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Design & Characterization of a Bio-Inspired 3-DOF Tactile/Force Sensor for Human-Robot Interaction Purposes

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***Abstract*—This paper presents the design, fabrication and validation of HexaTactile, a soft tactile sensor array based on six barometers, each of which is covered by a silicone layer in the form of an incomplete pyramid. HexaTactile consists of six soft and highly sensitive tactile modules which are placed on six sides of a cube to allow simultaneous measurement of the force in the positive and negative directions along the x, y and z axes. Some of the advantages of this sensor can be regarded as its high precision, excellent linearity (coefficient of determination r^2=0.99), low cost and low noise. The accuracy of the sensor is 0.01 N, within a range of 4 N and therefore HexaTactile can be suitably attached to a robot end-effector for safe human-robot interaction applications.**

***Index Terms*—MEMS barometer, Silicone rubber, Soft tactile/force sensor, Tactile module, I2C multiplexer**

I. INTRODUCTION

By the advent of robotic science in recent decades and the insertion of robots into the same workspace with humans, the need for proper control through force feedback with the goal of human-robot interactions is felt more than ever. The capability of the force sensing is of importance in increasing the ability of robots in complex environments. The skin is the biggest organ of the human body and can detect force, temperature and other complex environmental conditions. Development of electronic devices by mimicking the human skins feature is a new research topic that could find broad applications in robotics, artificial intelligence, and human-robot interfaces [1]. In human skin, the response to mechanical stimulus is mediated by mechanoreceptors that are embedded in the skin [2]. As such, two main parts are needed to make a soft tactile sensor:

- The first part involves a transduction mechanism that detects the force applied to the sensor (such as a mechanoreceptor).
- The second part involves a soft and flexible deformable layer that covers the transduction mechanism and transfers the external force to mechanical deformation, measured by the transduction mechanism (such as skin surface).

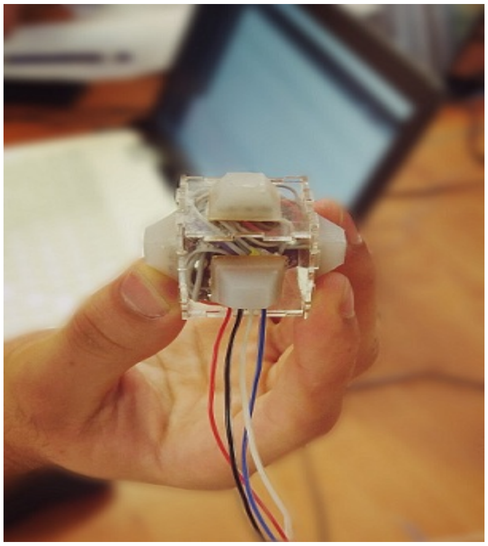

Fig. 1. The so-called HexaTactile prototype.

Today, high plasticity of elastomers such as silicone rubber along with their unique properties, such as suitable physical and chemical properties, ease of their use and their low price, makes them widely be used as a soft layer in the structure of soft sensors. There are various transduction mechanisms to make these sensors, including capacitive [3]–[5], piezoresistive [6], [7], piezoelectric [8], [9], magnetic [10], [11] and optic [12]–[14], which have their own advantages and disadvantages. [2], [15]. The idea of using MEMS barometric pressure sensors as transduction mechanisms for tactile sensing was introduced in [16]. In the latter study, a core of soft foam rubber with an embedded pressure sensor is covered in an airtight sleeve. Deformation of the foam rubber core also results in a measurable increase in pressure. In [17], Yaroslav et al. proposed ”TakkTile” project for the first time. The strategy used in the foregoing project was to attach a barometric pressure sensors to PCBs and then cast urethane

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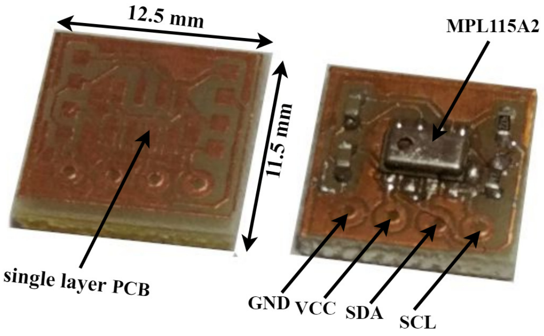


Fig. 2. Single layer printed circuit board, which have 4 pin header,designed to protct electrical connection (left), MEMS barometer on a PCB (right).

