

3-Dimensional Soft Magnetic Tactile Sensors for the Human-Friendly Robot Vizzy

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Abstract—In this paper we present a low-cost and easy to fabricate 3-axis tactile sensor based on magnetic technology. The sensor consists in a small magnet immersed in a silicone body with an Hall-effect sensor placed below to detect changes in the magnetic field caused by displacements of the magnet, generated by an external force applied to the silicone body. The use of a 3-axis Hall-effect sensor allows to detect the three components of the force vector, and the proposed design assures high sensitivity, low hysteresis and good repeatability of the measurement: notably, the minimum sensed force is about 0.007N. All components are cheap and easy to retrieve and to assemble; the fabrication process is described in detail and it can be easily replicated by other researchers. Sensors with different geometries have been fabricated, calibrated and successfully integrated in the hand of the human-friendly robot Vizzy. In addition to the sensor characterization and validation, real world experiments of object manipulation are reported, showing proper detection of both normal and shear forces.

I. INTRODUCTION

Tactile sensing is essential to ensure a safe interaction between the robot and its surroundings, which may include both objects and humans [1],[2]. A soft contact surface and the ability to measure the complete force vector (i.e. both normal and shear forces) with high sensitivity, low hysteresis and good repeatability are critical features; moreover, when the sensors are integrated into robotic hands, constraints of size, weight and complexity (i.e. number of wires and connections) become important as well.

This need has motivated a large research and development effort over the past thirty years (see [3] for an extensive review, up to the year 2010). However, only a few of these sensors have been integrated in robot hands, and therefore it is not easy to assess their impact for robotic manipulation and human-robot interaction; in this respect, interesting works are for example [4],[5],[6].

Moreover, although more and more companies are now commercializing tactile sensing solutions, like the FlexiForce by

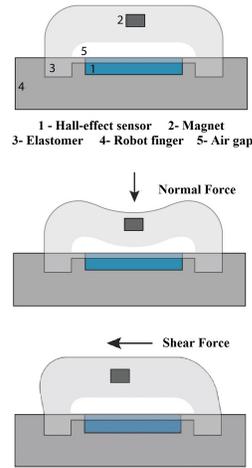
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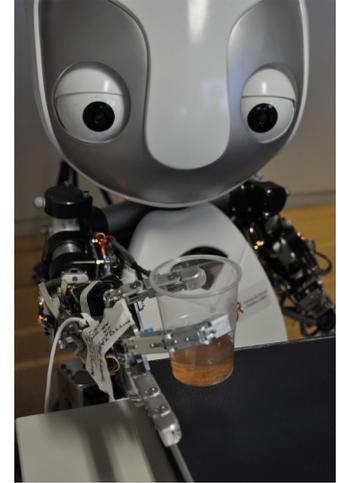
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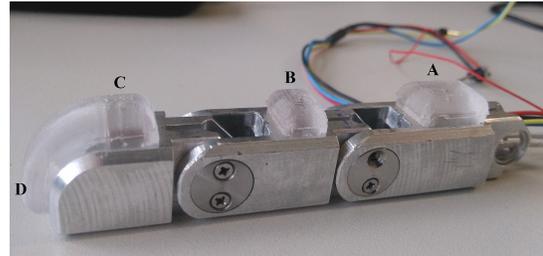
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(a) Sensor design scheme.



(b) Vizzy lifting a plastic cup.



(c) One finger of Vizzy equipped with four 3-axis sensors.

Fig. 1: The proposed 3-axis soft tactile sensor integrated in the hand of the human-friendly robot Vizzy.

Tekscan [7], the 3D Force Sensor by OptoForce [8], the QTC sensors by Peratech [9] and the BioTac fingertip by Syntouch [10], the price of these devices is still relatively high, and the specification (e.g. overall size, sensing performance) might be inadequate for specific robotic applications.

