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Low-cost 3-axis soft tactile sensors for the human-friendly robot Vizzy

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Problem

Galen Robotics has designed a hand-over-hand cooperatively controlled surgical system that is used for head and neck microsurgery. This system can sense tool-to-robot forces to reduce hand tremor and increase surgical precision. For some applications however, it is useful to also control tool-to-tissue forces. Our group is working on a drill that has the ability to measure these forces and communicate them to the Galen system. This could potentially allow for the implementation of safety controls, surgical skill evaluation, and unbiased comparison of surgical techniques. Our group's current design utilizes strain gauge force sensors developed by the BLAM lab which results in the drill being somewhat bulky. The Hall effect force sensing techniques described in the paper I reviewed could provide physical advantages over our current strain gauge force sensing apparatus.

Summary

This paper describes a "low-cost and easy to fabricate 3-axis tactile sensor" that is based on principles of magnetism. The sensor that was developed consisted of a small magnet that was immersed in silicone and a Hall effect sensor placed below to detect changes in magnetic field that are caused by displacement of the magnet. This displacement is caused by applying an external force to the silicone body. Since a 3-axis Hall effect sensor was used, three force vector components are able to be detected. The design yielded high sensitivity, low hysteresis, and good repeatability for force measurement. The components were cheap and easy to assemble and the fabrication process was described in detail for repeatability. A successful real-world experiment was performed that integrated these force sensors onto the finger of a human-friendly robot.

Introduction

The features that these researchers required in their tactile sensor were a soft contact surface and the ability to measure the complete force vector (normal and shear forces) with high sensitivity, low hysteresis, and good repeatability. Companies are commercializing tactile sensors [1], [2], [3] but the price of these devices is still relatively high and the specifications are inadequate for certain robotic applications. The paper offers three main contributions to the robotics community. First is a novel solution for 3-axis soft tactile sensing with state of the art performance. Second, they include a detailed description of how the sensor can be fabricated at a low cost and without the need for specific technical expertise. Third, the researchers demonstrate a real-world application of the sensor by integrating it into a robotic hand and performing an object manipulation task.

Technical Approach

The sensor that was described in this paper consists of a soft elastomer with a permanent magnet inside and a Hall effect sensor. The Hall effect sensor is placed below the elastomer containing the magnet and the application of a force will change the magnet's position, causing a variation in the magnetic field. These sensors were placed on the fingers of Vizzy, the human friendly robot. In Figure 1, the sensor design scheme is shown. Notably, the Hall effect sensor that is used is a 3-axis sensor so it can detect magnetic field variations caused by the application of both Normal (Z) and Shear (X, Y) forces. The decision to include an air gap to improve sensitivity was inspired by a paper by Jamone et al [4]. Figure 2 shows the configuration of these sensors on one finger of the Vizzy robot.

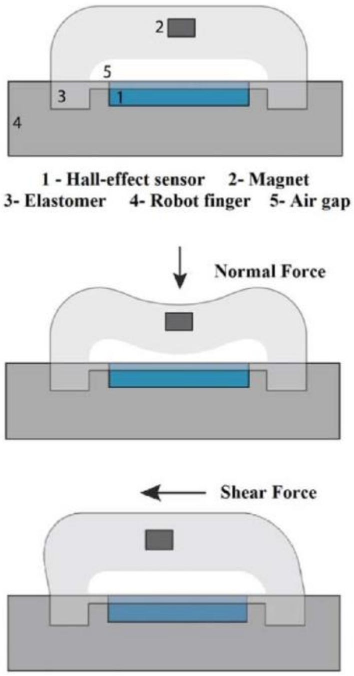


Figure 1: Sensor Design Scheme

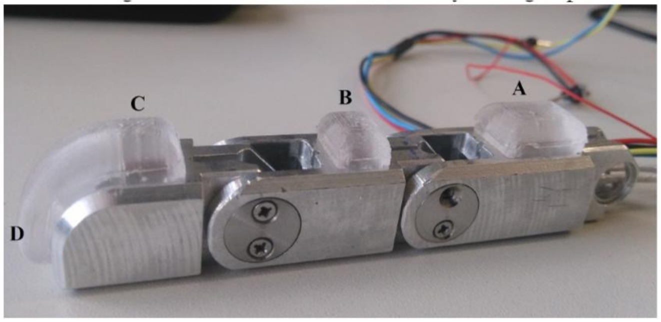


Figure 2: Vizzy finger equipped with four sensors

This idea of using Hall effect sensors to measure forces is not novel to this paper as such concepts were discussed in [5] and [6]. Furthermore, in 2013 a paper was published outlining an initial prototype that was similar to this design but there was no characterization or real-world experimentation reported or documented [7].

