Soft 3D Tactile Sensor for Artificial Fingertips
—Design, Fabrication, and Testing of the Sensor—

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This paper proposes a novel tactile sensor developed to be used in artificial fingers to measure force and detect vibrations. The sensor measures magnetic flux in space using three orthogonal ratiomatric linear sensors (RLS) placed around a cylindrical niobium magnet. The change in magnetic flux near the RLS is proportional to the inverse third power of the distance from the magnet to the RLS. The magnet and the sensors are covered by a soft overlay which can be deformed when forces are applied. By measuring the change in magnetic flux near the three RLS and using beam bending theory, we could calculate forces applied at the tip of the soft sensor structure.

***Key Words*:** Tactile sensors, force sensors

1. Introduction

Tactile sensing is considered vital for the development of the intelligent robotic systems. Similar to human fingers, robots fingertips will be the most important tactile sensing surface of the robot. Therefore, artificial tactile fingers should have the same capability of the biological fingertips but with a simpler sensor construction.

In recent years several artificial fingertips were developed which has tactile perception. These had different methods of measuring force, detecting vibrations which are components of tactile perception. Among them, few were designed to mimic a biological finger. Most of the fingertips used sensors which used MEMS based technologies. Ho [1] developed a MEMS based soft fingertip and conducted texture recognition. Boissieu [2], Oddo [3] developed similar MEMS based fingertips and conducted research on surface textures identification. Jamali [4], and Takamuku [5] developed anthropomorphic fingertips where randomly distributed strain gauges and Polyvinylidene Fluoride (PVDF) films embedded in silicon. Liu [6] developed a robot finger that can detect contact location, normal and tangential forces and vibration. Howe [7] developed a soft fingertip that has accelerometers to detect vibrations. It was used for slip perception. Chathuranga [8] also developed such a soft fingertip using accelerometers and force sensors. Above mentioned sensors have one or two sensing modalities of sensing. It is achieve by using different sensing structures sensitive to only one modality.

The proposed design is a simple construction with one sensing method for detecting both force and vibration modalities. Its simplicity and easy construction is favorable to be used in robotic fingertips as a quickly replaceable component.

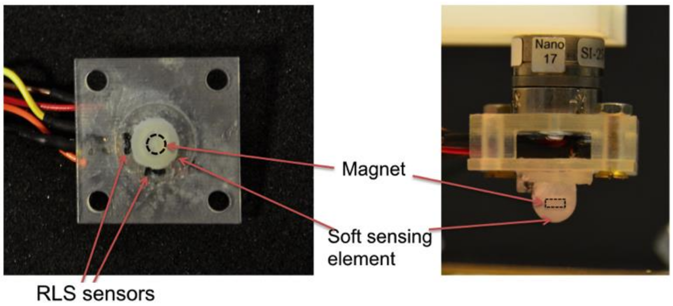

Fig. 1: Tactile sensor

2. Theory and Construction of Tactile Sensor

The tactile sensor (Fig. 1) used in these experiments was made from a soft material (Smooth-on Dragon Skin 30). A Niobium cylindrical magnet with a diameter of 2 mm was embedded in the soft material. The soft material was cylindrical ($\Phi = 8$ mm) in shape with a hemisphere at the end. Outside this soft layer ($a = 5$ mm from center of magnet) were three Honeywell SS495A ratiomatric linear sensors (RLS) orthogonal to each other. When an external force was applied to the soft silicon material, the material deformed, displacing the magnet inside and causing the magnetic flux to change near the RLS. The change in magnetic flux around a cylindrical magnet at point $P(x, y, z)$ (Fig. 2) can be expressed as:

$$B = \mu_0 H_z = \frac{1}{4\pi} \int q \frac{h}{\left|\vec{h} + \vec{r_0}\right|^3} ds \qquad (1)$$

where H_z, μ_0 and q are the z components of magnetic field intensity, permeability in free space, and magnetic charge density respectively [9]. The vector $\vec{r_0}$ is the position of RLS relative to the base coordinates and $\vec{h}$ is the vector from magnet coordinates to base coordinates. Tactile forces applied to sensor will cause the magnet to change its position $(\Delta x, \Delta y, \Delta z)$ from the base coordinates. Expressions for $\Delta x, \Delta y$, and Δz are complex, but it could be calculated from the following equations.

