Development of a Hall-Effect Based Skin Sensor

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***Abstract*—In this paper we introduce a prototype of a novel hall-effect based skin sensor for robotic applications. It uses a small sized chip that provides 3-axis digital output in a compact package. Our purpose was to evaluate the feasibility of measuring 3-axis force while maintain a soft exterior for safe interactions. Silicone was used to produce the soft skin layer with about 8 mm thickness. An MLX90393 chip was installed at the bottom of layer, with a small magnet approximately 5mm above it to measure 3-axial magnetic field data. To evaluate the sensor's performance, an experiment was conducted by measuring normal and shear force when applying total forces of 0.7-14N in the normal and tangential directions of the sensor. The test revealed that the sensor prototype was able to differentiate the components of the force vector, with limited crosstalk. A calibration was performed to convert the measurements of the magnetic field to force values.**

Keywords—tactile; skin; sensor; magnetic

I. INTRODUCTION

To ensure a safe and robust interaction, a robot that shares its workspace with humans benefits from a soft surface as well as a contact force measuring ability. In order to appropriately react to contact forces, it is beneficial if the force sensors were distributed in the robot skin and could measure not only normal forces, but also shear forces.

Several researches have been conducted in recent years to develop a distributed tactile sensor for robot skin [1]. For example, a soft capacitive-type sensor that could measure force in 3-axis was introduced in [2]. Although this sensor had high sensitivity and could measure normal and shear forces, the sensing area was approximately 13mm x 13mm per sensor (from the center of one transducer to another). Moreover, the manufacturing requires several manually-done processes at the moment. A magnetic based tactile sensor for fingertips has been commercially produced [1]. Using a small magnet, it enables to measure force in three-axial direction. However, the output signal from this sensor has to be amplified first before it can be read by a microcontroller. The amplifier has a rather big size, meaning that a lot of space is required for integrating this device into a robot.

In this paper, we present a novel hall-effect based tactile sensor that can measure three directional force data in limited space. It is both physically small and easy to produce. We evaluate the feasibility of measuring 3-axis force while maintaining a soft exterior for safe interactions.

The rest of this paper is organized as follows. In Section II we provide a review of related Hall-Effect based tactile sensors. Section III described the sensor principle and the production process. Section IV describes the experimental procedure that was used to evaluate the sensor and Section V presents the results. Section VI draws conclusions and presents future work.

II. RELATED WORKS

The idea of using Hall-effect sensors and magnets to measure a tactile response was originally proposed in [3] and [4], where only preliminary prototypes were presented, and then not investigated anymore until recently [5]-[9]. In [7] Hall-effect based tactile sensors are integrated on a robot hand and used in object classification experiments; a full characterization of the sensor and more real world experiments are reported in [8]. However, the sensor is based on 1D Hall-effect sensing, and therefore only normal forces can be measured. The work in [5] instead proposes a 3D sensor, with a design similar to the one we present; however, no accurate characterization is reported, therefore it is not easy to evaluate the quality of the measurements. The work described in [6] and [9] is more mature, and it has been successfully applied to real robotic scenarios; however, even though many simulation analysis are presented, also this work lacks a complete characterization of the real sensor. Moreover, the design they propose (with a rubber dome and four Hall Effect sensors) imposes constraints on the minimum size of the whole system. Instead, the current paper uses a single small-sized chip with digital output and the surface of the sensor is flat.

III. SENSOR DESCRIPTION

In this section, a brief explanation of the structure of the sensor is provided, as well as the production process.

A. Sensor Concept

The force vector can be detected by measuring a magnetic field change. To achieve that, a magnetometer (MLX90393) chip produced by Melexis [10] is used. A single MLX90393 chip is capable to provide 3-axis magnetic data and temperature data through the I2C fast mode protocol (4-wire). The chip is mounted on a printed circuit board (PCB). We embedded the chip inside a soft material, in particular silicone rubber, and implanted a small magnet above it as shown in

[1] http://bl-autotec.co.jp/english/index.html

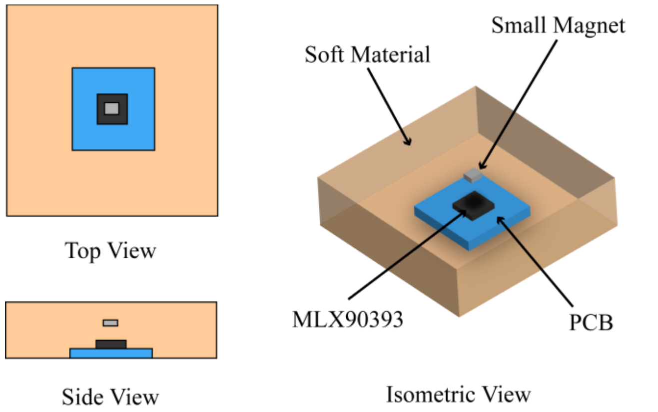

Fig 1. Conceptual design.