The goal of these researchers was to produce a sensor that consists of cheap and easily obtainable components to allow others to practically benefit. These sensors were designed specifically for providing Vizzy with touch sensing. The Hall effect sensor that was used was a Melexis MLX90393 magnetic node. It is 3 mm x 3 mm and has a 16-bit output proportional to the magnetic flux density sensed along the X, Y, Z axes [8]. A flexible printed circuit board (PCB) was used so that it could bend to fit the finger geometry. The elastomer part was made of Polydimethylsiloxane (PDMS) which is a widely used silicon polymer. 3D printed molds were used to give the PDMS the desired shape depending on where the sensor was to be located on the finger. The data from the sensors was acquired with an Arduino board through I2C communication protocol. Furthermore, to convert output of the Hall effect sensor into force values, a characterization is required. An Arduino Leonardo board was used to read Hall effect sensor output and a semi-spherical 3-axis optiforce sensor from OptoForce [2] was used. The force sensor was connected to a micropositioning system that moves in a single direction to apply forces of different intensities. Synchronized data was collected from the OptoForce sensor connected to the PC and from the Hall effect sensor using an Arduino through an I2C protocol. After characterization, sensor measurements were validated with the sensor mounted to the finger of Vizzy as shown below in Figure 3.

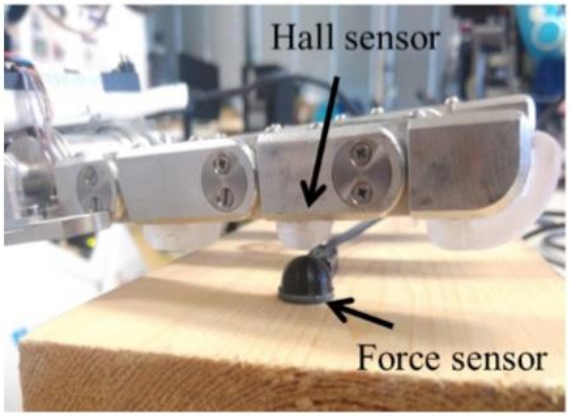


Figure 3: Validation Configuration

Results

The results presented in this paper pertain to calibration and validation. Included are also results for experiments that demonstrate good repeatability, low hysteresis, and high sensitivity of measurements. Furthermore, a real-world example of force detection is demonstrated.

For calibration, an increasing force step movement was used, where the sensor was pressed against the main OptoForce sensor with increasing intensity over the three main directions (X, Y, Z), always returning to the initial position. During shear force movement (X and Y), a constant normal force of 1N was maintained. This process was repeated 10 times for each direction. Below is a figure that shows the response in time of the Hall effect sensor and the reference force sensor.

