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Тема / Topic	**Конструкция датчика силы на базе оптоэлектроники/ Design of Optoelectronics Based Force Sensor**

Работу выполнил / Thesis is executed by	**Раза МухаммадИльяс/ Raza Muhammad Ilyas**	подпись / signature
Руководитель выпускной квалификационной работы / Graduation Thesis Supervisor	**Гапонов Игорь Юрьевич, профессор/ Gaponov Igor Yurievich, Professor**	подпись / signature
Консультанты / Consultants		подпись / signature

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Abstract

Sensors are widely used in many kind of robotics systems for controlling, optimizing, and monitoring the operation and the performance. They measure large number of useful physical parameters. Among these, force and torque are primary measurements. This work presents a complete design and implementation of the uni-axial force sensor. This force sensor is based on an optoelectronic sensor which is known as a light fork. This design can be used for various robotics applications to measure the force. The simplicity of design and its low cost, make it more feasible to measure the force applied by different robots by the deformation of a properly designed mechanical structure integrated into the actuation module. This force sensor provides good linearity and sensitivity for applied force.The work contains the complete scheme of electronics schematics with PCB design. The electronics design contains the STM32f405 microcontroller, which has internal memory to save the calibration data. The mechanical design is also described in this work with proper dimension and length to construct the obstacle and and case of the sensor. The design of sensor can be modified for calibration and integration with robotics module. The methodology of this work describes the basic working principle and also proper mechanism to measure the force applied on the top surface of the sensor with arrangement of four optoelectronics sensors.

Chapter 1

Introduction

Nowadays, robotics systems and manipulators are used in many applications like medical systems and industries which are capable of adapting to the dynamic changes occurring in the environment. To measure these changes a number of features are required. Among these features, force and torque are primary measurements and also have importance in the design of wearable robotics devices like exoskeletons and prostheses. These devices require the efficient sensing scheme to control the forces exerted by an unstructured environment or by the robotics system on the humans or objects. The main purpose of the force sensor is to measure the force up-to maximum accuracy as much as possible. These measured force values are feedback to the robotic controller, so that it can adjust and control the force on a pre-defined scale.

In general, the force sensor contains the small transducer which measures the physical change due to force and then converts these signal into an electrical signal which can be converted into a digital signal using ADC(Analog to Digital Converter). This data is processed by the Microcontroller to calculate the magnitude of the force. The general working mechanism of the force sensor has been shown in the fig1.1

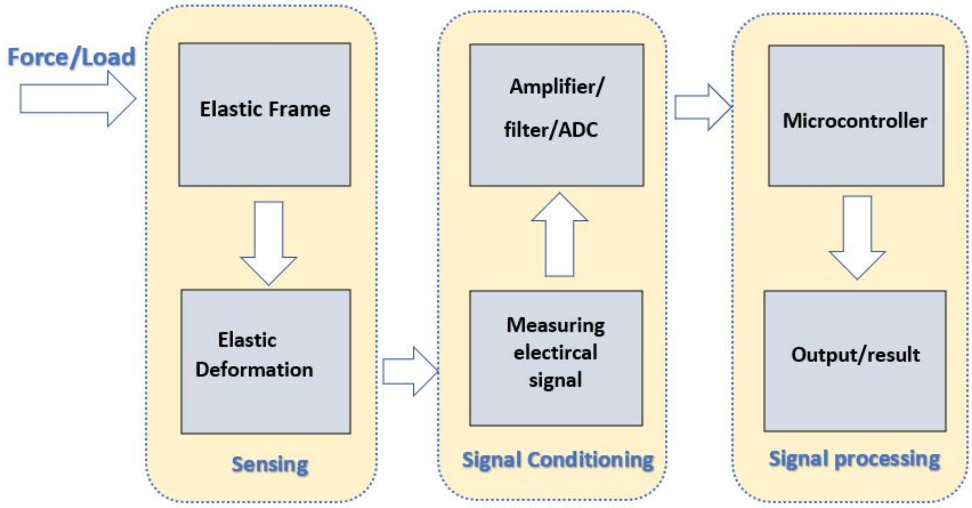


Figure 1.1: General design of Force sensor

1.1 Requirements and specifications

There are many commercial force sensor are available, that are used in different robotics systems. The price of these commercially available sensors is high, which make them expensive to use them in single robotics system. The objective of the work is to design the uni-axial force sensor with low cost and compare-able accuracy with industrial sensors. On the other hand, Some robotics systems have different and complex mechanical structures. In these cases we need structure of force sensor in different shapes. For example in the legged robot, the shape of the sensor should be in spherical form to fit it in the joint. The main objectives are listed below for the design of this force sensor:

- Design of low cost sensor.
- Easy design of sensor to measure the force.
- Flexible mechanical design modified according to system requirements.

- Accuracy of the sensor in comparison with commercial sensor.

1.2 Thesis Outline

The Outline of thesis is organized as follow:

- **Chapter 2** contains the literature review about different type of the sensor like strain gauges, Piezoelectric and optoelectronics based force sensor. In this chapter, working of difference sensor and theirs advantage and disadvantages also discussed.

- **Chapter 3** describes the methodology strategy for design of force sensor. Mathematical model and working principle of proposed model has been explain in detail.

- **Chapter 4** contains the three section of implementation. In first section schematics and PCB design of sensor is discussed. In second part mechanical design of force has been explained. In last section, process of calibration of force sensor is given.

- **Chapter 5** describes about experimental setup and evaluation of the proposed force sensor to measure the force. There are various experiment has been performed to check result and validity of the sensor.

- **Chapter 6** contains the conclusion of the proposed design of the sensor and possible future works to design multi-axes force sensor using the optoelectronics based technique.