In this paper we present the design, development and characterization of a 3-axis tactile sensor which has been fabricated with different geometries and integrated in the robotic hand of the human-friendly robot Vizzy (see Fig. 1). The sensor main body is made of a silicone elastomer, which offers a good balance between softness and robustness. The transduction technology is magnetic: together with the physical properties of the silicone and a smart design of the sensor structure, this solution provides high sensitivity of the measurement. The components of the systems are cheap and easily retrievable, making this overall system a low-cost, easy to fabricate and easy to reproduce tactile sensor for robotic

applications. A detailed description on how to fabricate and assemble the sensor is provided.

This paper offers three main contributions to the robotics community: i) we propose a novel solution for 3-axis soft tactile sensing, with state of the art performance, especially in terms of sensitivity (i.e. minimum sensed force); ii) we offer a detailed description on how the sensor can be fabricated by other researchers at a very low cost and without the need of specific technical expertise; iii) we showcase a possible real world use of the sensor by integrating it in a robotic hand and by performing an object manipulation task.

The rest of this paper is organized as follows. In Section II is presented a description of the sensor design and production process. Section III shows the experimental methods used to characterize the sensor and Section IV the results. Finally, Section V draws conclusions and outlines the future work.

II. SENSOR DESCRIPTION

A. Sensor Design and Working Principle

The sensor is composed by a soft elastomer with a permanent magnet inside and a magnetic field sensing element (i.e. Hall-effect sensor), disposed as shown in Fig. 1a. The Hall-effect sensor detects the magnetic field generated by the magnet; therefore, when the magnet position changes due to an external force applied on the elastomer, a variation in the magnetic field is detected, that can be converted in a measurement of the applied force. The use of a 3-axis Hall-effect sensor allows the detection of magnetic field variations in the 3 axis, and consequently the three components of the applied force (i.e. both normal and shear forces). The air gap left between the Hall-effect sensor and the elastomer is crucial to increase the sensitivity of the sensor for small forces; this design is inspired by a recent work [11] in which a 1-axis Hall-effect sensor was used.

The idea of using Hall-effect sensors and magnets to measure forces was originally proposed in [12] and [13], and then not investigated anymore until recently [5],[14],[15],[16]. The work in [16] proposes an initial prototype which is very similar to the sensor we present; however, no proper characterization or real world experiment is reported. The work described in [5],[15] is instead more mature, but the design they propose (with four Hall Effect sensors) imposes constraints on the minimum size of the whole system, and the minimum detectable force seems to be considerably higher than our sensor (by a factor of ten). Recently, a Hall-effect based skin sensor was proposed [17] in which multiple small 3-axis tactile elements were connected together in a matrix structure; however, a design different from the one we propose here (i.e. without air gap) did not allow to reach high sensitivity in the measurements.

B. Components and integration

Our goal was to design a easy to produce sensor using cheap and easily retrievable components, to allow other researcher to practically benefit from our work. Moreover, we were interested in providing our robot Vizzy with the sense of touch. Vizzy is a humanoid robot for assistive robotics;

it has an anthropomorphic upper torso and wheels on the lower body. It was designed with an attractive and friendly appearance to favour natural interaction with humans. The lower body wheeled platform allows very good mobility, both indoors and outdoors, and the upper body combines grasping ability, human-like visual perception, eye-head movements and arm gestures [18]. In the following we provide the details of the sensor fabrication and we describe how we integrated multiple sensors in the hand of Vizzy.

To measure the magnetic field we use a tri-axis magnetometer (Melexis MLX90393 [19]). This 3x3mm single chip Hall-effect sensor has a 16-bit output proportional to the magnetic flux density along X, Y and Z axis. To integrate the Hall-effect chip in the finger and have reduced dimensions of the overall sensor, a flexible printed circuit board (PCB) that could bend to fit the finger was used. The PCB is composed by 18 μ m of copper on top of 25 μ m of polyimide. The pattern on the copper was made by optical lithography and wet etch microfabrication techniques. One chip per sensor is used; the images in Fig. 2 show the Melexis chip mounted on the flexible PCB (a) and the PCB integrated in the robot finger (b).