$$(\Delta x + a)^2 + \Delta y^2 = \sqrt[\frac{2}{3}]{\frac{C}{V_x}} - \sqrt[\frac{2}{3}]{\frac{C}{V_z}} \qquad (2.a)$$

$$(\Delta y + a)^2 + \Delta x^2 = \sqrt[\frac{2}{3}]{\frac{C}{V_y}} - \sqrt[\frac{2}{3}]{\frac{C}{V_z}} \qquad (2.b)$$

$$\Delta z = \sqrt[3]{\frac{C}{V_z}} - h_0 \qquad (2.c)$$

where

$$C = \frac{kql_mS}{4\pi}$$

and k is the ratio of magnetic field to voltage conversion by RLS, l_m is the half height of the magnet and S is the cross sectional area of magnet, and V_x, V_y and V_z are the absolute voltages detected by the RLS. The magnet surface is fixed at h_0 = 3 mm, and the constant q is set at 1.15 wb/mm^2. The RLS outputs a voltage proportional to the change in magnetic flux, indicating that the voltage read out from

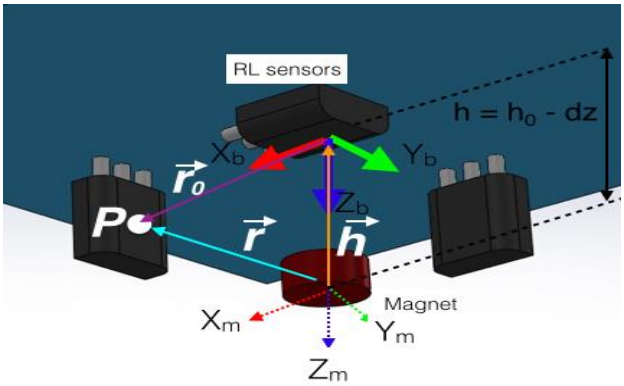

Fig. 2: Coordinate system used for the calculation of the change in magnetic flux near RLS. The RLS sensors are perpendicular to each other, resulting in x; y; z orthogonal coordinates.$X_b; Y_b; Z_b$ are base coordinates and $X_m; Y_m; Z_m$ are magnet coordinates

the RLS is an indication of deformations due to external forces. These RLSs are connected to the computer via an AD converter to measure their voltages. It should be noted that $\Delta x, \Delta y$ values are coupled with Δz.

After the calculation of $\Delta x, \Delta y$ and Δz, the force in F_x, F_y, and F_z can be calculated assuming the sensor as an elastic beam. From the bending theory (Fig. 3)

$$F_x = 3\frac{EI}{L^3}\Delta x \qquad (3.a)$$

$$F_y = 3\frac{EI}{L^3}\Delta y \qquad (3.b)$$

$$F_z = K_e \Delta z \qquad (3.c)$$

is calculated. Here, I is the moment of inertia of the cross section of the soft cylinder, E younds modulus of soft material, $K_e$stiffness of soft material and L the length of the cylindrical beam from the base coordinates to the point of the applied force, which is assumed as the bottom of the magnet.

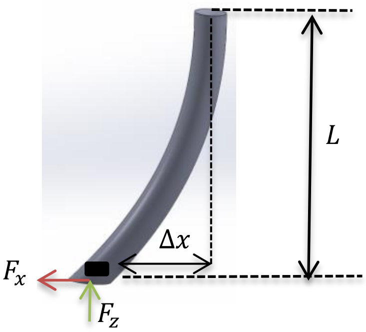

Fig. 3: Forces F_x, F_y, and F_z are applied to the sensor. The soft material is considered as a bent beam under the above forces.

