Magnetic 3-axis Soft and Sensitive Fingertip Sensors Integration for the iCub Humanoid Robot

Alexis C. Holgado[1], Nicola Piga[2], Tito Pradhono Tomo[1], Giulia Vezzani[2], Alexander Schmitz[1], Lorenzo Natale[2], Shigeki Sugano[1]

***Abstract*— The humanoid robot iCub is currently equipped with an array of capacitive sensors that provide pressure information throughout the body of the robot. Even though for some applications this type of data is sufficient, it is not always the case for the fingertips of the robot. In particular, the current sensors do not provide enough information for performing agile manipulation, where both intensity and direction of the exerted force on the fingertips are relevant for the proper execution of the task. In this paper, we present a single 3-axis small magnetic sensor module and we show its effectiveness when integrated into the fingertips of the iCub. The sensor module is derived from uSkin, presented in previous works from our laboratory. Replaceable fingertips were designed, built and integrated via software into the low level communication network of the robot, providing fast 3D information about the contact between the fingertips and objects. Additionally, we present two experiments demonstrating tasks that would not be possible to perform with the current fingertip sensors.**

I. INTRODUCTION

Most living creatures rely on some type of tactile sensory system to interact with the world. Humans strongly rely on it to get local information when interacting with objects. The sense of touch is fundamental for object grasping and manipulation. It has been proved that some manipulation tasks are almost impossible without the sense of touch and require several trials to relearn how to accomplish the task without tactile information [1], [2].

Tactile information is essential also for robots manipulating objects. For example, the sense of touch can be used to adapt the grasp of an object or to actively explore the object in hand. In addition, tactile sensors can provide information about objects that is hard or even impossible to acquire with other sensors, such as weight, texture and slipperiness [3]. Furthermore, skin sensors that are in direct contact with objects provide better information than sensors located in robot joints [4]. In humanoid robots, tactile sensing is especially important because these robots are often required to operate in presence of uncertainty in dynamic environments.

However, integrating tactile sensors into fingertips (in particular soft, distributed, and 3-axis) has proved to be a challenging task, mainly because of the reduced space that is usually available in the fingers in human-inspired robots. It is also desirable that the tactile sensors require minimal wiring, so as to not hinder movement or consume considerable amount of space. Digital output is another helpful feature, in order to be more robust against noise, with the added benefit that no amplifiers or analog-to-digital converters need to be used (which would make the footprint of the overall system larger).

[1] Faculty of Science and Engineering, Modern Mechanical Engineering, Waseda University, Tokyo, Japan. contact: aholgado@fuji.waseda.jp

[2] Humanoid Sensing and Perception, Istituto Italiano di Tecnologia, Genoa, Italy {nicola.piga, giulia.vezzani, lorenzo.natale}@iit.it

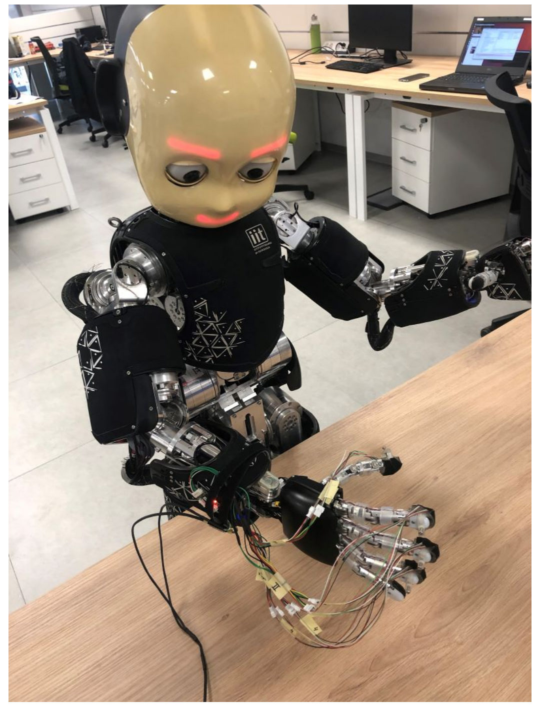

Fig. 1: The iCub with new sensitive 3-axis fingertips mounted on the right hand.

The Sugano Laboratory at Waseda University has been working on sensors with these characteristics and developed the previously presented "uSkin" [5]. uSkin has been, until now, used in a distributed matrix of 4 x 4 sensors aligned in a rectangular array measuring 21.3 x 26 x 5.85 *mm* [6]. Even though this form factor of uSkin was small enough to be included in phalanges of the Allegro hand [5], [7], [8], or in the base of the palm of the iCub [6], the sensors had to be redesigned to fit in the iCub's small fingertips.

Therefore, the objective of this work is to develop a smaller version of the sensor that could be integrated into the fingertips of the iCub, providing a 3-axis soft, distributed and higher-sensitivity sense of touch for the robot.

The main contribution of this paper is the design, implementation and tests of a smaller version of uSkin sensor with custom adapters for the iCub fingertips that are easy to attach and detach (Fig. 1). Our solution is simple to fabricate and can be easily mounted on existing iCub robots without major modifications. As such, this work can have a strong positive impact on the community of iCub users.

The rest of this paper is organized as follows. Section II reviews previous versions of fingertip sensors in iCub and other related works. Section III, describes the sensor operating principle, general structure and assembly process, as well as details on each component layer. Section IV explains integration into the iCub robot, the design of the custom thimble-like adapter and the software modules that were implemented to integrate sensors into the iCub framework. In Section V, we describe two experiments performed with the new fingertip sensors mounted on the hand of the robot to test the integration and expanded capabilities they provide. Finally, Section VI offers conclusions and discusses possible future work.