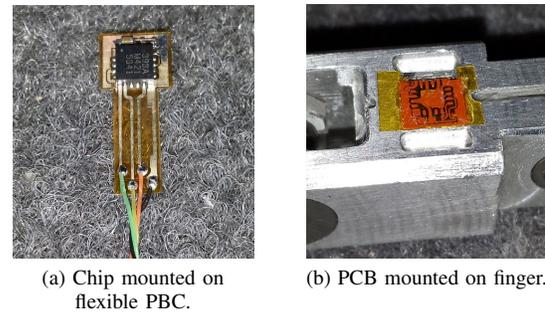


Fig. 2: Details of the Hall-effect chip and flexible PCB.

The sensor elastomer part was made of Polydimethylsiloxane (PDMS), a widely used silicon based polymer. Characteristics like flexibility, stability, low cost and easy fabrication make it suitable for this application. To fabricate the PDMS structures the first step was to design and make the molds. Three different geometries were needed, one for each phalanx of the finger. The molds were made of plastic using 3D printing technology; the CAD design of the molds are freely available at <http://limoman-project.blogspot.pt/p/material.html>.

For the PDMS we used the Kit Sylgard 186 Silicone Elastomer [20], a kit that consist in two parts, the base and the cure agent. The parts are mixed and then the air removed with a vacuum system. After, the material is injected in the molds and goes to the oven during 2h at 70°C. The base:cure ratio suggested on the kit is 10:1, however we wanted a softer material for our sensor; therefore, tests with different ratios were conducted, maintaining the same conditions of mixing and curing temperature. The 20:1 ratio proved to be suited for this application, showing a good cure, soft behaviour and enough resistance to the contact with environment. A permanent magnet is placed in the respective spot inside



Fig. 3: Printed molds and PDMS parts fabricated.

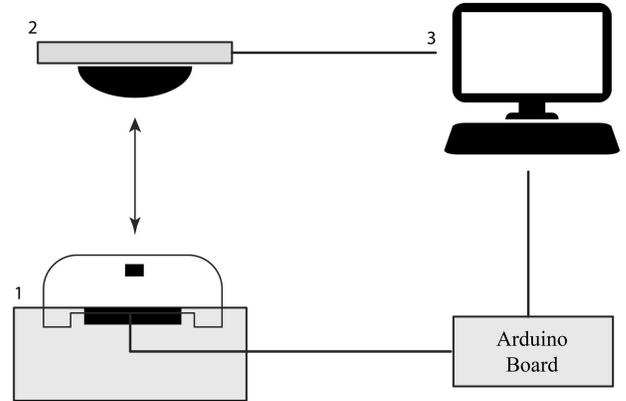
the molds and covered with the same PDMS. It was used a neodymium disk magnet with 1mm diameter and 1mm height with grade N45 (maximum energy product of 45 megagauss oersteds)[21].

Each finger of the robot hand has been equipped with four sensing elements, as shown in Fig. 1c. Sensors are labelled from A to D, from the bottom part of the finger to the fingertip. The fingertip presents two sensing elements (C and D) but only one elastomer part. The data from the sensors is acquired with an Arduino board through I2C protocol, requiring four wires per sensor.

III. CHARACTERIZATION METHODS

To convert the output of the Hall-effect chip, which measures a magnetic field, into force values, a characterization is required. We used a setup composed by: an Arduino Leonardo board to read the Hall-effect sensor output, a commercial force sensor to obtain the force reference and a motorized micropositioning system. As reference force sensor we used a semi-spherical 3-axis optic sensor from OptoForce [8] with a 10mm diameter, a nominal capacity of 10N and a resolution of 400 counts/N. The force sensor is connected to the micropositioning system, that moves in a single direction with a minimum step of $4\mu\text{m}$, and forces with different intensities and directions were applied to the surface of the elastomer of our sensor, on a location centred on the magnet. Synchronized data was collected from the OptoForce sensor, directly connected to a PC, and from our sensor (i.e. from the Hall-effect chip), using the Arduino through a I2C protocol with an acquisition rate of 25Hz. In figure 4 is presented a scheme of the characterization setup. The results of the characterization are reported in Section IV-A.

After the characterization was done, the sensor measurements have been validated with the sensor mounted on the finger of Vizzy, to test the system in a realistic scenario. The



1 - 3D Tactil Sensor 2 - Force Sensor 3 - Computer

Fig. 4: Measurement acquisition scheme.

finger with the sensors was controlled to tap on the OptoForce sensor, that was fixed on a table as showed in Fig. 5, applying forces of varying intensities and directions. The results of the validation are reported in Section IV-B.