3. Testing of the Tactile Sensor

The tactile sensor is capable of measuring force and detecting vibrations. Figure 4 show the calculated voltage and the measured voltage for a vertically applied force. Figure 5 shows the frequency response for dynamic forces.

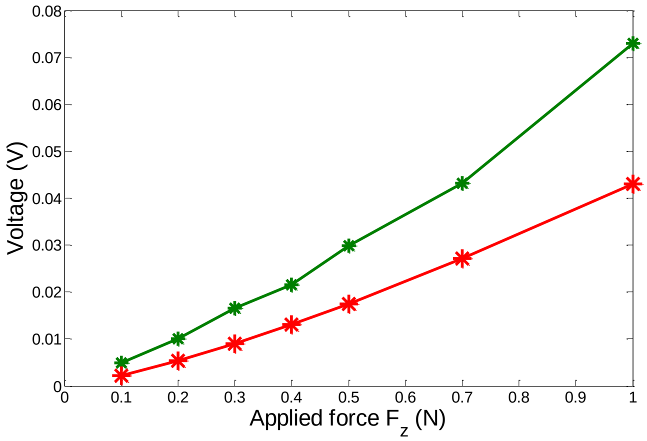

Fig. 4: Calculated force for an applied force F_z. Red line shows the simulated values while green presents actual voltage measured from the RLS sensor in the z direction.

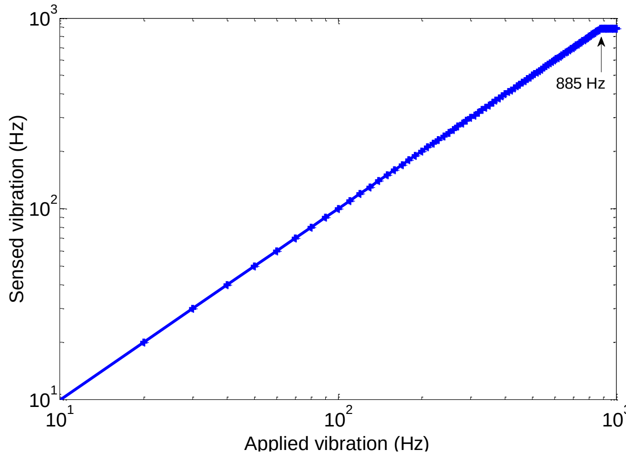

Fig. 5: Frequency response of the tactile sensor. It has the ability to detect vibrations up to the frequency of 885 Hz.

4. Discussion and Future Work

This paper introduces a novel tactile sensor for artificial fingertips. It operates by measuring the deformation of a soft cylinder and calculating the compressive and bending forces applied at the end of the cylinder. The 3D deformations are calculated by measuring the changes in the magnetic field when a magnet is displaced from its initial position. The magnetic field is measured by three orthogonal RLS and the special displacement in calculated from those measurements.

The analysis shows that the force calculated from the sensor three sensor voltages obtained can be fitted to a third order polynomial. Though the force calculations require computationally intensive steps, the cheap construction of the sensor provides advantage to many existing force sensors. The sensor is capable of detecting vibrations up to 885 Hz (Fig. 5) making it acceptable to be considered as mimicking human tactile systems which has a maximum detectable frequency of about 500 Hz [10]. The calculated and measured force values (Fig.4) have some deviation and it could be explained from the non-homogeneous properties of the soft overlay. It contained air bubbles inside the material affecting significantly with the displacement calculations. Furthermore, the calculation of the magnetic field neglects the orientation of the niobium magnets. It is believed the magnet's orientation is a significant variable and future research need to account that as a variable.

The sensor's force calculations in x and y directions are coupled with the z directional displacement. Furthermore, additional experiments have to be carried out to investigate the effects of properties in the soft overlay affecting the calculated force values. Additionally the effects of miniaturize further the sensor to be used as tactels in tactile sensor arrays.

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