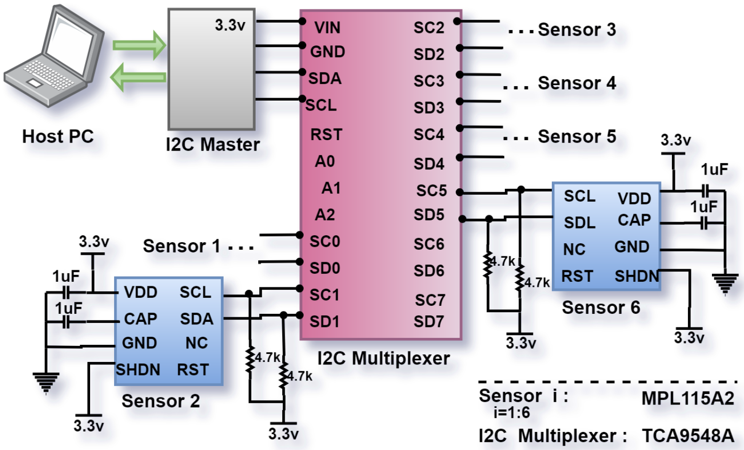


Fig. 3. A general overview of electronic and communication schematic of the HxaTactile.

rubber over the sensors. Then, earlier than the urethane rubber has time to cure, the sensors are placed in a vacuum chamber to draw all the trapped air out. This step is referred to as degassing which brings the urethane rubber in contact with the pressure sensor's diaphragm. As such, the sensor is covered from the environment and it increases the force sensing range and sensitivity as well. In [18], a footpad with integrated force sensing capabilities is presented which addresses these issues in ground locomotion. The foot is made of a polyurethane rubber with an embedded array of high barometric pressure sensors with analog output, which uses a neural network to allow normal and shear forces to be detected indirectly. In [19], a prototype introduced by Joshua et al. has been experimentally calibrated, filtred and tested. In the foregoing study, an atraumatic grasper is presented for Minimally Invasive Surgery (MIS) procedures which uses the aforementioned TaKKtile sensors for active pressure monitoring. In [20], an approach was presented for accurately localizing touch over curved, three dimensional surfaces. The core of this method is embedding sparse Takktile pressure sensors in a soft volume and using a purely data-driven approach to learn the mapping from these sensor readings to the location of the indentation. From the study conducted in the literature, it can be concluded that use of MEMS barometric pressure sensors as a transduction mechanism has the following advantages:

- Reduces the complexity of design and manufacturing;
- low price;
- Easily customized.

This project is followed by a study conducted previously in [21], [22] at the Human and Robot Interaction Laboratory in which a 3-DOF force sensor equipped by five load-cell is built. In fact, the proposed force sensor can regarded as an extension version of the latter sensor for which load-cells are replaced by MEMS barometers. The main contribution of this paper consists in designing and fabricating a 3-DOF soft tactile sensor "HexaTactile" (Fig. 1). The HexaTactile consists of six tactile modules, which are placed on each side of the cube, based on MEMS barometric pressure sensors that cast by RTV silicone rubber.

In this work, the fabrication process of tactile modules based on the approach presented in [17] in which the printed circuit board (PCB) design, casting material and chip selection method are modified according to the purpose of the project.

The remainder of the paper is organized as follows. In Section II, design and fabrication steps of tactile modules, challenges and their solutions are explained. In Section III, the system features are expressed by calibrating and applying different loads to the sensor. Section IV is dedicated to Graphical User Interface (GUI) and sensor's communication.

II. DESIGN AND FABRICATION

HexaTectile is composed of 6 barometers, which are molded by silicone. Its construction consists of two parts: first, the design andcommissioning of barometers and then molding discussion

A. *Electrical Description*

The HexaTactile consists of six MEMS barometric pressure sensor (MPL115A2 Freescale Semiconductor). This pressure sensor contains a silicone diaphragm which is fitted with a Wheatstone bridge. The air pressure is measured by passing air through this diaphragm, according to the method proposed in [17] and the model of the elastomer. It should be noted that the cost of the sensor significantly reduces while its accuracy increases.