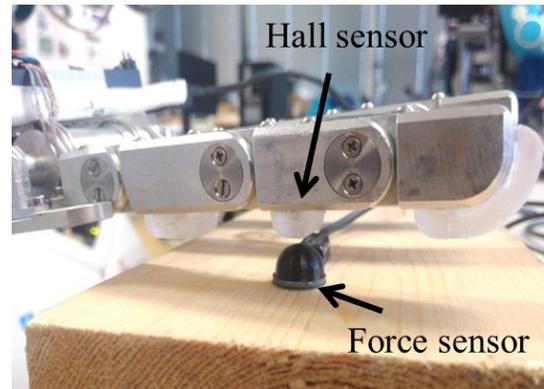


Fig. 5: Validation setup with the sensors mounted on the finger of Vizzy.

IV. RESULTS

Experimental results are presented in this section. We first discuss the calibration (Section IV-A) and validation (Section IV-B) of the sensor; then we report additional data that demonstrates the good repeatability, low hysteresis and high sensitivity of the measurements (Section IV-C and Section IV-D). Finally, we show a real world example of detection of both normal and shear forces during a object manipulation task (Section IV-E).

A. Calibration

The movement performed for calibration was a increasing force step movement were the sensor is pressed against the optical force sensor with increasing intensity, over the three main directions (X, Y, Z), always returning to the initial position in between. During X and Y movements (i.e.

shear forces), a constant force of 1N is maintained in the Z direction (i.e. normal force) to generate the shear forces. The same process was repeated 10 times for each direction. Figure 6 shows the response of both the Optoforce and the Hall-effect sensor during one repetition in one direction (Z).

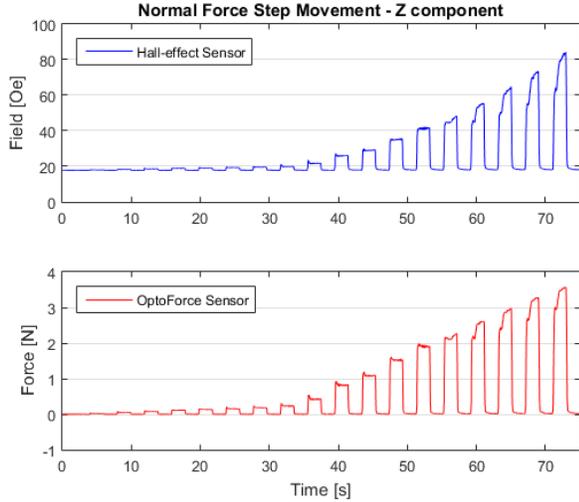


Fig. 6: Response in time of the Hall-effect chip and the reference force sensor during a vertical step movement.

With the data obtained during the calibration movements the sensor output in the three components (X,Y,Z) was calibrated. We performed quadratic regression for the Z component (i.e. normal force) and liner regression for the X and Y components (i.e. shear forces); after preliminary observations we determined that these simple regression methods were sufficient to obtain a good characterization of the sensor response. Since the behaviour of the sensor is very similar in the X and Y direction, we discuss only the characterization in the Y and Z directions.

The plot in Fig. 7 shows the characteristic curve for normal force detection. The force output F_z can be obtained from the sensor reading S_z using the following quadratic relation: $F_z = a \cdot S_z^2 + b \cdot S_z + c$, where the parameters identified through regression are: $a = -0.0006682$, $b = 0.1202$ and $c = -1.921$. The plot in Fig. 8 shows the characteristic curve for shear forces detection. The force output F_y can be obtained from the sensor reading S_y using the following linear relation: $F_y = a \cdot S_y + b$, where the parameters identified through regression are: $a = -0.5822$ and $b = 2.252$.

B. Validation

In the validation experiments we measure the calibrated output of one of the sensors mounted on the robot while a finger is applying pressure on the reference force sensor, as shown in Fig. 5, during step movements in different directions. We use a Savitzky-Golay filter [22] to smooth the sensor output.