II. RELATED WORKS

The iCub humanoid robot [9] is equipped with tactile sensors all over its body [10] and on its fingertips [11]. The latter in particular allowed the iCub to successfully execute several manipulation tasks, such as object surface reconstruction [12], localization [13], recognition [14], [15] and grasp stabilization [16].

ICub current fingertips are the evolution of two previous versions presented in [17], [18]. The old sensors [17] had rectangular shape sensitive zones implemented with a normal, non-flexible, printed circuit board (PCB). In this version, the sensitive zones were painted with conductive ink on the inner support and connected to the rigid PCB via wires, making the production process difficult and error-prone. In order to fit the small iCub fingertips, the sensor used measured 14.5 x 13 *mm* and had a round shape to resemble a human fingertip. A flexible PCB was wrapped around the inner support. Above the flexible PCB a layer of soft silicon foam was cast, and on top of it a thin layer of conductive silicone rubber, connected to ground, was placed. The fingertips incorporated a capacitive pressure sensor system. The capacitance varies according to the distance of the conductors. The silicon foam acted as a dielectric while the conductive silicone rubber layer acted as the conductive part. The flexible PCB includes 12 round patches, which represented the conductive parts for 12 capacitors. When pressure was applied to the surface of the fingertip, the foam got compressed and 12 measurements of capacitance were produced. These values were used for estimating the pressure applied to the sensor.

The current version of the sensors mounted on the iCub described in [11] replaces the silicone foam and the conductive silicone with a three-layer fabric, inspired by the one developed for the large scale tactile sensors on the iCub body [10]. Fig. 2 shows the currently mounted sensors on the iCub. In particular, the three layers incorporate a deformable neoprene layer, a conductive textile material (lycra), which is connected to ground, and a top protective textile layer. These modifications in the design made the production process easier, because the three-layer fabric is

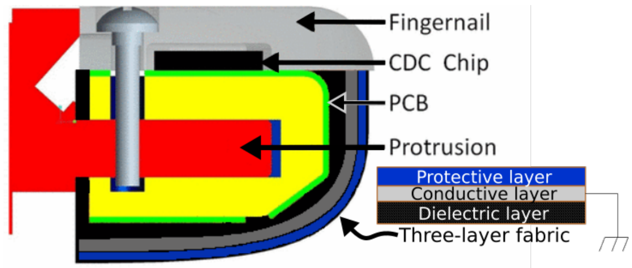

Fig. 2: Current version of the sensors [11].

manufactured using industrial techniques. Which in turn, resulted in fingertip sensors that are more consistent, reliable and robust. However, the current capacitive sensors have a limited resolution of 8-bit (range of 0-255 digits) and, most importantly, only provide normal force sensing capabilities.

To solve this problem, we implemented a Hall effect-based force sensing approach. The idea of using Hall effect-based skin sensing was introduced in [19] and [20]. Recently, small sized, digital 3-axis Hall effect sensors are becoming available. One example of this is the chip MLX90393, from Melexis, which is 3x3x1 *mm* in size, has 16-bit resolution and 4-bit I2C addresses in total that can be connected directly to a microcontroller. Using this chip, we successfully developed uSkin, a compact, soft, distributed 3-axis Hall effect-based skin sensor [5][7]. A 4 x 4 sensors version of uSkin was integrated for the first time on the iCub hand in [6]. However, due to the size of that version of the sensor it could only be mounted on the palm area, and was used to perform simple tactile exploration tasks.

The significance of our work compared to previous works (especially Hall effect-based) is that [21][22] show that the sensor can be integrated into a robot hand but only measure 1 axis; [23] proposes a 3D sensor, but the sensors were not used for distributed sensing; [24] [25] has been successfully applied to real robotic scenarios, but the design they proposed (with a rubber dome and four Hall effect sensors) imposed constraints on the minimum size of each sensor. The work in [26] proposed 3-axis sensing but only one sensor for one finger phalange was implemented. Finally, in [27] a similar design of the single module version of uSkin is presented. However, considering the dimensions of the manufactured sensor (12 x 12 x 8 *mm*), it could not be integrated into the fingertips of the iCub. Furthermore, the selected communication protocol (SPI) requires more cables, possibly hindering movement of the fingertips, and the Arduino control board also presents limitations for integration into the iCub current software framework.

III. SENSOR DETAILS

As mentioned in Section I, in this work we present a smaller version of the uSkin product introduced in previous works [6][5][28]. The 4 x 4 version of uSkin has 16 3-axis Hall effect sensors that connect through I2C connection to a microcontroller, called MTB [14][29], developed at Istituto Italiano di Tecnologia (IIT). The active sensor integrated

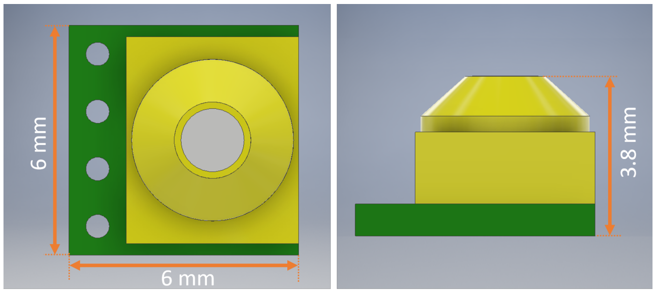

Fig. 3: Render of a single sensor with dimensions.

circuit used is an MLX90393 chip from Melexis, which provides digital output for 3-axis magnetic readings with a range of 0 to 65535 (16-bit) per axis. For this work we design a smaller module with only 1 sensor, measuring a total of 6 x 6 x 3.8 *mm*. A render of the sensor is presented in Fig.3. The redesign resulted in a size reduction making the sensor suitable to accommodate two sensing units per fingertip of the iCub. Details about sensor structure, assembly and sensing principle follow.