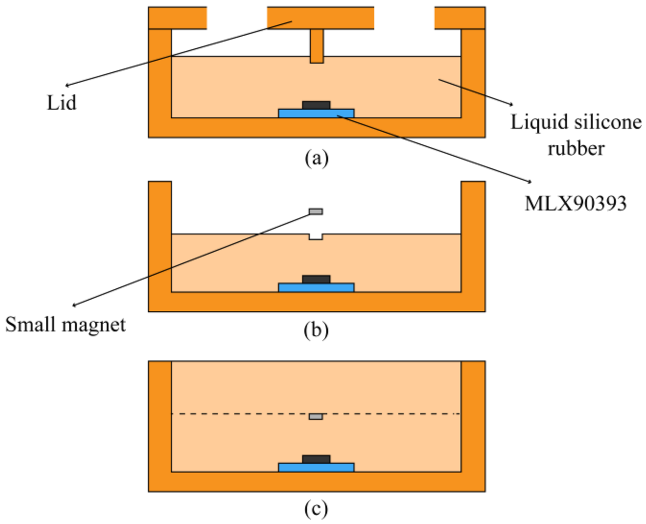

Fig. 2. The molding process. (a) Liquid silicone rubber was poured into the molding cast. (b) A small magnet was placed inside the hole. (c) More liquid silicone rubber was poured above the first layer to cover the small magnet.

Fig. 1. The soft material acted as an external cover and transmitted the force applied on the top surface, displacing the small magnet from its initial position causing magnetic field changes.

B. Soft Outer Layer

The molding process was divided into two steps. First, we placed an MLX90393 chip at the middle of a molding cast, supported with four guidance points and double-sided tape. The chip was covered by liquid silicone rubber until it reached approximately 5mm height above the chip. We selected Ecoflex Supersoft 30 (from Smooth-On) as a soft material since it is strong and has high strain properties. Please note that an optimal material selection was not the focus of this paper. To distribute the magnetic field evenly, the position of a small magnet should be centered. We used a guidance lid (Fig. 2(a)) to create a hole for placing a small magnet in the center. The magnet that used for this prototype was Nd-Fe-B, a Neodymium magnet coated with nickel. The dimension was 2mm x 2.5mm x 1.7mm.

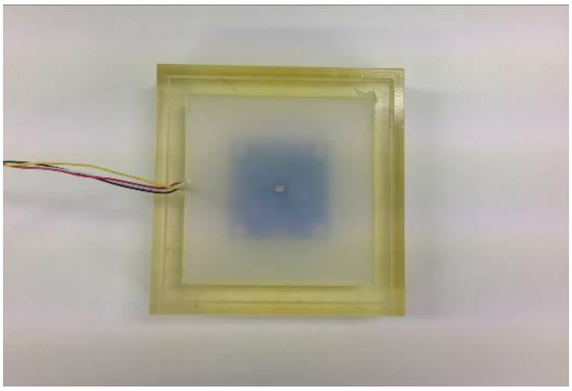

Fig. 3. The first prototype of Hall-effect based skin sensor.

Afterwards, we placed a small magnet inside the hole and poured more liquid silicone rubber to cover it. The sensor had 8 mm thickness overall (above the PCB) with the small magnet covered by approximately 2 mm of silicone. The area of this sensor was 55mm x 55mm. The final form of our skin sensor can be seen in Fig. 3.

IV. EXPERIMENTAL SETUP

Two experiments were conducted in order to calibrate the sensor and to evaluate its capability of tri-axial force measurement. The first experiment was a normal force test where multiple magnitudes of force were applied on the sensor top surface in an increasing staircase fashion in order to observe the sensor's response when only the normal force is applied. In the second experiment, the sensor was pushed with both normal and shear force at various proportions of forces in order to test the response of the sensor when various magnitudes of shear and normal forces were applied to the sensor.