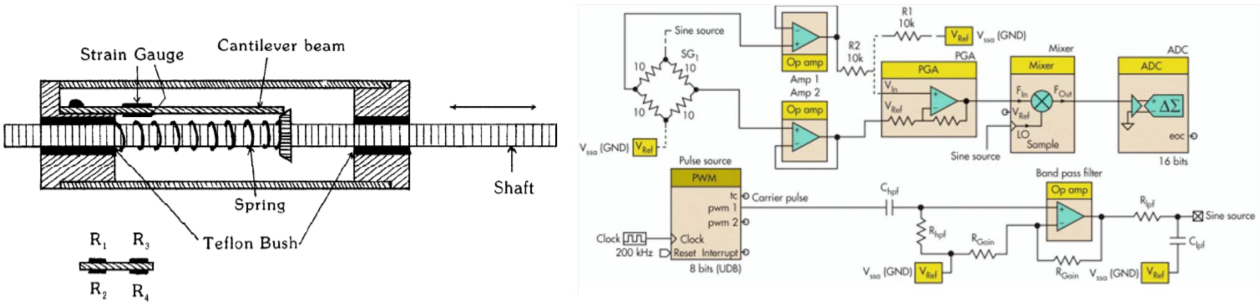
Chapter 2

Literature Review

There are many types of uni-axis and multi-axis force and torque sensors are available in the market. Their working principle and literature review has been discussed in the following sections.

2.1 Strain gauges-based force sensors

Most of the force sensors contain strain gauges-based structures which include the thin-film resistors or semiconductor components for sensing the force[1]. When there is strain is induced in mechanical structure due external load, as change occurs in the strain guage material. These change cause to produce the electrical signal. The value of signal is proportional to applied load or force. By using calibration method, this signal is converted to force [1]. Strain gauge based force sensor is shown in fig 2.1. Strain gauge sensors has some advantages that they have very good linearity but this system required the complex electronics design for signal acquisition, sensitivity to noise and temperature. Electronics design is given in fig 2.1b. Further, the strain gauges based sensor requires a well and proper design for mechanical structures as given in fig 2.1a. This produced difficulty sometimes while integrating with the complex mechanical system of the robot. So strain gauges based sensors have significant limitations in term of easy design. This brings the robotic designer to rely on some new sensors which have less complexity and feasible with the robotics system during integration.

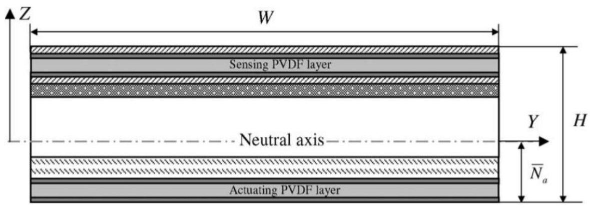


(a) Strain-guage based sensor design **(b)** Circuit design for signal acquisition for strain-guage circuit

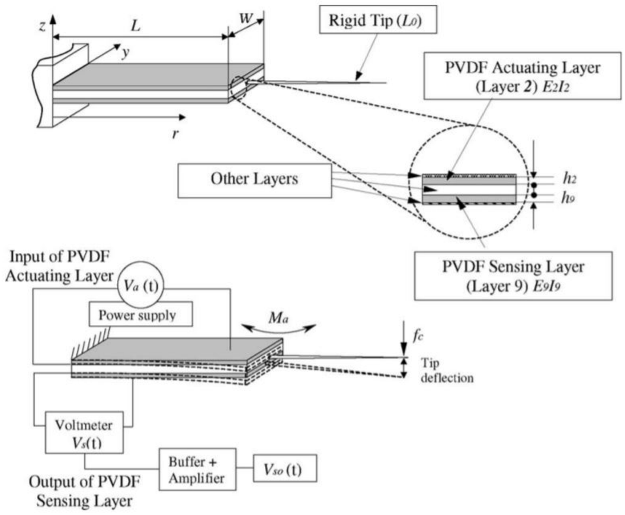
Figure 2.1: Strain gauge circuit design scheme

2.2 Piezoelectric based force Sensor

The article [2] presents the related work to design of the force sensor using piezoelectric material. The sensor has been developed by soft cantilevered beam structure and using piezoelectric material polyvinylidene fluoride(PVDF) for sensing layer which has been symmetrically embedded in composite sensor beam shown in fig 2.2. The working principle is that when external force is applied its produce the deformation in the soft layer. This deformation due to force is recorded by PVDF, using feedback controller. These changes measured through electronics circuits. Then electrical signal are used to calculate the force in calibration process. The sensitivity of sensor is extremely good, but there is difficulty to design the sensor, is need of special labs for piezoelectric material and very care is needed for proper design sensors.



(a) Soft cantilevered beam structure using PVDF

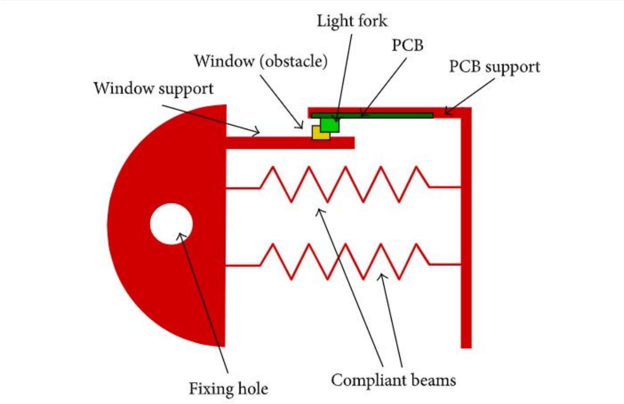


(b) General Piezoelectric based sensor design

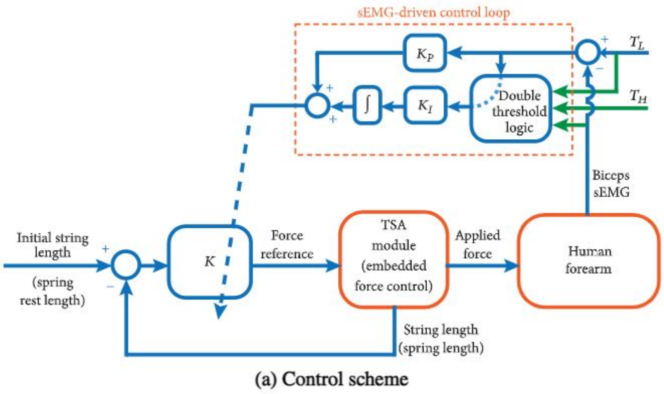
Figure 2.2: Piezoelectric sensor design

2.3 Optoelectronics based sensors

Optoelectronics components are used in various application in the electronics like switching and isolation.Theoretically use of these sensors has been discussed by the several authors [3], [4], [5]. The optoelectronics sensors exploit the reflection beam which is emitted by the source and received by the detector or receiver. This beam is disturbed by the external elastically coupled elements.Thus detector can able to detect this deformation by the complaint structure due to external force[6].There is force sensor in fig 2.3, which contain the discrete optoelectronics for the robotics hand to measure the tendon force at the actuator side for force control and to compensate the frictions[7].