The sensor is a layered assembly of four components. Fig. 4 shows an exploded view of the sensor module with references in all layers. Describing the layers from the bottom to the top:

I. PCB board: The bottom layer is a 6 x 6 *mm* custom designed PCB that contains the MLX90393 chip with all necessary passive components for operation, and 4 connection points for I2C communication (+, SDA, SCL & GND).

II. Silicone cover: On top of the PCB, a single silicone part from uSkin is mounted with silicone glue. The material used for this part is Dragon Skin 30, from Smooth-On. This material proved to be easier to mold and have a better behavior regarding hysteresis; however, results about these findings are not in the scope of this letter. For material specifications, please refer to Table I. An important feature of this part is the designed hollow cavity with a dome-like structure. Advantages of this design have already been discussed in [6]. Check Fig. 5 for a section view of the silicone cover showing the hollow cavity.

III. Neodymium magnet: A strong and small neodymium magnet is placed and sealed with silicone glue in a hole molded at the top of the silicone cover. The magnets used are grade N50 with dimensions of 1.59 *mm* of diameter and 0.53 *mm* of thickness. These neodymium magnets present a pull of 226.8*g* and 729 surface gauss.

IV. Textile cover: Finally, the top layer is a flexible textile cover that is used to prevent the magnet and silicone part to be in direct contact with objects. For this sensor we use grip tape GM641, by 3M, manually cut in a shape to cover the complete fingertip adapter of the iCub (described in the next section). This soft elastomer tape comes from the manufacturer with adhesive, making it easy to mount and providing great friction transfer to the underlying silicone part. It also helps protect the subsequent layers of the sensor.

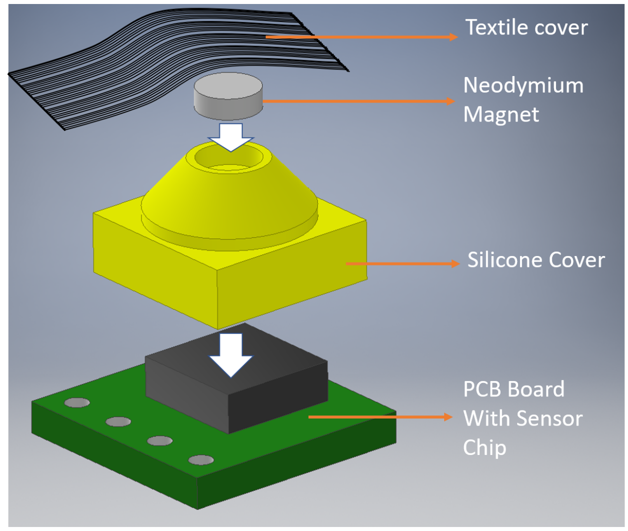

Fig. 4: Exploded view of sensor module (Note: The silicone part is transparent; however, in all figures it is presented in yellow color for better visualization).

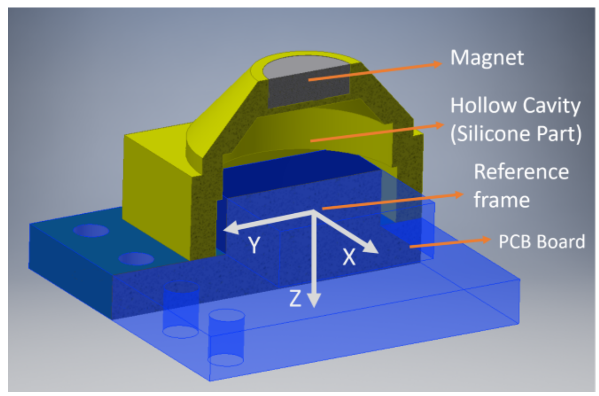

Fig. 5: Layers of complete sensor module with reference frame.

The sensing principle of the sensor is simple: when external forces deform the silicone part that holds the magnet, the displacement generates a spacial change of the magnetic field. This change is sensed by the MLX90393 chip, which generates an output read for values of x, y and z of the magnetic field.

TABLE I: Dragon Skin 30 specifications

Element	Value	Unit
Mixed Viscosity	20,000	cps
Specific Gravity	1.08	g/cc
Specific Volume	25.7	cu.in./lb.
Shore A Hardness	30	A
Tensile Strength	500	psi
Elongation at Break %	364	%

For this work, we implemented several enhancements in the firmware of the microcontroller MTB, which resulted in an improved reading speed of approximately 275Hz (in comparison with the previously 100Hz achieved in previous works like [6]). The main one being an optimization in the implementation of CAN bus messaging system.

It should be noticed that in the current work each sensor has 4 connections that are later joined into a common bus, before reaching the MTB controller. In practice, both sensor modules on each fingertip could be interconnected and only 4 wires would be needed per fingertip.

The manipulation of ferromagnetic small objects could pose a challenge to our sensor. Preliminary test results show that an object with a maximum weight of approximately $0.3g$ would remain in contact with the sensor module's magnet. However, any object with weight above this value does not seem to experience a noticeable force from the sensor's magnet. Another possible challenge would be a strong external magnetic fields close to the sensor module. A strategy to solve this problem could be to use one sensor to sense any external magnetic fields and generate an offset or other compensation strategy for the rest of the sensors.

IV. INTEGRATION INTO THE ICUB

The current section describes the integration of the presented sensors into the iCub robot fingertips. Some requirements were set for the integration:

1) The original fingertips, cables and controllers of the iCub cannot be modified, damaged or replaced.
2) As many sensors as possible should be included per fingertip.
3) For ease of use and maintenance purposes, the sensors need to be able to be attached and detached quickly and easily.
4) Interference of the movements of the robot fingers should be minimized, specially during manipulation tasks like when the fingers come close together (grasping).