In Fig. 9 we show the calibrated and filtered output of our sensor (i.e. Hall-effect sensor) together with the force reference obtained by the OptoForce sensor, during a vertical

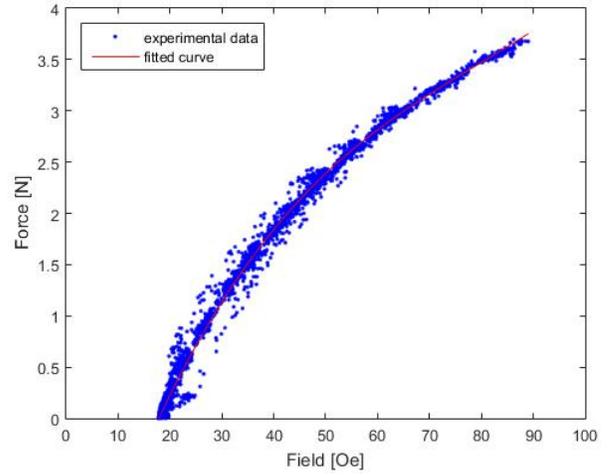


Fig. 7: Characteristic curve for normal force detection.

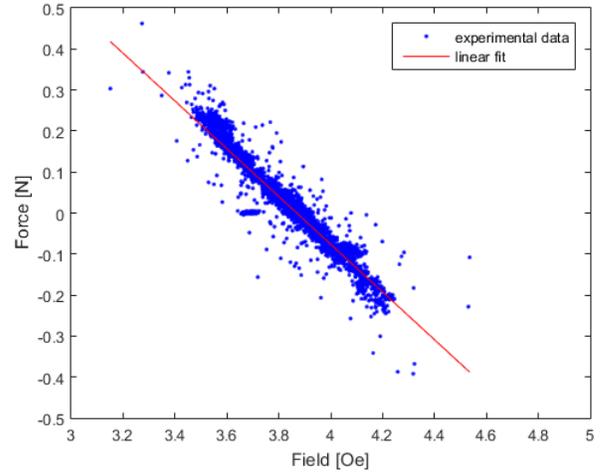


Fig. 8: Characteristic curve for share forces detection.

step movement that generates increasing normal forces. It can be seen how the sensor output reflects the force reference measurement. The same is shown in Fig. 10 for shear forces, detected during lateral movements of the finger while our tactile sensor was in contact with the reference OptoForce sensor maintaining a constant normal force of about 1N.

With respect to these validation measurements, we computed the NRMSE using the Matlab function *goodnessOfFit()*, which generate a value between $-\infty$ (bad fit) and 1 (perfect fit). We obtained values of 0.9123 for the normal force detection and 0.7908 for the shear forces detection, indicating a very good fit.

C. Repeatability and hysteresis

An additional experiment was conducted to observe the repeatability of the measurements and the impact of the mechanical hysteresis of the elastomer during fast repetitive stimulations of the sensor. The experiment consisted in the robot tapping on the OptoForce reference sensor applying consecutive pressures of the same intensity with a rate of

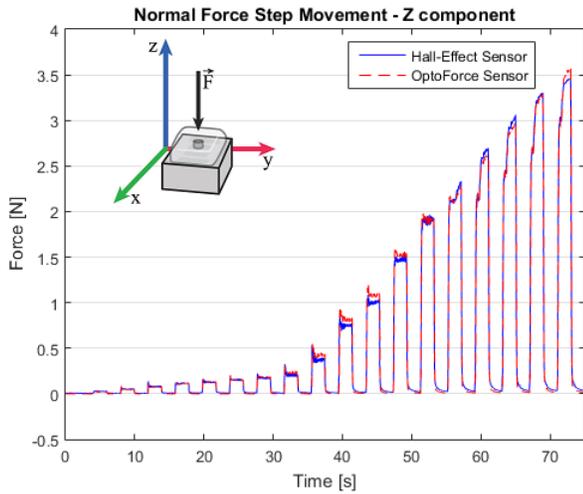


Fig. 9: Validation of the sensor for normal force detection.