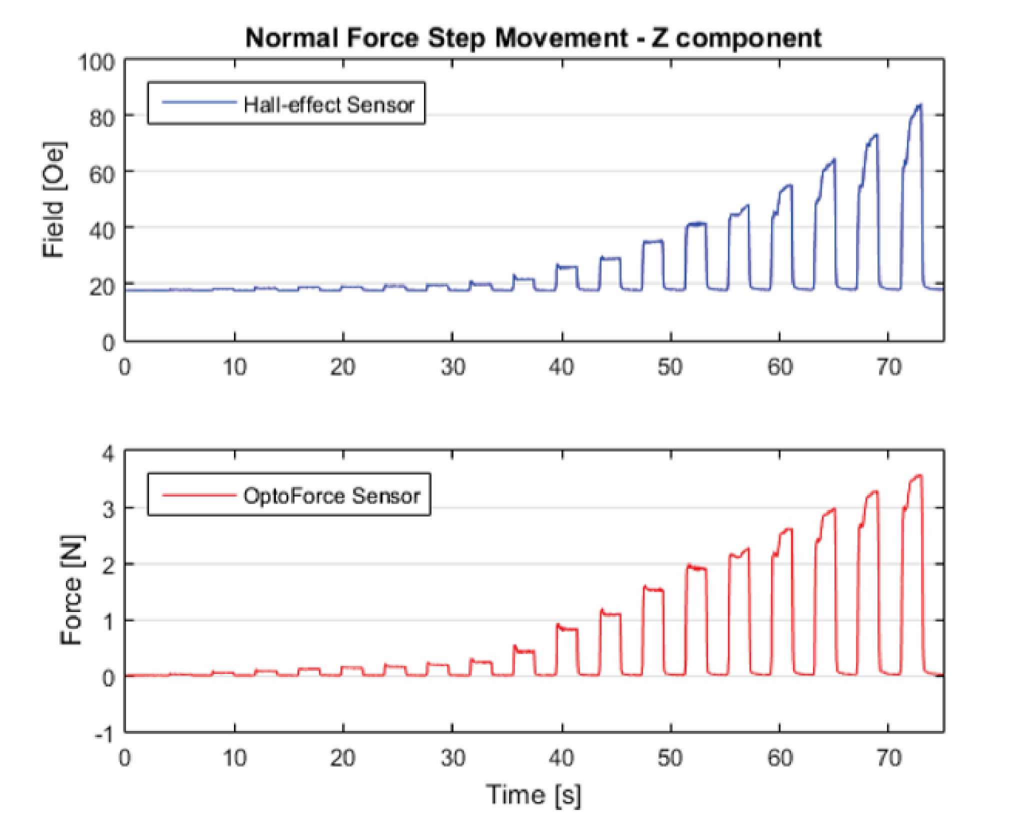
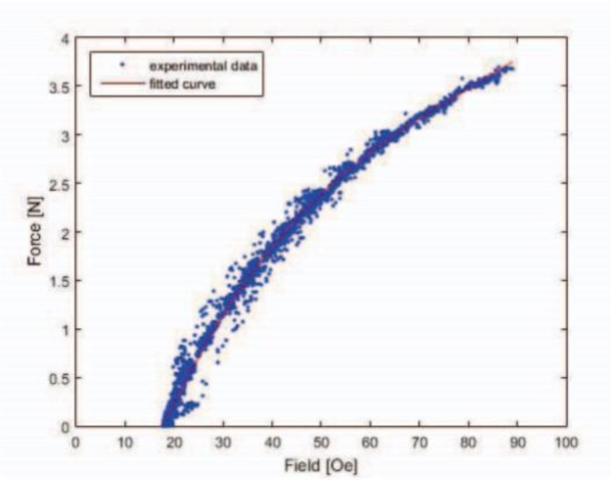
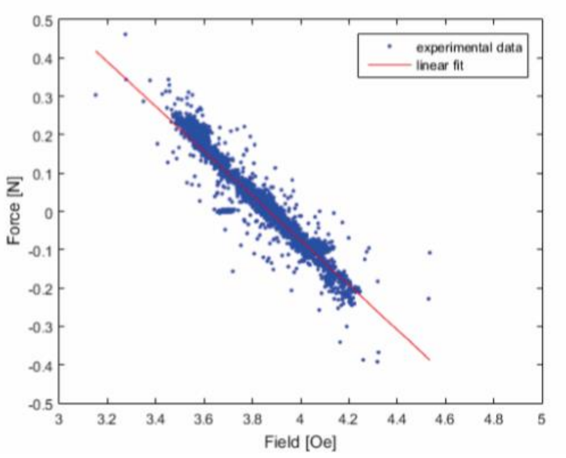


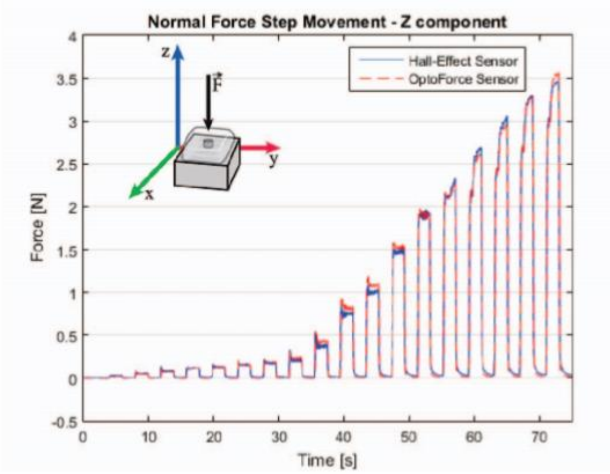
Figure 4: Response of Hall effect sensor and reference force sensor in time