A. Adapters Design and Assembly

To allow easy mounting/dismounting of the sensors, we decided on a thimble-like design. The thimble-like adapters (from now on referred to as 'adapters') are to be placed in the distal phalanges of the fingers of the iCub. With this design approach, the sensors can be attached and detached to all fingertips to run experiments. By attaching the adapters on the original fingertips, we avoid any modification on the existing hardware. Taking into account the dimensions of a single sensor unit and the size of the iCub fingertips, two is the maximum number of sensors that fit per fingertip for the current design. For the positioning of the two sensors, angles that follow the curvature of the existing fingertip were selected, resulting in approximately 6°and 49° of mounting inclination, as shown in Fig. 6.

Visual inspection results based on grasping several objects from the YCB benchmark showed that these placements usually put the sensors in contact with the object, and good reading values were to be expected.

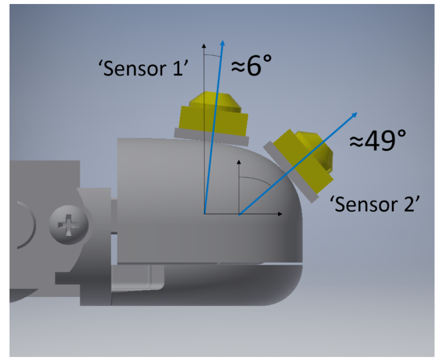

Fig. 6: Placement of sensors in fingertip. Labels for sensors 1 and 2.

Aiming for a simple system integration of the sensors, the adapters were designed to minimize the protrusion so that the originally intended anthropomorphic design of iCub's fingers is not compromised. Accordingly, the frontal as well as the lateral sides of the adapter were designed to conform with iCub's finger shape and to have a thickness of only $1mm$. The backside allowed the mounting of the adapter using a lock screw. When the screw is locked, it presses against the iCub's fingernail fixing the adapter against the original fingertip. Figure 7 shows renders of the current iCub finger with and without the adapters attached. All fingertips of the iCub have the same dimensions, so only one adapter design was needed.

A computer-aided design (CAD) model was completed and 3D printed with photopolymer resin at IIT facilities. Four adapters were produced and 2 sensors were pasted with strong glue on each of the prototypes. Finally, as previously mentioned, a top layer of grip tape was manually cut to match the fingertip dimensions and was placed to cover them completely. Figures in 8 show the result of the assembly process.

B. Software Integration

In order to integrate the sensors within the software architecture of the iCub humanoid robot, we developed an intercommunication software module based on the middleware Yet Another Robot Platform (YARP) [30]. Using YARP, sensor readings are made available through a publish/subscribe mechanism to other software components that control the robot. The software driver we developed interfaces directly with the sensors via the open source networking stack SocketCAN [31] and exposes the incoming data using YARP. The transmitted data consists in a vector D of N triplets, one for each sensor,

$$D = \{(x_1, y_1, z_1), \ldots, (x_N, y_N, z_N)\}$$

each triplet being proportional to the magnetic field measured by the associated sensor.

Once the data is sent over the network, other client components (performing, for example, data collection or closed-loop control of the fingertips) can access that data by simply connecting to this port. No additional knowledge of the underlying CAN protocol is required. It is worth stressing

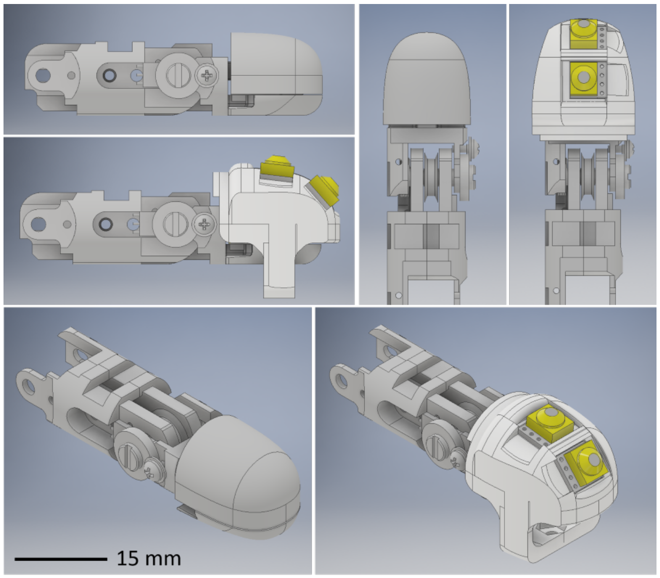

Fig. 7: iCub finger with and without fingertip adapter. The adapter has been designed to be as compact as possible.

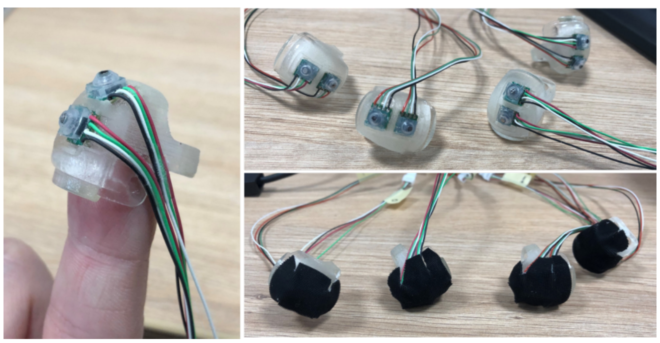

Fig. 8: Manufactured and assembled fingertip adapters with sensors. Bottom right shows the sensors with the final grip tape cover.

that, because YARP provides ROS compatible protocols [32], the sensor readings can also be read by ROS components. A scheme describing the communication layout is reported in Fig. 9.