The test setup used for the first experiment is shown in Fig. 4. It mainly consists of a manually-operated X-Y table with a vertical mounting stand and a force-controlled actuator unit. The actuator unit is composed of a voice coil motor (VM5050-190 from Geeplus), a linear bushing, an aluminum shaft adapter, a 6-axis force/torque (F/T) sensor (Nano1.5/1.5 from BL Autotech) for monitor the pushing force during the experiment, and a 30x30mm^2 acrylic push plate which is used to push on the proposed sensor. The force generated by the voice coil motor (VCM) was regulated by a motor driver circuit which the main component is the LMD18245 chip (from Texas Instrument); the circuit control the motor's terminal current according to the voltage command which was provided by an Arduino Due. The actual forces exerted by the VCM were measured by the 6-axis F/T sensor and sent to an Arduino Uno. Two microcontrollers were used due to the different required voltage level of our sensor (3.3V) and that of the F/T sensor (5V). During all experiments, the data from the F/T sensor and the readout from our sensor were recorded into the SD cards installed on both the Uno and Due respectively with the synchronized sampling rate of 100 Hz.

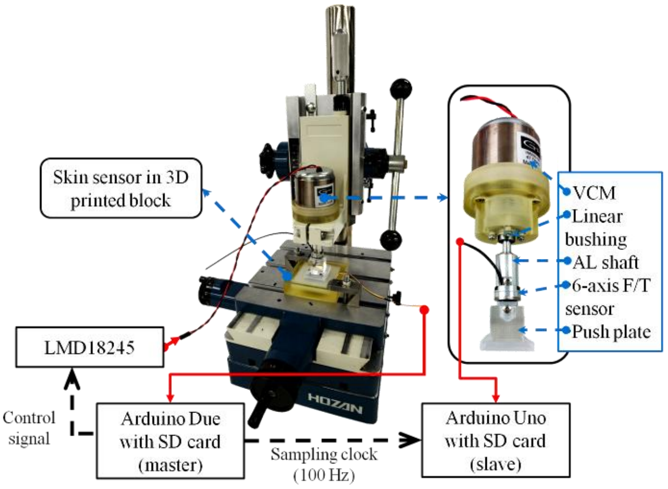

Fig. 4. Experimental setup used in this paper.

Fig. 5. The addition of the adjustable angle tilt stage and the angled push plate. The figure shows the 30-degree setup where the stage is adjusted to 30 degrees and the 30-degree push plate is used.

In the normal force experiment, the proposed sensor was mounted directly on the flat and sturdy X-Y table. In the second experiment, the sensor was mounted onto an adjustable angle tilt stage before fixed on the table. The tilt stage can be positioned at 15, 30, and 45 degrees with respect to the horizontal plane. The flat acrylic push plate was replaced by a set of angled push plates which have the angle of 15, 30, and 45 degrees as well. The angled plate was used was used corresponding to the angle of the tilt stage. An example of the tilt stage setting to 30 degrees and the 30-degree push plate can be seen in Fig. 5. By using the tilt stage and the angled push plates, the normal and shear force can be exerted on the sensor simultaneously by a single linear actuator.

In all the experiments, the sensor was pushed by the VCM with an stepwise force which its magnitude was increased with a 10-second interval per each magnitude. The force was varied from approximately 70 gf. to 1450 gf. All the data was filtered with a Savitzky-Golay filter. A set of normal force test and the shear force tests at 15, 30, and 45-degree were performed.

V. Results & Discussion

The data of the sensor of the normal force test is shown in Fig. 6 and that of 45-degree shear force (y-direction) is shown in Fig. 7; the corresponding force acquired from the F/T sensor is shown as well. It can be seen from Fig. 6(a) that when only the normal force was applied, the sensor's readout S2 which should correspond to the force in y-direction showed some changes as the pushing force increased. Furthermore, as can be seen in Fig. 7, there was also a change in the response of S1 (corresponding to the x-axis), even though the actual force in x-direction was almost zero.

A. Sensor Calibration

All the data explained previously (with different pushing angles) was used for calibrating the sensor. For the current paper, it was assumed that each sensor response, namely S1, S2, and S3 individually correspond to the force in the x-, y-, and z-direction, respectively. Furthermore, only a 1st order polynomial was used. This is because it was found that the 1st order has better fitting compared to the 2nd order one. The equation used in the calibration is as follows:

$$F_{i,Hall} = a_i \times S_j \qquad (1)$$

where:

- i is x, y, and z
- j is 1,2, and 3, respectively

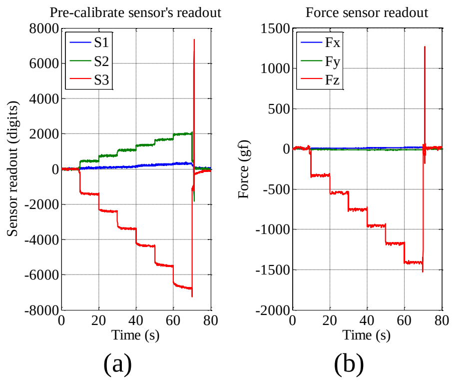

Fig. 6. The sensor's readout (a) and the corresponding force from F/T sensor (b) when only the normal force is applied.