At the first step, a MPL115A2 pressure sensor is mounted onto a custom single layer printed circuit board of size 12.5mm by 11.5mm. As shown in Fig. 2, this PCB has a total of 4 pin headers: power (VCC), ground (GND), data line (SDA) and clock line (SCL). The number of PCB headers has been reduced by one compared to Takktile project. As all barometer sensors are manufactured with the same preassigned I2C address, in order to connect multiple sensors, in [17] chip selection implemented through the RST pin by means of I/O

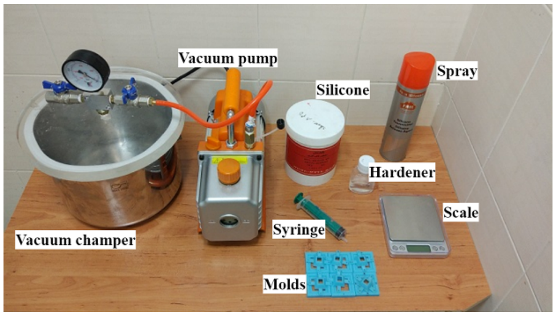


Fig. 4. Supplies used to mold the MEMS barometers.

expander which leads to have a PCB with a total of 5 pin headers: power (VCC), ground (GND), data line (SDA), clock line (SCL) and chip select line (CS). In HexaTactile, the connection of six sensors is done through the I2C multiplexer (TCA9548A, Texas Instruments). This I2C multiplexer can bind up to eight I2C of the same address. It serves selects and sends commands to the selected set of I2C pins. Figure 3 depicts the functional block diagram of Hexatactile.

B. Rubber Casting

The tactile module consists of three parts, namely, plexiglass surface, PCB and deformable layer. In order to build tactile module, which converts the external force to the mechanical changes that are measured by the pressure sensor, after placing the PCB on the plexiglass surface with a double-sided adhesive, it fits inside the mold, which is designed in a CAD software and is printed with a 3D printer. Then degassed RTV silicone rubber with a Shore hardness of 25A is injected into the Sprayed mold. The equipments used for molding pressure sensors are shown in Fig. 4. In the next step, before the silicone rubber has time to cure, the sensors are placed in a vacuum chamber to draw all the trapped air out. This step is called degassing and it brings the silicone rubber in contact with the pressure sensor's diaphragm, as shown in Fig. 5.

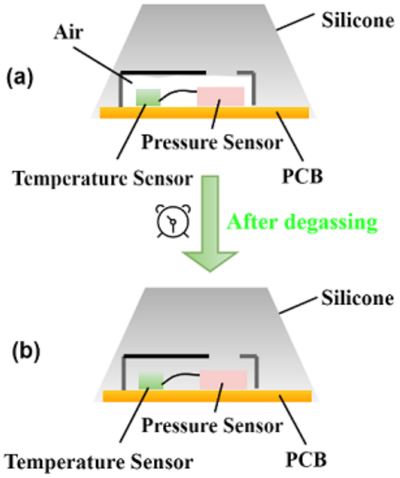


Fig. 5. Effect of degassing on tactile module building, (a) Without degassing, the air is between the diaphragm and the , (b) By degassing, the air between the diaphragm and the silicone is completely removed.

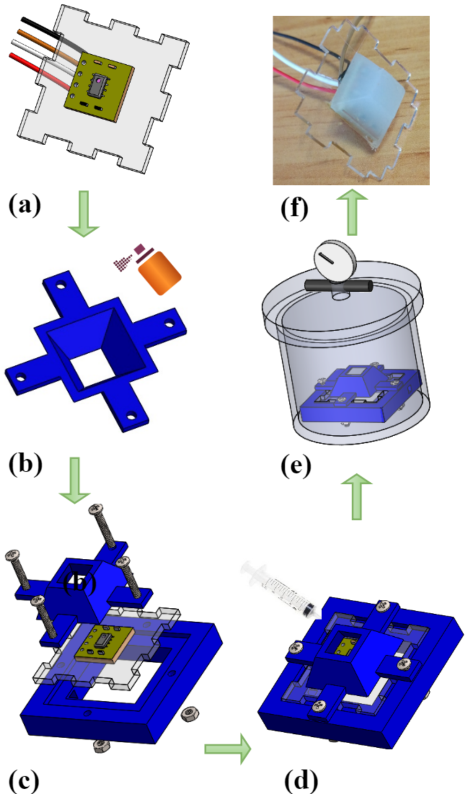


Fig. 6. Schematic of the casting process;(a) Paste the pcb onto the plexiglass sheet by double-glue, (b) Spray top of mold for easy silicone separation, (c) Insert the sensor into the mold, (d) Inject silicone rubber, (e)Insert the mold in a vacuum chamber and degassing procces, (d) completed tactile module.