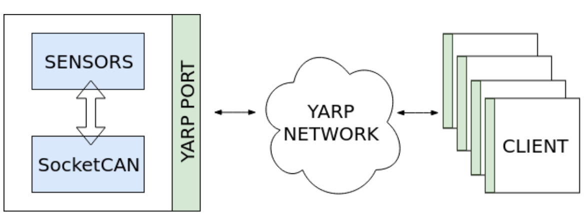

Fig. 9: Data from the sensors is made available to client modules using YARP publish/subscribe mechanism.

V. EXPERIMENTS

As mentioned in previous sections, the iCub is currently equipped with 12 capacitive sensors per fingertip that provide normal force interaction readouts with an 8-bit resolution.

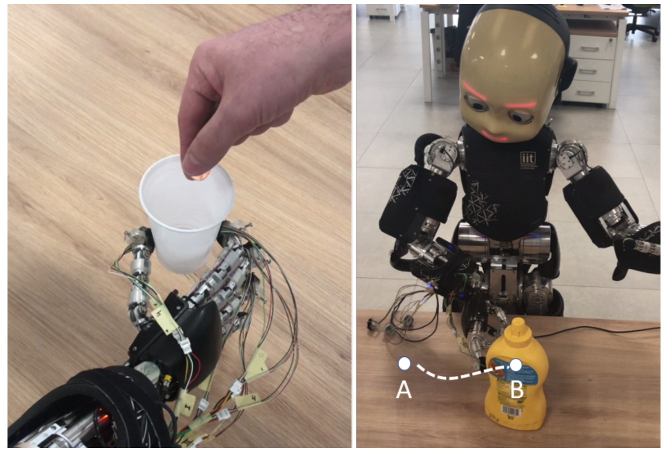

Fig. 10: [Left] Exp. 1, dropping 1 cent euro coins into empty plastic cup. [Right] Exp. 2, learning to estimate weight from pushing object across a table. Index finger moves from point A to B. An approximation of the minimum jerk trajectory between the points is marked with a dashed line.

Meanwhile, the adapters presented in the current letter have two magnetic sensors per fingertip, each providing 3-axis readouts with resolution of 16 bits. These differences make any direct comparison between current and new approaches not very relevant. Instead of a direct comparison, two experiments were performed to prove the expanded capabilities the new sensors provide. These two tasks cannot be accomplished with the current iCub fingertip sensors. An example would be to consider pushing an object when the applied force is not absolutely parallel to the surface of the object; we argue that in this usual situation having 3-axis force sensing capabilities would be beneficial.

On the first experiment, the iCub was programmed to lift an empty plastic cup using the new fingertips. When the grasping and lifting movements reached a stable position, 5 coins of a 1 cent euro mark were manually dropped into the plastic cup. Please see Fig.10 (Left) for a visual reference of the position of the cup for the experiment. The hypothesis is that the coins will generate a small change in the shear force that the sensors experience.

The empty cup weighs approximately $2g$ and each 1 cent euro coin weighs approximately $2.3g$. The objective of this experiment is to check if small changes in weight can be perceived by the iCub. Because the current sensors do not provide 3-axis information, it would be close to impossible to sense any change in the weight of the object because the produced force is roughly perpendicular to the sensor's normal axis. Information from the sensors was read at a speed of 275Hz. Tactile data recording starts 10 seconds into the experiment, which corresponds to the moment when the initial positioning command to grasp and lift the cup has been completed and a stable position has been reached. Readout from sensors have been offset by a baseline number calculated at the beginning of the experiment, using the first 20 readings of each axis.