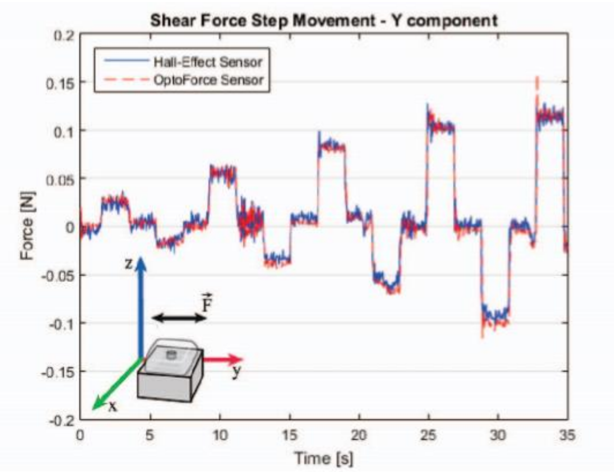
A quadratic regression was performed for the Z component and linear regressions were performed for each of the X and Y components. Below are characteristic curves for normal force (left) and shear force (right).





The next step was validation. The researchers measured the calibrated output of one of the sensors mounted on the robot while a finger applied pressure on the reference force sensor. This is shown above in Figure 3. Below are the validation plots for both the normal force detection (left) as well as the shear force detection (right). The normalized root-mean-square error was computed using the MATLAB function goodnessOfFit() that generates a value between –Infinity (bad fit) and 1 (perfect fit). A value of 0.9123 was obtained for normal force and 0.7908 for shear force. This indicated a very good fit.





These sensors showed good repeatability and limited hysteresis. Experiments to test this involved the robot finger tapping on the OptoForce reference sensor while applying consecutive pressures of the same intensity at a rate of 0.6 Hz. The minimum force detected by the sensor was 7.2mN for the normal force and lower than 20mN for the shear force. The nosie level was computed to be ±2.5mN.

Finally, the response of the sensor was tested in a real-world robotic task. Vizzy was tasked with grabbing and lifting a plastic cup. The robot lifted a cup that was empty as well as a cup that had liquid in it. The response of one of the fingertip elements in this task was recorded for both situations. The behavior was as expected and for the cup that was filled with liquid, the force sensor reading was verified based on the amount of liquid in the cup.

Assessment

This paper outlined a novel approach to tactile force sensing in robotic applications. The researchers showed how such a sensor could be built using low-cost components and without any specific technical expertise. They also demonstrated the performance of these sensors to be state of the art in many regards. Thus, given that these researchers outlined an accessible process to build and calibrate a force sensor in a cost effective way, our group saw it as very relevant to our project. The Hall effect sensors are much smaller than the current strain gauge force sensors we are using. Also, the fact that direct contact with the strain gauges from the drill to the drill sleeve is not needed is a huge advantage. A flexure material with an enclosed magnet, like the elastomer described in the paper, would provide a much more stable connection between the drill and drill sleeve and would be something worth experimenting with in future design iterations.

The positive aspects of this paper are that it clearly outlined the development and testing steps for this novel sensor. Additionally, the diagrams were very helpful to understanding the experiments that were performed as well as the data that was collected. The paper was explicit in stating the exact components used, making the construction of such sensors easy to replicate. There were not many negative aspects related to the content in the paper, but in relation to our project, one aspect the paper did not address is using this Hall effect force sensing close to an area where electrical current is flowing, such as the surgical drill with current running through it, as would be the case in our project. The current would create a magnetic field that could interfere with the force readings of the sensors. One way to potentially deal with this may be by adding some sort of magnetic shielding material around the drill. Another minor negative aspect of this paper was that there were many grammatical mistakes. Even though these mistakes did not detract from the overall meaning, they could have been easily corrected. However, in conclusion, this paper was very helpful in illustrating a novel and cheap alternative force sensing method that could provide several advantages over our group’s current design.

References

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