Accordingly, the sensor is protected from the environment and it increases the force sensing range as well [17]. After the degassing step, the mold is placed in the room for hours to drain silicone (the basic planar casting process is illustrated in Fig. 6). As aforementioned, the principles of work are based on the molding of the pressure sensor and the direct contact of the elastomeric layer with the diaphragm surface, which is a circle of one millimeter in diameter. Therefore, the elastomer layer was used in the form of an incomplete pyramid, so as to illustrate the useful and necessary sensor requirements while completing the full coverage of the PCB layer.

III. SENSOR CHARACTERIZATION

The Hexatactile contains of six tactile sensors that operate independently and without interference, so they can be calibrated individually.

A single module of the type used in the HexaTactile prototype was evaluated and tested. Firstly, an appropriate test platform was developed to perform the characterisation of the sensor. As shown in Fig. 7, the platform consists of tactile module, sensitivity scale with 0.01 gram accuracy, ball screw with a linear displacement step of 0.01 mm and N Arduino Mega. The sensor was mounted on a sensitivity scale and using a ball screw; the sensor was loaded in numerous

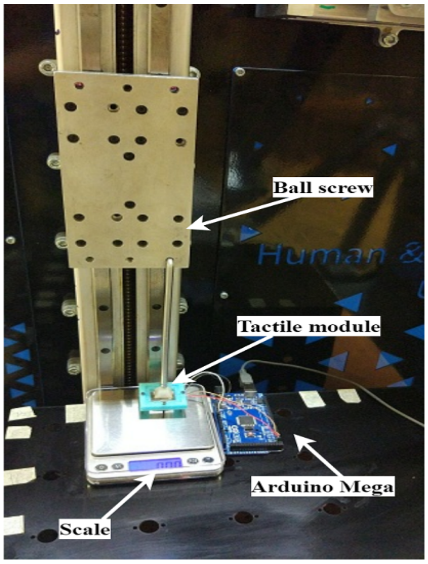


Fig. 7. Setup for calibration of modules.

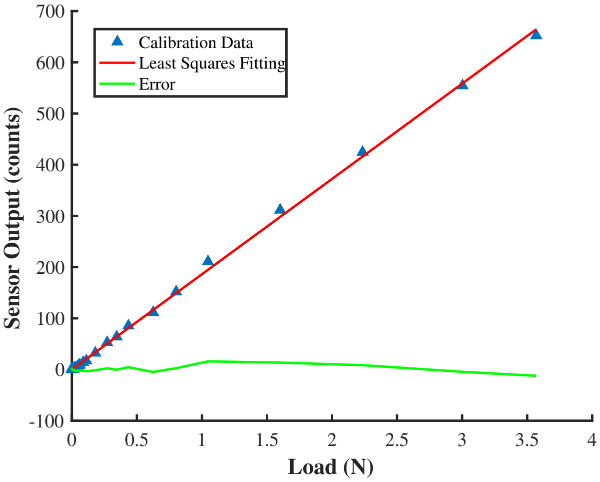


Fig. 8. Sensor output based on different loads.

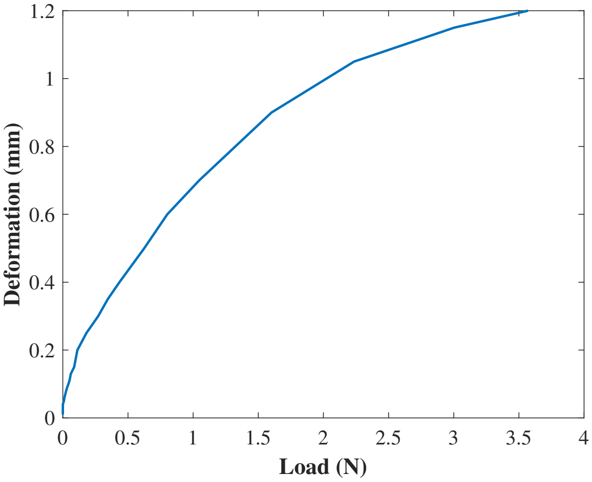


Fig. 9. The amount of deformation of the silicone layer with respect to different loads.