The result of this experiment is presented in Fig.11. All

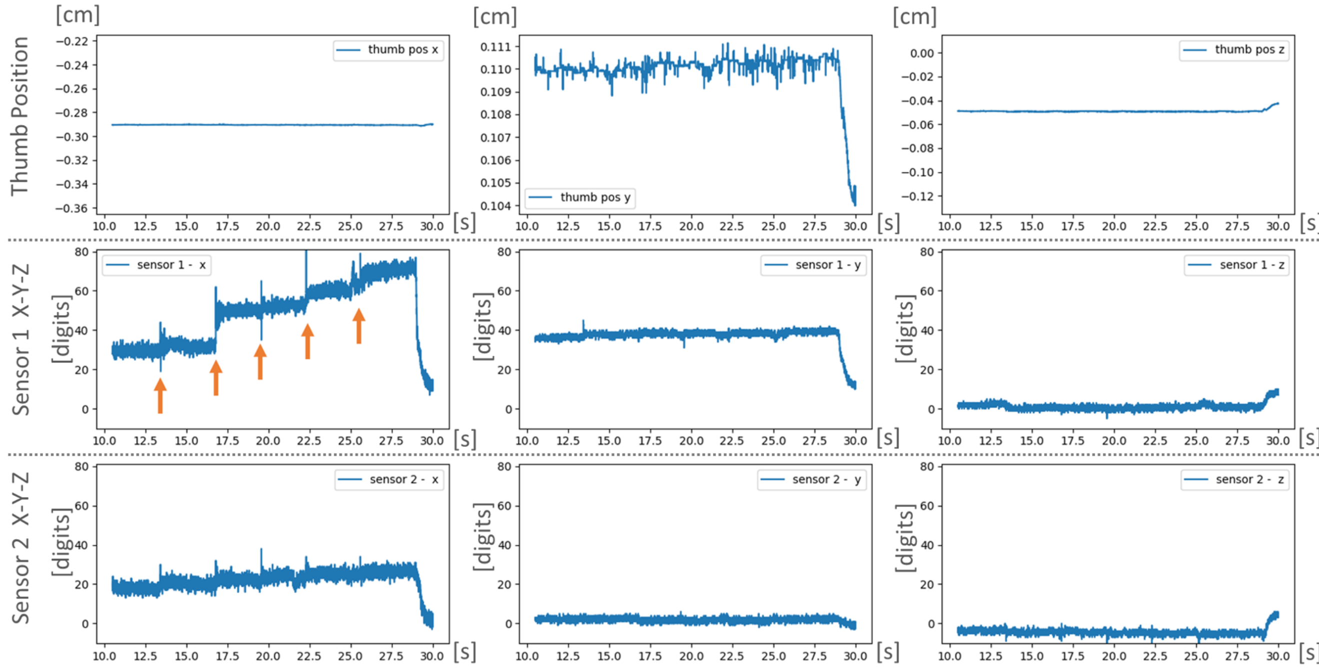

Fig. 11: Experiment 1 results. Dropping 1 cent euro coins (2.3g) into plastic cup. Non-filtered readouts from both sensors in right thumb. Orange arrows mark coin dropping events. Due to the mounting position of the sensors, we notice activity on the X axis (shear force, coordinates frame on sensor) of both sensors while the thumb mainly moves in Y axis (coordinates frame on the iCub). Small sequential increases can be noticed in the signal after each coin drop.

graphs shown are based on raw data from all 3-axis readouts from the sensors with no post-processing or filtering. The first row of three graphs represent positions in X, Y and Z of the thumb of the robot, respectively (using a reference frame fixed on the robot body). Following the same order of axes, the next two rows correspond to readouts from sensor 1 and 2 respectively. Sensor 1 is closer to the center of the fingertip (corresponding to the mounting position of 6°), and sensor 2 is the one closer to the tip of the fingertip (with a 49° mounting position, like shown in Fig.6).

The impact events of the coins dropping into the cup, marked with orange arrows, can be noticed in the graph with sudden peaks in the readings. After the initial impact, the forces stabilize and an increase of 10-15 digits in X values can be seen, which we argue represents the added weight of the coins dropped into the cup. However, the sensors used for these experiments have not been calibrated, thus the added weight cannot be calculated directly. Another expected result is the fact that the added weight of the coins do not produce any noticeable change in the Z axis of the sensors (normal axis); even with a 16-bit sensing resolution. So it can be expected that the current sensors of iCub would not be able to feel the added weight either.

On the second experiment, the fingertip of the robot's right index finger was used to push an object with different weights across a table. The objective of this experiment was to use the 3-axis information from the sensors to train the robot to learn to estimate the object weight by pushing it a little before grasping it. This could prove useful to select manipulation and grasping strategies depending on the weight of the object before performing the task.

The iCub's high-level movement control produces minimum jerk trajectories, which are considered to be a more natural way to move [33]. These trajectories are not straight lines in space but of a higher order. For the iCub, this means that moving from point A to point B, where both points are in the same plane and have the same height (from the table), the generated trajectory will be a spline with a shape similar to Fig.10 (Right). Correspondingly, the finger is forced to slide along the object that is being pushed, generating shear forces on the fingertips that could not be sensed with the current iCub sensors.

For this experiment, an object from the YCB benchmark set depicted in Fig.10 (Right) was used. The distance between points A and B was set to be $15cm$, and the same movement was performed when recording training and validation data sets. The mustard container was loaded with rice to simulate 5 different weights: $45g$ (empty container weight), $100g$, $200g$, $300g$ and $500g$. For each weight, 20 repetitions were recorded to be used as training set, for a total of 100 trials. Finally, 3 repetitions of 6 validation cases with different weights were recorded using values: $55g$, $65g$, $235g$, $245g$, $470g$ and $480g$. The validation cases were chosen in pairs with $10g$ of difference, to check if the system could detect small differences in weight.

One important ability for handling various objects is the estimation of the object's weight. Therefore, the objective of this experiment was to train the robot to estimate the weight of the object that was being pushed across a plane table. Even though friction is a very complex physical phenomenon that largely depends on the surface characteristics and the motion dynamics, in our case, the weight estimation will majorly depend on the weight of the object itself. Hence, we expected a linear relation between the weight and the sensor measurements. Accordingly, we chose the rather simple, however, computationally efficient multiple linear regression (MLR) method to let the robot learn to detect weight differences. For the consideration of more complex relations, e.g. the tribological pairing of different materials together with iCub's joint dynamics, more complex and computationally more expensive methods like neural networks might be suitable.

The MLR was implemented with Accord.NET Framework [34] in C#, using *MultipleLinearRegression* class included in the *Accord.Statistics* assembly. For the training of the regression algorithm, the independent variables were chosen to be the skin sensor data only, i.e., the two times 3-axis raw sensor time-series measurements. The robot performed 20 repetitions of pushing the five objects with the respective weight of 45g, ..., 500g resulting in a total of 100 trials, each of approximately 8 seconds. Each training sample was obtained by stacking the 6 sensor readings for the duration of the trial, obtaining a vector of 12768 elements (2128 time steps x 6). The weight of the object that was being pushed was defined as the target of the regression. Note that the regression was performed with raw data from all three axes of the two sensors on the index finger, without any pre-processing or filtering. Only a baseline offset was calculated from the first 20 readings of each axis at the beginning of the collection.