(a) Structure of optoelectronics sensor for robotics hand



(b) Feedback controller for design

Figure 2.3: Optoelectronics based sensor design scheme

The article [8] explains the micrometric based force sensor. This measure the differential of the light intensity using optoelectronics devices and a pair of fiber optics the highly accurate and with good sensitivity for two degrees of freedom. There is another article [9] Which discuss the work on bases of calculating the coupling power of the optical devices between photodiode and surface-emitting that is separated by a deformable transducer layer.The force is applied the transducer layer changed which receive the power less from transmitter so this change in power is used to calculate force. In the article [3], an optoelectronics sensor is built on the compliant mechanical structure to measure the force for human-force interactions. The working principle was that, when force is applied displacement of the handle piece inside is measured using the infrared “reflective object ” sensor elements. These sensors are mounted on a PCB board and attached with the inner side of the sensor. There is 6-axis F/T optical sensor is design using a 2-axis photo-sensor which measure the deformation caused by external force or load on the complaint structure[10]. This sensor is 6-axis measurement but the manufacturing and design of the sensor is complex. There is more accuracy is needed to design for calibration.

Another work done on the two types of the sensor(3x3) arrays which are built using fiber Bragg gratings(FBG) and transducers for tactile sensation[11]. This used to measure the normal force applied on the array of the sensor. This sensor has good sensitivity and spatial resolution. The transducer is designed in such a way that it is not affected by the light loss. There is another work related to optoelectronics based force sensors which work on CCD or CMOS cameras to measure the deformation which is caused by the external force [12]. In this work,there is a rectangular box of transparent silicone rubber with dimensions of 10 $\times$10 $\times$4-cm is fixed with an acrylic board. We printed the collection of Different color markers with height of 0.6 mm in diameter are placed inside the box a CCD(color charge-coupled) camera is placed 15 cm below the marker.When force is applied the camera measures the displacement, this displacement is used to calculate the amount of the force.

This tactile based sensor contains the urethane foam and array of IR emitter and detector which are surfaced mounted [13].The foam layer creates the optical cavity above the emitter detector layer. The optical devices mounted below the polymer surface.when the force is applied on the cavity it deforms the optical properties. This change in the properties is used to measure the force which created these changes.

Another optical tactile based sensor has been proposed in [14].This use the LED phototransistor couples and there is deformable elastic layer is placed above the optoelectronics devices.These optoelectronics components are organized in form of matrix. LED illuminates the reflecting surface of the bottom side of the deformable layer.This deformation is occur due to external force which has been applied. Due to this reflection of the LED is changed which produced the variation of the current on photo detector. Which may be positive or negative .So these changes used to calculate the amount of the force. There is a 3D structure based tactile sensor that is discussed in [15]. The main working principle of this sensor is that it measures the force with three separate photodiodes. Three sensors are used to measure the three directional forces imposed on the sensor. The LED through the light on the inner surface of the dome, each sensor works independently. Each side only produced the reflection on the specific region. So this reflection is used to measured the force from all three sides of the sensor.

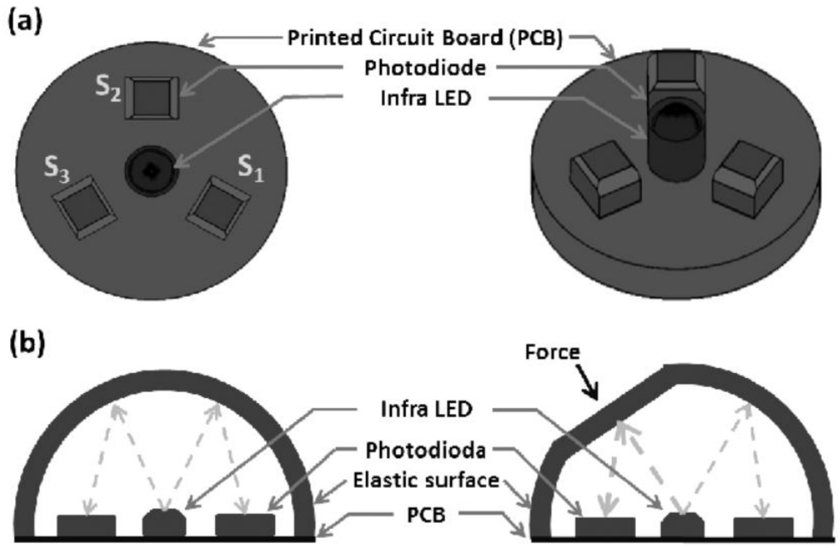


Figure 2.4: 3D structure based tactile sensor

Another article [16] descibes the alternative solution using fiber optic. This contained on Fabry-Perot strain interferometer. These contains the two flat semi transparents mirrors. Light propagates between them by reflection. There is some light transmitted and some light reflected . The distance between these two mirror fibers is usually in nanometers. When force is applied and this distance changes, the reflection angles and strength are changed. These changes are used to measure the amount of the force applied on the surface of the sensor. These types of sensor are compatible in high field magnetic resonance imaging (MRI). The machine learning techniques are investigate the sensors describe in the [17]. This LIM(light intensity modulated) force sensors are widely used in the field of flexible system and surgical robotics. In this article there are three LIM force sensor are fabricated and machine learning regression techniques for compensation of temperature and ambient light sensitivity using on board environmental sensor data. These number of design and implementation of force sensor provide the importance and use of the optoelectronics devices in sensor.

