96%</td>
</tr>
<tr>
<td>1.0</td>
<td>0.90%</td>
<td>1.04%</td>
<td>7.56%</td>
</tr>
<tr>
<td>1.2</td>
<td>0.88%</td>
<td>0.53%</td>
<td>6.15%</td>
</tr>
<tr>
<td>1.5</td>
<td>0.17%</td>
<td>0.38%</td>
<td>3.36%</td>
</tr>
</tbody>
</table>

The experimental flow chart for calibration is shown in Figure 5. A large number of calibrated data collected and the decoupling calibration network for 3-D flexible tactile sensor array received by the algorithm after calibration. All these steps finished automatically under the control of the calibration procedure. The algorithm gets the decoupling calibration network of the sensor by the Radial Basis Function Neural Network algorithm (RBFNN), with the spread of 0.8, 0.9, 1.0, 1.2 and 1.5, and the relative error decoupling results is shows in Table 1. The results show that the maximum relative error of \(F_x\) is 3.36%, the maximum relative error of \(F_y\) is 0.38%, the maximum relative error of \(F_z\) is 0.17%, where the maximum
relative error of 3-D force decreased with the increase of the spread.

In which, $\delta F_i$ is the average of the relative error of 3-D force.

$$\delta F_i = \frac{\sum_{t=1}^{100} \left| F_{i t} - F_{i}' \right|}{100}$$

$\delta F_i$ is the average of the relative error of 3-D force.

Figure 5. The experimental flow chart for calibration.

6 CONCLUSION

This paper presents a novel calibration apparatus and corresponding calibration method for 3-D flexible tactile sensor arrays based on gantry structure, which is a kind of device with simple structure, high precision, low cost and simple operating method. Under the control of the calibration procedure it can change the angle of 3-D force loading mechanism, positioning and accurate 3-D force loading. The loading mechanism posture is determined by the direction of the resultant force, with which 3-D force is loaded by the loading head of horizontal and vertical rotating mechanism, under the closed-loop control of horizontal and vertical encoder. Combined with the XYZ axis grating ruler and the horizontal/vertical angle encoders the device achieves accurate positioning on sensor surface. In the closed loop control of standards force sensor, different types of force with different loading mechanism and loading method realize an independent or combined 3-D load loading.

This calibration apparatus and calibration method are not only applicable to the 3-D tactile flexible sensor arrays, but also suitable for the independent, rigid 3-D tactile sensor calibration. Different loading head and calibration method is selected for different kind of works, which is especially suitable for a pure shear loading on the surface of a 3-D flexible tactile sensor arrays. It can achieve 3-D force calibration automation with loading and loading-off intelligently, which can be used not only for sensor calibration experiment but also for the sensors design experiment with different sensor array size, different precision and sensor range. It solves the accurately measurement of the 3-D tactile flexible sensor arrays and promote the use of such sensors.

ACKNOWLEDGEMENT

This paper is financially supported by NSF of Anhui (No.1308085QF104; No.1408085QF123).

REFERENCES