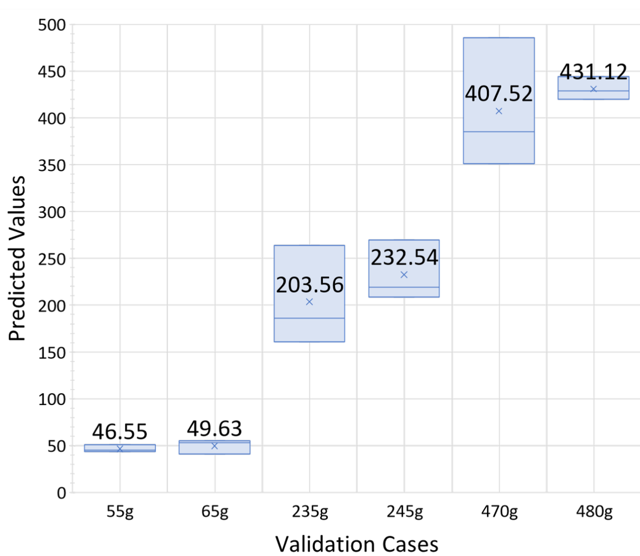

Fig. 12: Experiment 2 results. Validation cases and predicted values of linear regression.

After running the training, the validation cases were tested obtaining the results shown in Fig. 12. The graph was created using 3 repetitions of each of the 6 validation cases, the mean of the 3 cases is marked with a cross and its values are included in the figure. It can be noticed that the predicted values fall near the known weights, albeit with some inaccuracy. Three groups of predictions can be easily recognized for the three pairs of validation cases with 10g of difference between weights. However, it can be noticed that the prediction is not accurate enough to discern between the different items of each pair. We argue that some part of the inaccuracies of these results could be due to the fact that some transient periods of the data (for example, the transition between static and dynamic friction or stick-slip events) could present similar shapes or magnitudes even at different weights. Without more complex data processing, these regions would be difficult to detect, filter and compensate.

VI. CONCLUSIONS AND FUTURE WORKS

In this work we have presented the design and implementation of a new 3-axis sensitive fingertip adapter for the iCub robot. Four models have been manufactured and integrated into the iCub fingers, including software to interact with the middleware software YARP used to control the robot. To validate the sensor integration we ran experiments demonstrating tasks that would have been difficult or impossible to perform with the current fingertips, proving the additional capabilities that 3-axis tactile information could offer with respect to the existing solution.

In future works we plan to test the sensor module to identify sensor characterization values. We will also investigate the use of the sensor for the estimation of tangential forces and implement more sophisticated object manipulation strategies. Furthermore, we plan to develop a complete fingertip adapter that can fit a bigger number of sensors to replace the current last phalange of the iCub. Lastly, strategies will be studied to use the information provided by the new sensors for improved manipulation tasks with the robot.

ACKNOWLEDGMENT

The authors would like to thank M. Accame, who helped with MTB integration at Istituto Italiano di Tecnologia, and A. Geier, N. Yalta and S. Funabashi from Waseda University, who provided general advice and suggestions regarding machine learning techniques. This research was partially supported by the JSPS Grant-in-Aid for Young Scientists (B) No.17K18183 and (B) No. 19K14948 and the Grant-in-Aid for Scientific Research No. 19H02116 and 19H01130. Part of this research was conducted at IIT with the support of Top Global University, Waseda University. Additional financial support was provided by the Ministry of Education, Science, Sports and Culture of Japan (Monbukagakusho).

REFERENCES

[1] G. Westling and R. S. Johannson, "Factors influencing the force control during precision grip," *Experimental Brain Research*, vol. 53, pp. 277–284, 1984.

[2] Robotic Materials, "Why making robotic manipulation harder than it is?." https://roboticmaterials.com/rm/why-making-robotic-manipulation-harder-than-it-is/, [Online: Sept. 17, 2019].

[3] G. Metta and P. Fitzpatrick, "Better vision through manipulation," *Adaptive Behavior*, vol. 11, no. 2, pp. 109–128, 2003.

[4] Z. Kappassov, J. A. Corrales Ramon, and V. Perdereau, "Tactile sensing in dexterous robot hands review," *Robotics and Autonomous Systems*, vol. 74, 07 2015.

[5] T. P. Tomo, W. K. Wong, A. Schmitz, H. Kristanto, A. Sarazin, L. Jamone, S. Somlor, and S. Sugano, "A modular, distributed, soft, 3-axis sensor system for robot hands," in *IEEE-RAS Humanoids*, IEEE, 2016.

[6] T. P. Tomo, M. Regoli, A. Schmitz, L. Natale, H. Kristanto, S. Somlor, L. Jamone, G. Metta, and S. Sugano, "A new silicone structure for uskina soft, distributed, digital 3-axis skin sensor and its integration on the humanoid robot iCub," *IEEE Robotics and Automation Letters*, vol. 3, pp. 2584–2591, July 2018.

[7] T. P. Tomo, A. Schmitz, W. K. Wong, H. Kristanto, S. Somlor, J. Hwang, L. Jamone, and S. Sugano, "Covering a robot fingertip with uskin: a soft electronic skin with distributed 3-axis force sensitive elements for robot hands," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, IEEE, 2017.

[8] Wonik Robotics, "Allegro Hand." http://www.simlab.co.kr/Allegro-Hand.htm, [Online: Sept. 17, 2019].

[9] G. Metta, L. Natale, F. Nori, G. Sandini, D. Vernon, L. Fadiga, C. Von Hofsten, K. Rosander, M. Lopes, J. Santos-Victor, *et al.*, "The iCub humanoid robot: An open-systems platform for research in cognitive development," *Neural Networks*, vol. 23, no. 8, pp. 1125 – 1134, 2010.

[10] A. Schmitz, P. Maiolino, M. Maggiali, L. Natale, G. Cannata, and G. Metta, "Methods and technologies for the implementation of large-scale robot tactile sensors," *IEEE Transactions on Robotics*, vol. 27, no. 3, pp. 389 – 400, 2011.