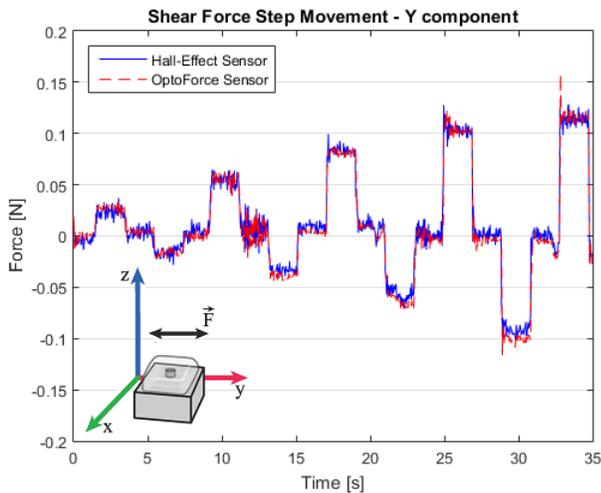


Fig. 10: Validation of the sensor for share forces detection.

0.6 Hz (one pressure each 1.6 seconds, which was the speed limit imposed by the robot actuation) during several repetitions. The plot in Fig. 11 shows the filtered output of our sensor together with the output of the OptoForce reference sensor. It can be seen that the sensor always measures the same force when the pressure is applied, and that the output quickly goes back to zero when the pressure is released, with an average recovery time of about 0.3s, which is in line with the behaviour of the OptoForce sensor. This shows that the mechanical hysteresis is very limited, permitting fast and reliable measurements.

D. Minimum sensed force and average noise

One of the most important features of a tactile sensor is the minimum force it can detect, and, in the particular case of robotics, it is very important to quickly detect the transition from when no contact is present to when a force is applied. To determine the minimum force a number of measurements were performed using the calibration setup described in Section III. With an initial position right before

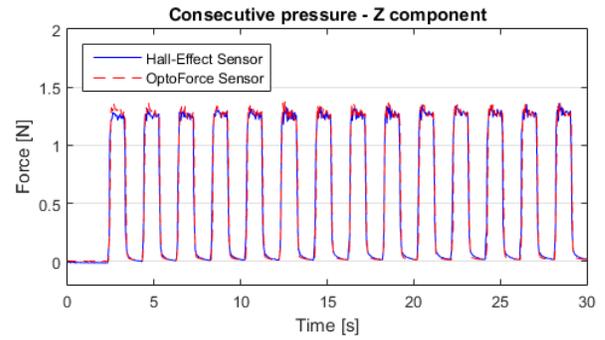


Fig. 11: Sensors response from consecutive force experiment.

the contact, vertical displacements were made, starting from the minimum allowed ($4\mu\text{m}$) and increasing $4\mu\text{m}$ at a time, always returning to the initial position. This process was repeated multiple times, and the data analysis showed a minimum sensed force of 7.2mN for the normal force; to the best of our knowledge, this is the state of the art if we consider sensors that are integrated in robotic hands. A precise evaluation of the minimum sensed shear force was not possible due to the limitation of the calibration setup, that did not allow to generate very small shear forces; however, we could determine that the minimum sensed shear force is lower than 20mN . Moreover, a large amount of data samples of the sensor resting and with no forces applied was collected with an acquisition rate of 25Hz, and it was used to make a noise analysis, from where it was obtained a noise level of $\pm 2.5\text{mN}$.