Chapter 3

Methodology

Theoretical background for the design of the force sensor has been described in the previous chapter, where we have studied the different methods to design the force sensor. For effective measurement of the force, the transducer should need repeatability, accurately and predictably characteristics. In this work, our main focus is to design the cheap and easily manufactured uni-axial force sensor for different robotics systems. Method of design and mathematical model has been described below in subsections

3.1 Optoelectronics Devices

Optoelectronics devices are a major field in electronics. These devices are used to measure the light intensity and convert them into an electrical signal, Value of the output depends only on the intensity of the light received by the receiver of the optoelectronics device. There are many sensors that work on the principle of optoelectronics devices. In general, the optoelectronics sensors contains LED(Light-emitting diode) which act as transmitter for light whereas PD(photodiode) act and receiver, when LED transmit the light and PD receive the light on its surface, its start to conduct the electrical signal depending on the amount of light. There is no physical connection between LED and PD. The basic mechanism of optoelectronics sensor is shown in 3.1

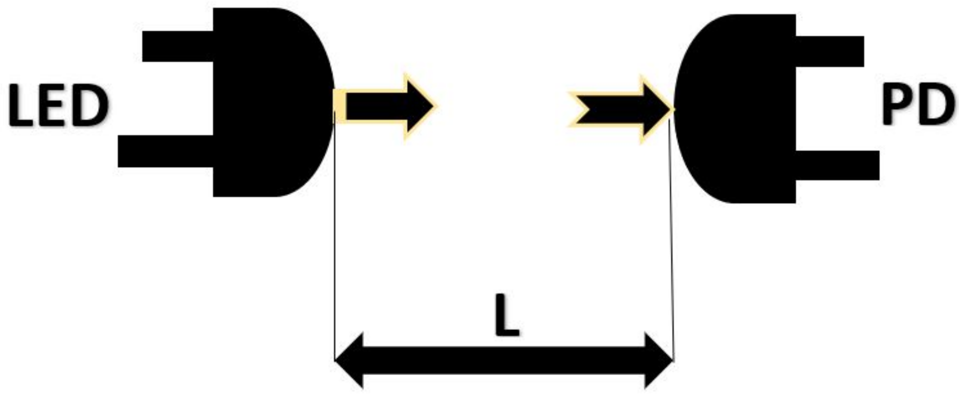


Figure 3.1: General Design of optoelectronics sensor

3.2 Photo-micro-sensor (OMRON EE SX1108)

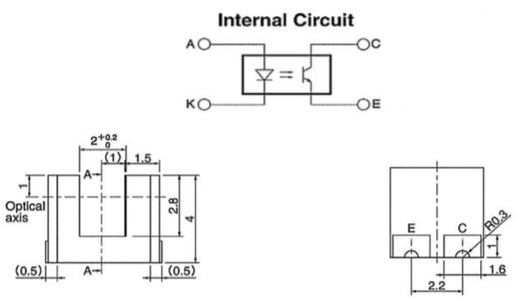
There are many Photomicrosensos available.However for this design, the OMRON EE SX1108 is used.The main properties of this sensor are:

- It is more sensitive compare to the other sensors
- Both LED and PD are embedded together in a compressed structure and precise relative position.

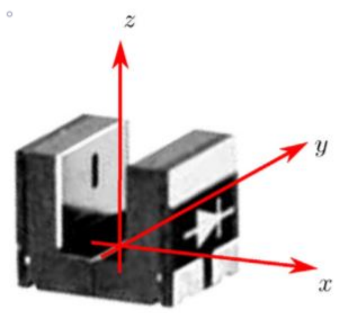
- Both an LED and a PD face each other and provide a thin window that restricts the light cone coming from the LED to the PD just focused on a specific region.

- Produce output with high resolution and accuracy in response to the input

Details of the sensor design is reported in fig 3.2. Particularly light fork sketch, dimension, and the internal circuitry are given in fig 3.2a and 3D model is shown with reference frame in fig 3.2b.This detail is given in datasheet of OMRON EE SX1108.



(a) Sketch and Dimension



(b) 3D view with reference axis

Figure 3.2: OMRON EE SX1108 sensor detail

The light cone in the proposed sensor design is well shaped, providing a very steep and linear transition. Region between the fully covered and the fully free light conditions and allowing a good sensitivity and linearity to be obtained.

3.3 Working principle of the sensor

The Working Principle of the sensor is based on the modulation of the current flowing through the PD, which is control by the mechanical component called obstacle. This obstacle used to partially intercept the path of the light emitted by the LED and received by the PD.When there is no obstacle present between them, its limits the light flow, and LED is considered as a source of point light and PD as the receiver surface. As depicted in fig 3.3. In this scenario current flow through the PD only depends on the relative position between PD and LED. From fig 3.3, Left point $\overrightarrow{A}$ represents the LED which is assumed as the point light source, on the right side the line $\overrightarrow{CD}$ represents the PD surface. Optical axes of both LED and PD are aligned and presented by the line $\overrightarrow{n_{led-pd}}$. point $\overrightarrow{B}$ represents the point of intersection of the optical axis and PD surface. from middle point B its represent the receiving angle of light on PD surface from a point source at distance $\overrightarrow{d}$.

An obstacle is introduced in between LED and PD as shown in fig 3.4 . Some amount of light from LED is intercepted by the obstacle and optical power is measured in the form of P(sigma). The position of the obstacle is define by the variable which is from range o to 1. It means when the value is zero there is no occlusion and 1 means full occlusion and no power transmitted. the equation when there is no obstacle is calculated by the following equation

$$P(\sigma) = K \int_{-\frac{\theta}{2}}^{\frac{\theta}{2}} I(\theta)R(\theta)d\theta \tag{3.1}$$

where k is used to represent the device characteristics.$I(\theta)$ and $R(\theta)$ are used to represent he radiation pattern of LED and responsivity pattern of the PD. In case, there is obstacle came between them, equation of transmitted power is