[11] N. Jamali, M. Maggiali, F. Giovannini, G. Metta, and L. Natale, "A new design of a fingertip for the iCub hand," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 2705 – 2710, 2015.

[12] N. Jamali, C. Ciliberto, L. Rosasco, and L. Natale, "Active perception: Building objects' models using tactile exploration," in *IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, pp. 179–185, IEEE, 2016.

[13] G. Vezzani, U. Pattacini, G. Battistelli, L. Chisci, and L. Natale, "Memory unscented particle filter for 6-DOF tactile localization," *IEEE Transactions on Robotics*, vol. 33, no. 5, pp. 1139–1155, 2017.

[14] G. Vezzani, N. Jamali, U. Pattacini, G. Battistelli, L. Chisci, and L. Natale, "A novel Bayesian filtering approach to tactile object recognition," in *IEEE-RAS International Conference on Humanoid Robotics (Humanoids)*, pp. 256 – 263, 2016.

[15] M. Regoli, N. Jamali, G. Metta, and L. Natale, "Controlled tactile exploration and haptic object recognition," in *International Conference on Advanced Robotics (ICAR)*, pp. 47–54, IEEE, 2017.

[16] M. Regoli, U. Pattacini, G. Metta, and L. Natale, "Hierarchical grasp controller using tactile feedback," in *IEEE-RAS International Conference on Humanoid Robotics (Humanoids)*, pp. 387–394, IEEE, 2016.

[17] A. Schmitz, M. Maggiali, M. Randazzo, L. Natale, and G. Metta, "A prototype fingertip with high spatial resolution pressure sensing for the robot iCub," in *IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, pp. 423–428, IEEE, 2008.

[18] A. Schmitz, M. Maggiali, L. Natale, B. Bonino, and G. Metta, "A tactile sensor for the fingertips of the humanoid robot iCub," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 2212–2217, IEEE, 2010.

[19] J. J. Clark, "A magnetic field based compliance matching sensor for high resolution, high compliance tactile sensing," in *Proceedings, 1988 IEEE International Conference on Robotics and Automation*, pp. 772–777, IEEE, 1988.

[20] W. C. Nowlin, "Experimental results on bayesian algorithms for interpreting compliant tactile sensing data," in *Proceedings, 1991 IEEE International Conference on Robotics and Automation*, pp. 378–383, IEEE, 1991.

[21] L. Jamone, G. Metta, F. Nori, and G. Sandini, "James: A humanoid robot acting over an unstructured world," in *IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, pp. 143–150, IEEE, 2006.

[22] L. Jamone, L. Natale, G. Metta, and G. Sandini, "Highly sensitive soft tactile sensors for an anthropomorphic robotic hand," *IEEE Sensors Journal*, vol. 15, no. 8, pp. 4226–4233, 2015.

[23] C. Ledermann, S. Wirges, D. Oertel, M. Mende, and H. Woern, "Tactile sensor on a magnetic basis using novel 3d hall sensor-first prototypes and results," in *International Conference on Intelligent Engineering Systems (INES)*, pp. 55–60, IEEE, 2013.

[24] S. Youssefian, N. Rahbar, and E. Torres-Jara, "Contact behavior of soft spherical tactile sensors," *IEEE Sensors Journal*, vol. 14, no. 5, pp. 1435–1442, 2014.

[25] E. Torres-Jara, I. Vasilescu, and R. Coral, "A soft touch: Compliant tactile sensors for sensitive manipulation," *CSAIL, Mass. Inst. Technol.,Cambridge, MA, Tech.Rep.*, 2006.

[26] T. Paulino, P. Ribeiro, M. Neto, S. Cardoso, A. Schmitz, J. Santos-Victor, A. Bernardino, and L. Jamone, "Low-cost 3-axis soft tactile sensors for the human-friendly robot vizzy," in *IEEE International Conference on Robotics and Automation*, 2017.

[27] A. Dwivedi, A. Ramakrishnan, A. Reddy, K. Patel, S. Ozel, and C. D. Onal, "Design, modeling, and validation of a soft magnetic 3-d force sensor," *IEEE Sensors Journal*, vol. 18, pp. 3852–3863, May 2018.

[28] T. P. Tomo, S. Somlor, A. Schmitz, L. Jamone, W. Huang, H. Kristanto, and S. Sugano, "Design and characterization of a three-axis hall effect-based soft skin sensor," *Sensors*, vol. 16, no. 4, p. 491, 2016.

[29] G. Cannata, M. Maggiali, G. Metta, and G. Sandini, "An embedded artificial skin for humanoid robots," in *2008 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*, pp. 434–438, Aug 2008.

[30] G. Metta, P. Fitzpatrick, and L. Natale, "Yarp: Yet another robot platform," *International Journal of Advanced Robotic Systems*, vol. 3, no. 1, p. 8, 2006.

[31] M. Sojka, P. Pa, M. Petera, O. pinka, and Z. Hanzlek, "A comparison of linux can drivers and their applications," in *International Symposium on Industrial Embedded System (SIES)*, pp. 18–27, July 2010.

[32] F. Paul, C. Elena, D. D. andPaikan Ali, M. Giorgio, and N. Lorenzo, "A middle way for robotics middleware," in *Journal of Software Engineering for Robotics 5 (2)*, pp. 42–49, Università degli studi di Bergamo, 2014.

[33] U. Pattacini, F. Nori, L. Natale, G. Metta, and G. Sandini, "An experimental evaluation of a novel minimum-jerk cartesian controller for humanoid robots," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1668–1674, IEEE, 2010.

[34] "The Accord.NET Framework." http://accord-framework.net/, [Online: Sept. 17, 2019].