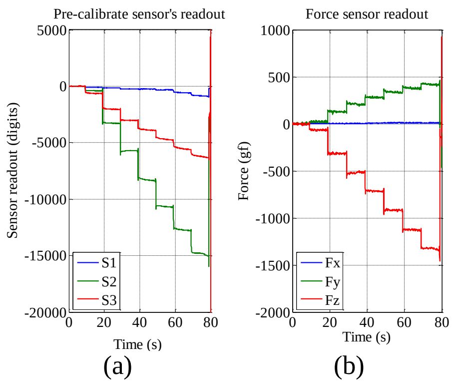

Fig. 7. The sensor's readout (a) and the corresponding force from F/T sensor (b) when the 45-degree shear force is applied in y-direction.

B. *Calibration Evaluation*

In order to evaluate the performance of the sensor after the calibration, additional tests were done using the same setup. The sensor data acquired from the tests was converted using the resultant parameters from the calibration, and the converted forces were compared to the actual force from the 6-axis F/T sensor.

The comparison of the normal force test is shown in Fig. 8, and the comparison of the 30-degree shear force in y-direction is shown in Fig. 9. It can be seen that even though some differences can be found in the force measurement, the sensor showed a similar pattern to the actual force especially on the axis where the main portion of force was applied. For example, Fig. 8 showed a good force pattern in the normal force direction, and Fig. 9 shows good results for both the z-axis and y-axis. The axis to which no force was applied also measured force, but minor compared to the axis to which force was actually applied.

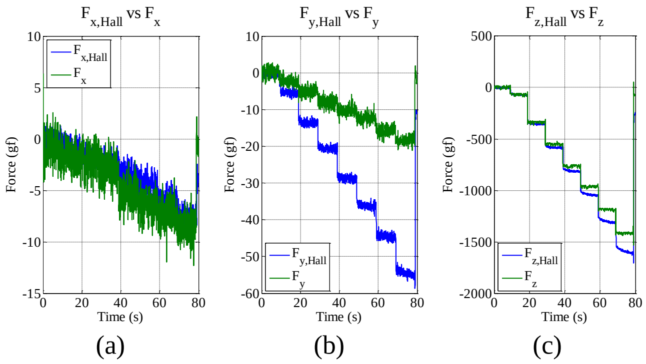

Fig. 8. The comparison of the calculated force and the actual force showing in x-direction (a), y-direction (b), and z-direction (c) when subjected to only normal force.

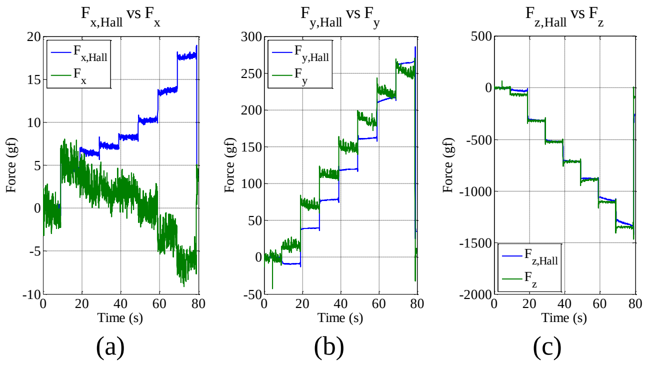

Fig. 9. The comparison of the calculated force and the actual force showing in x-direction (a), y-direction (b), and z-direction (c) when subjected to 30-degree shear force in y-direction.

VI. Conclusion & Future Works

This paper presented the concept design and a prototype of hall-effect based skin sensor. The experiment revealed that our current prototype can successfully detect the normal and shear forces. However, we found that when normal force applied in z-axis, our skin sensor also detected a small force in the y-axis. A possible explanation is that the magnet was not perfectly centered and aligned. For future work, we plan to use calibration that takes into consideration the cross-talk between the different axes.

The current prototype is rather thick, which is beneficial for safety reasons, but might not be appropriate for all purposes. In future work we will evaluate the importance of the thickness, and also try other materials for the soft layer.

For the further development, the MLX90393 chips can be integrated closed to each other. For example, within 2cm x 2cm space, 9 chips can be distributed evenly to detect distributed force. We are currently designing a custom PCB to achieve this.

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