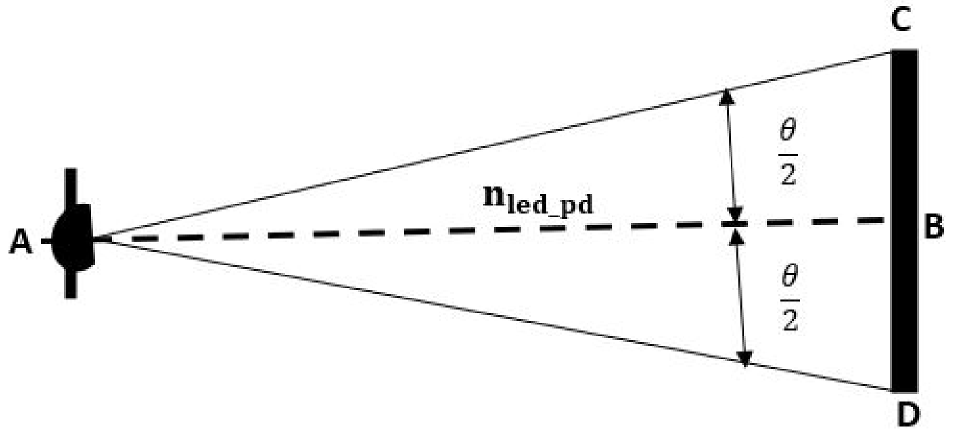


Figure 3.3: Representation of Intersection between LED and PD without obstacle

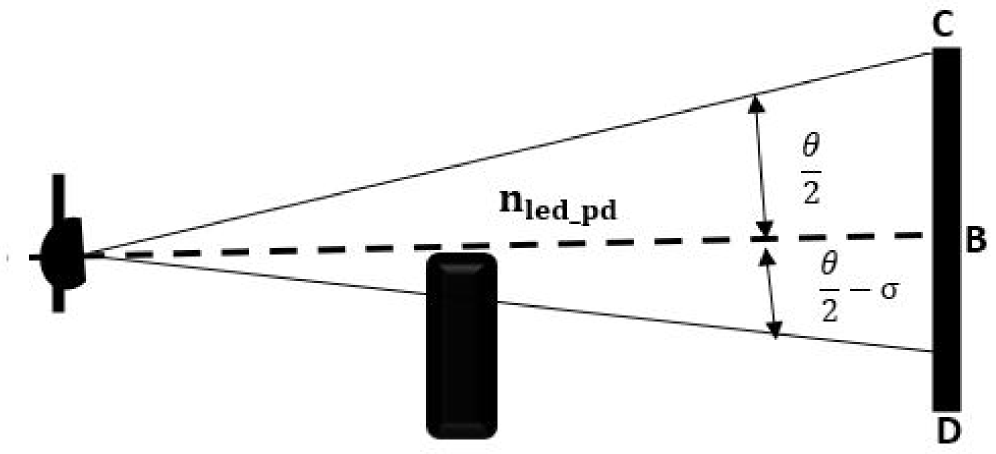


Figure 3.4: Representation of Intersection between LED and PD with obstacle

changed and represented by the following equation

$$P(\sigma) = K \int_{-\frac{\theta}{2}+\theta\sigma}^{\frac{\theta}{2}} I(\theta)R(\theta)d\theta \tag{3.2}$$

when σ =0 , then there is no occlusion,and $P(\sigma) = P_0$,but when obstacle moved between LED and PD and block the path completely then $P(\sigma) \longrightarrow 0$, and total occlusion is that $P(1) = 0$

the fig 3.4 shows optical axes of light fork of LED and PD n_{LED} and n_{PD} are well aligned and theirs respective angle α and β are zero another relation between relative light current and I_L and transmitted power $P(\sigma)$ can be relate using following relation

$$I_L = K_1 P(\sigma) \tag{3.3}$$

where K_1 represent the characteristic of PD.Similarly the output voltage V_0 of the sensor can be calculated by from

$$V_0 = R_{PD} I_L \tag{3.4}$$

When changes occurs in light power receive by the PD can be acquired by measuring output voltage V_0 the circuit is shown in the figure 3.5. The input voltage is V_{cc} .The maximum out voltage V_{max} will be selected to avoid from saturation of the PD of the sensor. The maximum displaced of the obstacle can be limited to σ_{max}.

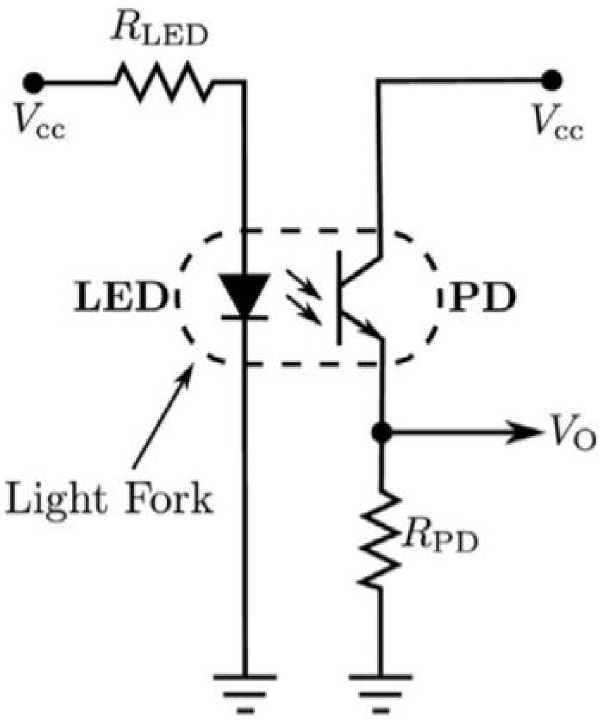


Figure 3.5: Electrical circuit presentation with V_{cc} voltage

The load resistance R_{PD} can be calculated from above equation

$$R_{PD} = \frac{V_{Omax}}{k_1 P(\sigma_{max})} \tag{3.5}$$

The light fork of the sensor is proposed in design with well shape.This provide linear and steep transitions of the region for fully covered and fully free light conditions, which allow good sensitivity and linearity with movement of the obstacle.When we move the obstacle inside the sensor its give linear relation with voltage value, these voltage value used for calculation of the force.

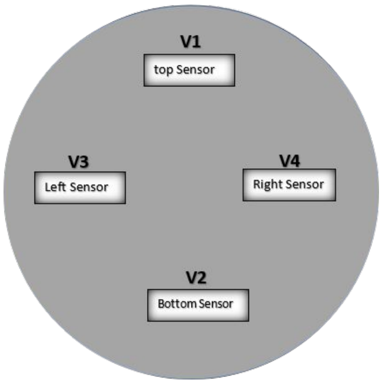


Figure 3.6: Four optoelectronics sensor based design

3.4 Four optoelectronics sensor based design

In the previous section, we have discussed the working of a single OMRON EE SX1108 sensor, which shows the linear relationship for output voltage, when an obstacle is introduced inside it. To measure the force from four sides left, right, top and bottom, to cover the whole 360 area, there are four force sensors that have been used to measures the total force as shown in fig 3.6.