conditions. Then, data from the tactile module was logged by an Arduino Mega and processed using computer algebra software. It should be noted that the sampling frequency of each tactile module is 400 Hz. Using this open loop method in calibration, the sensor output graph in terms of the force input is shown in Fig. 8. Due to linear behavior of tactile module, first order Least-Square (LS) fitting technique would be appropriate for calibration. From the LS equation, one has:

$$\beta = (\mathbf{X^T X})^{-1}\mathbf{XY} \tag{1}$$

where

$$\hat{\mathbf{Y}} = \mathbf{X}\beta \tag{2}$$

and

$$\text{Error} = \mathbf{Y} - \hat{\mathbf{Y}} = \mathbf{Y} - \mathbf{X}\beta \tag{3}$$

where X is an $n \times m$ input matrix, Y output $n \times 1$ matrix, beta coefficient $m \times 1$ matrix and $\hat{Y}$ is best linear fitting $n \times 1$ matrix.Figure 9 shows the correlation between externally applied force with respect to the sensor output alongside with the first order LS results and the corresponding error. According to the latter figure, it can be observed that the sensor is very linear with the Root Mean Squares Error (RMSE) equal to 1 and r^2 grater than 0.99 and the sensitivity is about 195 counts/N for tactile module with a silicone thickness of 5 mm. It is clear that the sensitivity of this sensor can be changed regarded to the type and thickness of the elastomer (hardness, etc.). The higher the thickness used the less sensitivity would result and vice versa, as well as the higher hardness is the less sensitivity can be obtained and vice versa. Figure 10 shows the relationship between silicone deformation and applied force to the sensor. As it can be seen from the latter figure, the maximum load generates a vertical deformation of about 1.3 mm.

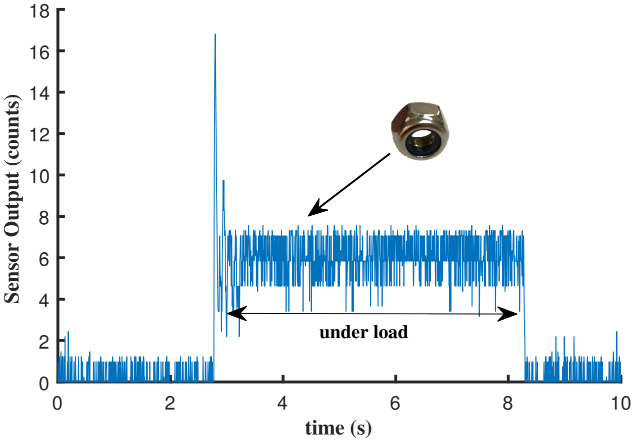
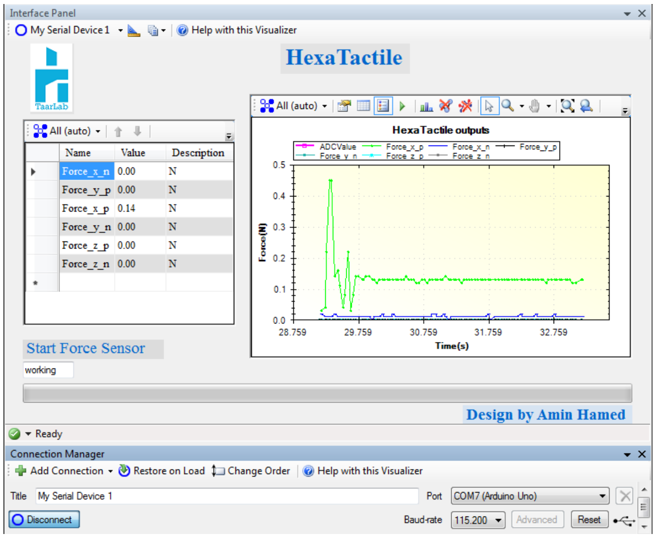


Fig. 10. Sensor output by placing constant load on it (a nut with 2 grams weigh) .



Name	Value	Description
Force_x_n	0.00	N
Force_y_p	0.00	N
Force_x_p	0.14	N
Force_y_n	0.00	N
Force_z_p	0.00	N
Force_z_n	0.00	N

working

Title: My Serial Device 1

Port: COM7 (Arduino Uno)

Baud-rate: 115.200

Fig. 11. Designed graphical user interface.