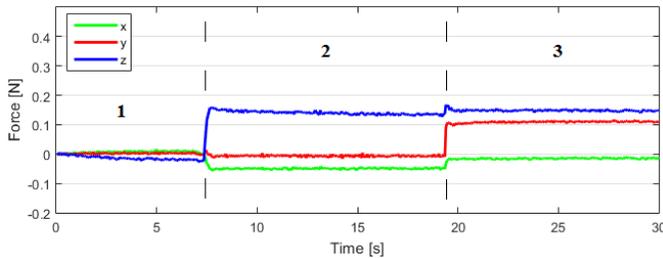
E. Real world interaction experiment

To see the response of the sensor during a real world robotic task, we performed an experiment in which Vizzy grabs and lifts a plastic cup, that was either empty or partially filled with water (and cinnamon, simply to add color). The thumb and the index fingers of Vizzy were used to perform a claw grab. The robot starts with the thumb in contact with the cup, and the index finger open and not in contact. The response of one of the fingertip elements (element C in Fig. 1c) of the index finger is recorded. We segment the task in three phases: no contact present (stage 1), first contact with the cup to grab it, when a normal force will be applied on the sensor (stage 2), lifting the cup, when a shear force will be detected due to the weight of the cup. Then, to return to the initial position, Vizzy lands the cup on the table and opens the two fingers. Fig. 12 and Fig. 13 display snapshots of the experiments, together with the output of the sensor over time.

Fig. 12 b) shows the behaviour of the sensor in the different stages of the movement. In stage 1 no contact is present and therefore all the components are zero. In stage 2 we have a normal force applied, meaning an increase of the Z component. Variations in the other components indicate the surface of the sensor was not exactly parallel to the surface of the cup. In stage 3 the cup is lifted and,



(a) 1 - Before contact 2 - Grabbing cup 3 - Lifting cup.



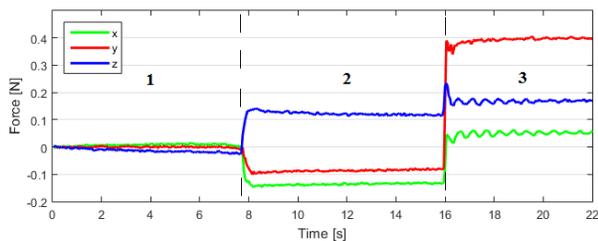
(b) Sensor response in time.

Fig. 12: Vizzy grabbing and lifting an empty plastic cup.

component stays approximately constant, there is a strong increase in the Y component, indicating the shear force generated by the weight of the cup (which is only 4grams). The high sensitivity of the sensor allows to manipulate a very light and fragile cup without deforming its shape, and to feel its weight when lifted.



(a) 1-Before contact 2-Grabbing cup 3-Lifting cup.



(b) Sensor response in time.

Fig. 13: Vizzy grabbing and lifting a plastic cup partly filled with water and cinnamon.

A similar behavior can be observed in the second case (Fig. 13). However, this time the increase in the Y component during stage 3 is much higher, as expected, due to the larger weight of the cup, which is partially filled with water. Notably, the increase in the Y component (+0.3N with respect to the previous case) is consistent with the increase in the weight, which is about 35grams. Although a precise estimation of the weight of the cup was not the scope of this experiment, as that would have needed the sensor to be exactly parallel to the surface of the cup, this is a further indication of the reliability of our sensor. Videos of the experiments can be found online at [\[project.blogspot.pt/p/videos.html\]\(http://project.blogspot.pt/p/videos.html\).](http://limoman-</p>
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V. CONCLUSIONS AND FUTURE WORK

This paper report the design, realization and characterization of a soft 3-axis tactile sensor based on magnetic technology. With the proposed design we fabricated sensors with different geometries to sensorize the hand of the human-friendly robot Vizzy. The process of fabrication and assembly is presented in details, making possible for researchers to easily fabricate their own sensors based on this design, with limited costs and without the need of specific expertise. The sensor was precisely characterized, integrated in the robot hand and then validated through a number of real world experiments. Our analysis show accurate and repeatable measurements of both normal and shear forces, short recovery time and a minimum sensed force of 7.2mN. Experiments of object manipulation showcase just one among many advantages of having 3-axis tactile measurement in a robot hand.

For future work, one of the possible advancements is in the magnetic sensing technology adopted. We choose to use a Hall-effect sensor chip in this work because it is a cheap and easily retrievable component; however, the use of a magnetoresistive sensor [23] would increase the sensitivity and also reduce the size.

Then, one known limitation of magnetic based tactile sensors is that magnetic fields are very difficult to shield, and therefore the presence of a strong external magnetic field would affect the sensor response, increasing the noise of the signal or even completely saturating the sensor; the placement of a reference magnetic sensor on the side of the finger to monitor the external fields and possibly compensate for them could help to deal with this problem.

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