3.5 Calculation of Force

There are four sensors used to generate the four voltage output. These values are used to measure the total force. To measure the force least-square method has been used.

3.5.1 Least square Method

The least-square is the method that is used to find the best value of the unknown variable in the large dataset which gives the best fit for the dataset by minimizing the error to satisfy expression with very small error.

From the discussion above we get the output from the sensors in form of voltage.So there are four sensors which produce the four voltage : At the start the known force has been used.

$$F_1 = \lambda_1 \; V_{11} + \lambda_2 \; V_{21} + \lambda_3 \; V_{31} + \lambda_4 \; V_{41} \tag{3.6}$$

$$F_2 = \lambda_1 \; V_{12} + \lambda_2 \; V_{22} + \lambda_3 \; V_{32} + \lambda_4 \; V_{42} \tag{3.7}$$

$$\vdots \tag{3.8}$$

$$F_n = \lambda_1 \; V_{1n} + \lambda_2 \; V_{2n} + \lambda_3 \; V_{3n} + \lambda_4 \; V_{4n} \tag{3.9}$$

These equations can be presented in to into matrix form below

$$\begin{bmatrix} F_1 1 \\ F_2 \\ \vdots \\ F_n \end{bmatrix} = \begin{bmatrix} V_{11} & V_{21} & V_{31} & V_{41} \\ V_{12} & V_{22} & V_{32} & V_{42} \\ \vdots & \vdots & \vdots & \vdots \\ V_{1n} & V_{2n} & V_{3n} & V_{4n} \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{bmatrix} \tag{3.10}$$

if we represent the force vector with F, voltage vector with V and unknown multiplier factors with B, then we can express them in following simple equation

$$F = VB \tag{3.11}$$

as F and V are already known we can calculate the value of vector B following equation

$$B = FV^{-1} \tag{3.12}$$

As F is applied known force and V's values are output voltage from all four sensors, these value are in large numbers and contain 1000s of values.Here, Least square method is used for calculation and give best value of the vector B which produces the minimum error and produce the most fit value which will satisfy the expression. after calculating the value of the vector B we can be able to calculate unknown force applied on the sensor.

$$F_{unknown} = \lambda_1 \; V_1 + \lambda_2 \; V_2 + \lambda_3 \; V_3 + \lambda_4 \; V_4 \tag{3.13}$$

Chapter 4

Implementation

In the previous chapter, the methodology of the force sensor has been discussed, In this chapter, we will discuss the complete process of implementation of the force sensor in detail. This implementation has required both electronics and mechanical design so we will discuss the following topics in this chapter.

- Electrical design of the sensor.
- Mechanical design of the sensor.
- Process of Calibration

4.1 Electrical design

Force sensor contains the four optoelectronics sensors for proper working of the sensor.the electrical parts required the complete circuit design. I will discuss the main parts of the design in following subsections

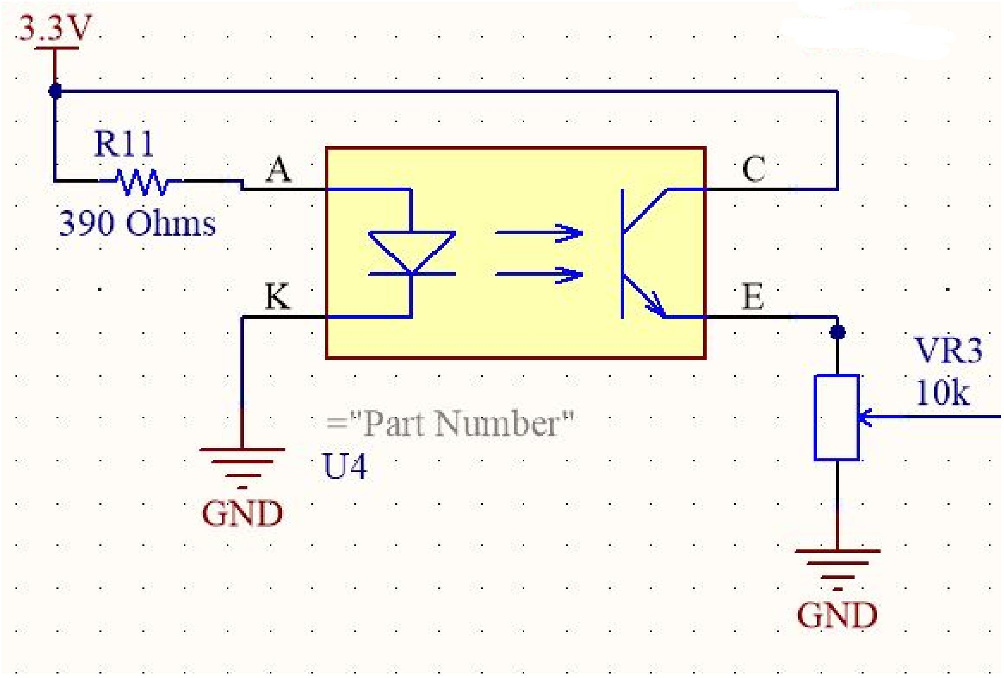


Figure 4.1: Circuit design of OMRON EE SX1108

4.1.1 OMRON EE SX1108 sensor

In this design I have used the four OMRON EE SX1108 sensor. These sensors are very sensitive to obstacles which are introduced inside the sensor. This sensor has four terminals which has been described in table I For proper

Terminal No	Name
Anode	A
Cathode	K
Collector	C
Emitter	E

Table I: Pin description of OMRON EE SX1108

working of this sensor its required electronics design with combination of the resistor as shown in this figure 4.1. VR3 is variable resistor used to adjust the sensitivity of the sensor.

4.1.2 Analog to Digital Converter

Analog to digital converter (ADC) is an electronics device used to convert the electrical signal in form of voltage or current into digital value. Because most of the microprocessor process the digital values with high speed.

AD6782B

The requirement of our design is to convert the output of the four sensors into digital values. So the minimum requirement is the ADC with four channel.For this purpose I have used the AD7682B sensor which has the following properties:

- 4-channel multiplexer with choice of selection of input.
- 16-bit resolution with no missing code
- It is Uni polar single-ended Differential
- There is build-in Internal temperature sensor available
- It has Serial interface compatibility with SPI (Serial peripheral interface).