The sensor response to a constant external force was tested by placing a 2 grams nut on the sensor. As shown in Fig. 10, the sensor has a fast and accurate response to the step input. In this case, the load is very light, the signal to noise can be obtained by referring to [23] as follows:

$$SNR = \frac{|\mu_u - \mu_p|}{\sigma_u} \tag{4}$$

where μ_u is mean value of sensor when not loaded, μ_p is mean value of sensor when loaded and σ_u stands for the standard deviation of the value when not loaded. According to Fig. 10, $\mu_u = 0.6$, $\mu_p = 5.8$ and $\sigma_u = 0.47$. Therefore, SNR for this load is 11.48. Repeating this experiment by a weight of 55 grams (sensor output of about 81 counts), SNR amount of 196 is obtained which can be regarded as a high rate for this sensor. The sensor output is saturated with about 680 counts. By placing sensors in an unload state for a while, the effective noise level was measured to have an average root-mean-square noise of 0.54 counts and a standard deviation of 0.47 counts, which is equivalent to applying 0.003 external forces on the sensor. The noise level is very small compared to the measurement range of the sensor. Finally, to reduce the effect of noise, an exponential filter on the sensor has been deployed and the sensor has the ability to detect external force of 0.01 N (1 grams load).

IV. SOFTWAR AND COMUCATION

As discussed in Section II, I2C multiplexer was used to network the tactile sensors and make HexaTactile. As a result, the final sensor has a I2C connection and it has a frequency of 100 Hz. In order to monitor intellectively sensor outputs, a Graphical User Interface (GUI) was designed by the "MegunoLink" software, where Fig. 11 demonstrates a general overview of this GUI. This GUI is capable of showing force in each direction, plotting each of these forces and the possibility of turning it on and off and calibration.

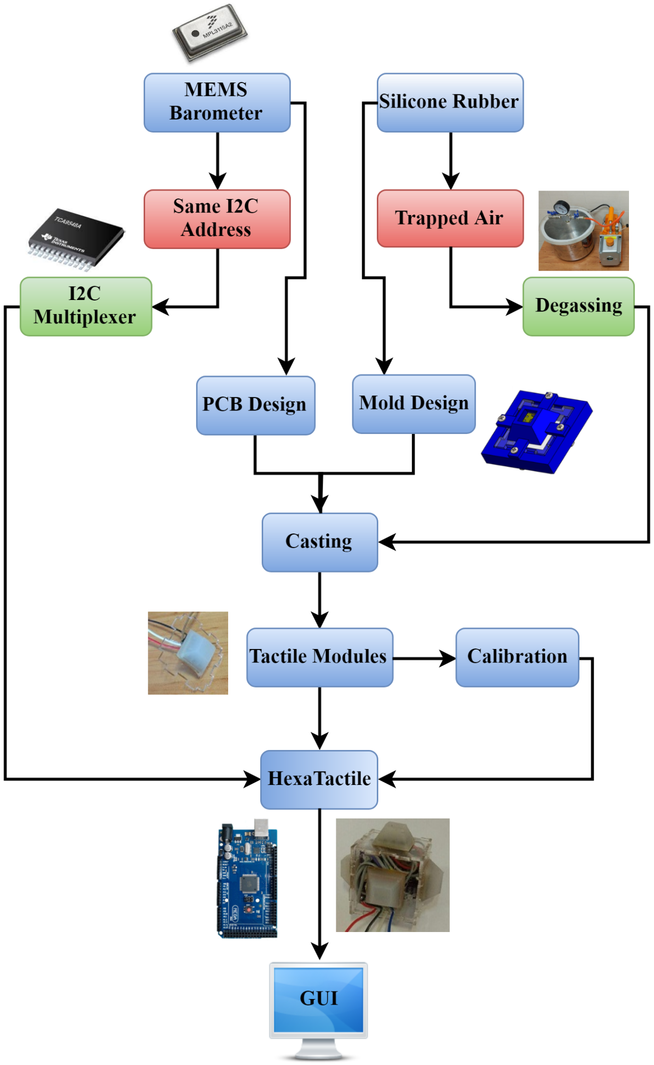


Fig. 12. Flowchart of HexaTactile implementation stages.

V. CONCLUSION AND FUTURE WORK

In this paper, a three-dimensional soft tactile sensor called HexaTactile was introduced that includes six tactile modules, each containing a barometer that is molded by silicone rubber. The two main parts were the manufacture of this sensor electronic and molding. In the first part, the use of I2C multiplexer to networking the modules and in the second part, degassing process and use of silicone were studied. Figure 12 depicts the main implementation strategy of the proposed HxaTactile. This sensor was designed for the purpose of human-robot interaction and manipulation and is suitable for installation on a robot's end-effector. Small dimensions, high accuracy, simplicity of design and construction, and low pricing are the features of this sensor that allows one to measure force. It yields an accuracy of 0.01 N and a range of 4 N in each direction. As future work, HexaTactile will be installed on the end-effector of a parallel robot to control it for human-robot interaction purposes.

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