As this ICS use the SPI interface to send data between microcontroller and ADC. This interface uses the separate clock and data lines with option of to choose the device which needs communication. There are four pins required to connect with Microcontroller these pins has following function described in the table II:

Pin Name	Type	Function
MOSI	Master output slave input	input
MISO	Master input slave output	output
SCK	Clock	serial clock output
NSS	Chip selection	optional selection

Table II: SPI pin descriptions

4.1.3 Microcontroller

Microcontroller is a small computer which is designed on the single metal oxide semiconductor (MOS) integrated circuit chip. In general microcontroller contain one or more CPU also with memory and input/output peripheral. Microcontroller is the main part of the design which is responsible for all computations and making decisions.There are a large number of the families available with different properties and benefits.I have used the STM-32F405 microcontroller in this design. This microcontroller has following main features.

Flash memory

Flash memory usually known as ROM, is a type of the non volatile memory which stores the data for lifetime. These memories don't lose the data when the power supply becomes off. This memory can be erasable. The STM32F405 has flash memory up-to 1 megabyte that is enough to store the programming data for our design.

CAN protocol

CAN protocol is used to communicate the electronics devices with each other for transmitting and receiving the messages in a network . CAN protocol contains the number of the rules which defines how data will be transferred from one electronics device to another device in a given network. In STM32F405 there are two CAN connections available so the device is capable of communicating with two networks at same time. These characteristics make this microcontroller family more reliable. In our design the purpose of CAN is to communicate STM32F405 with outer world devices, because this controller gives the output in form of force. These forces can be used for input for other controllers used in robotics systems.

ST-LINK

STM32F405 also support the ST-LINK that is in-circuit debugger and programmer. This is single-wire interface module(SWIM) and serial wire debugger (SWD).These interfaced are used to communicate with STM32F405 and program it.

Other Main feature of STM32F405

Some other features of STM32F405 have been given below:

- There are up-to three I2C interfaces available..
- Up to 4 USARTs/2 UARTs connection are present on STM32F405
- There are three SPI interfaces available on the Microcontroller

4.1.4 Power supply circuit design

Power supply for the electronics devices is very important for different components. There are different voltage required. In our design most of the component operate on the 3.5 volt and some of them operate on 5v. For this purpose i have used the electronics ics RT9013. This is high-performance regulator which offers the very low PSRR and low dropout.This give the 3.5v as the output and take 5v as input voltage in my design. There is an array of capacitors also used to reduce the further noise of the circuit. As shown in the figure 4.2

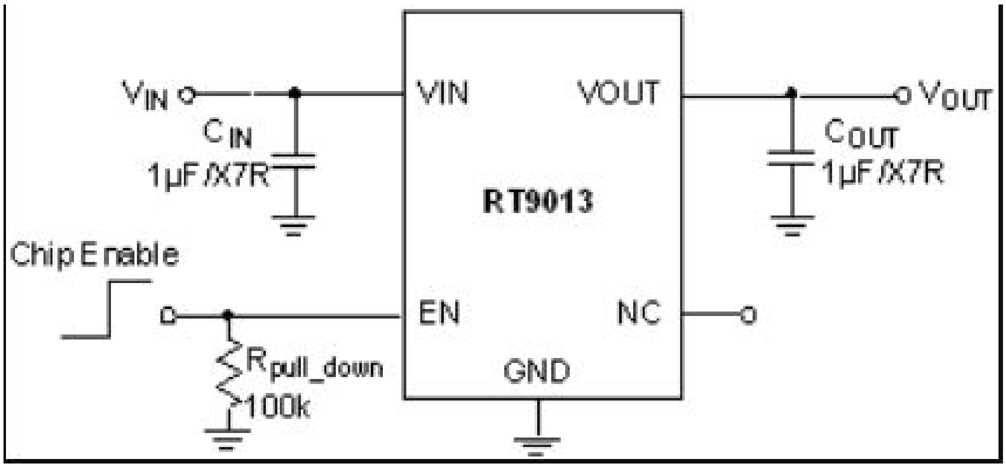


Figure 4.2: RT9013 circuit used for conversion from 5v to 3v

4.1.5 Schematics Design of the circuit

To design the schematics circuit design, I have used the Altium designer software. this software is used in industries to design the efficient and complex circuit design. There are some amazing features which make it easy for developers to make efficient designs.

- Its provides Project Sharing features, so more than one people can work on it.
- ECAD-MCAD collaboration which make its perfect for industries where altium designer work together with solid work designer for make the product

- 3D Model design of the final PCB design which looks like the real design
- Show the availability of the components from different suppliers like digikey and mouser etc.
- Make it easy for routing and placement of components.
- Very easy to design the board shape according to required design

The schematics diagram of the circuit has been shown below in the fig 4.3 and 4.4

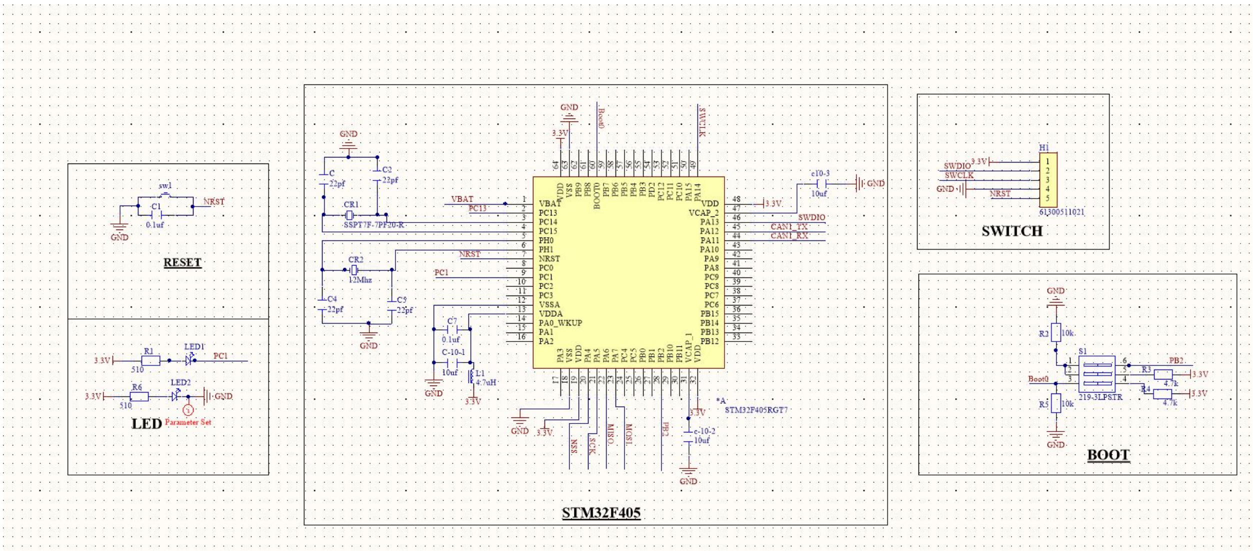


Figure 4.3: Schematics diagram of circuit part-1

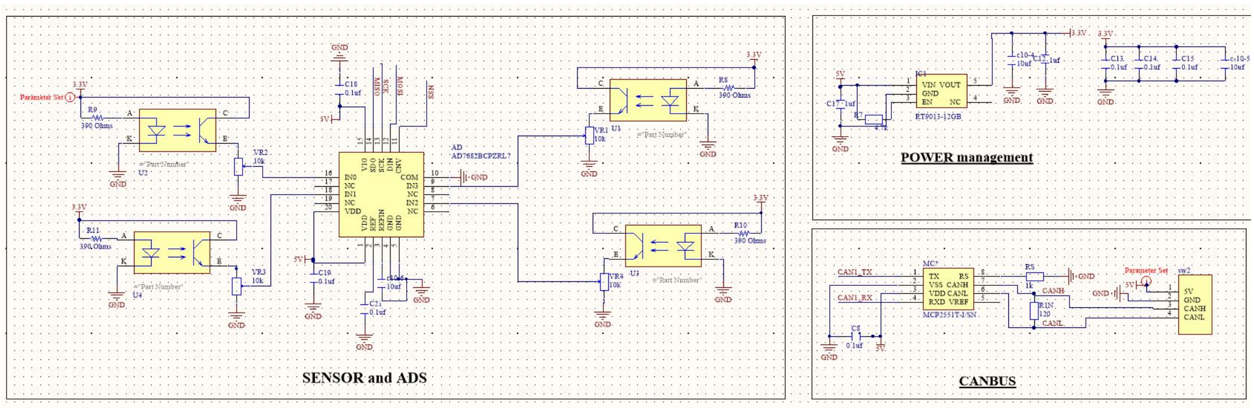


Figure 4.4: Schematics diagram of circuit part-2

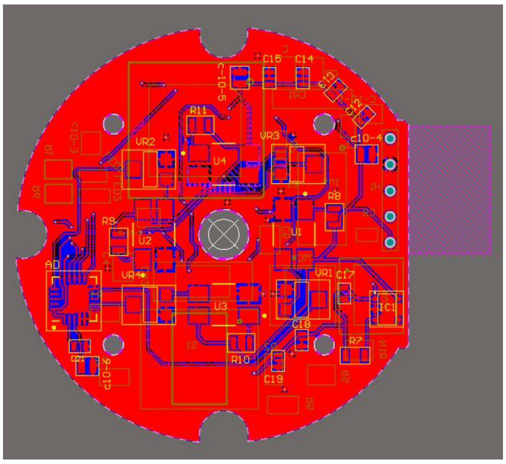
4.1.6 PCB design of the circuit

The PCB board has two top and bottom layers. The following list of the components has been used, given in the table III.

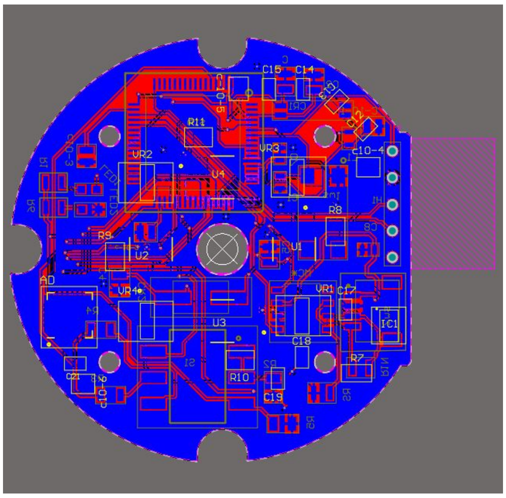
Designator	Comment	Part ID	Qty
ADS	ADC	AD7682BCPZRL7	1
cap1,cap2,cap3	10uf	C0805C106M8RACTU	3
cap1,cap2,cap3	10uf	C0805C106M8RACTU	3
C1, C7, C8, C13, C14	0.1uf	VJ0603Y104KXJCW1BC	5
C15, C18, C19, C2	0.1uf	VJ0603Y104KXJCW1BC	4
C12, C17	1uf	TMK107B7105KA-T	2
C, C2, C4, C5	22pf	C0805C220J8GAC7800	4
CR1	Crystal 32khz	SSPT7F-7PF20-R	1
CR2	crystal 12Mhz	ABLS7M-12.000MHZ-B-2-T	1
H1	Male connector	61300511021	1
IC1	egulator RT9013	RT9013-12GB	1
L1	4.7uH	AIML-0603-4R7K-T	1
LED1	Green	LT Q39G-Q1OO-25-1	1
LED2	Red	APT1608SRCPRV	1
MC*	CAN IC	MCP2551T-I/SN	1
R1, R6	510 ohm	RC0805FR-07510RL	2
R1N	120 ohm	Y1629120R000Q9R	1
R2, R5	10k ohm	MCU0805MD1002BP100	2
R3, R4, R7	4.7k ohm	RG2012L-472-L-T05	3
R8, R9, R10, R11	390 ohm	ERJ-6ENF3900V	4
RS	1k ohm	RG2012L-102-L-T05	1
S1	Dip Switch	219-3LPSTR	1
stm32	stm32f405GT	STM32F405RGT7	1
sw1	E-switch	TL3305AF160QG	1
sw2	JST Switch	SM04B-SRSS-TB(LF)(SN)	1
U1, U2, U3, U4	EE-SX1108	EE-SX1108	4
VR1, VR2, VR3, VR4	10K ohm	TC33X-2-103E	4

Table III: Component name with Digikey number

Final design of the board with Routing has been shown below with top and bottom layer can be view below in figure 4.5.



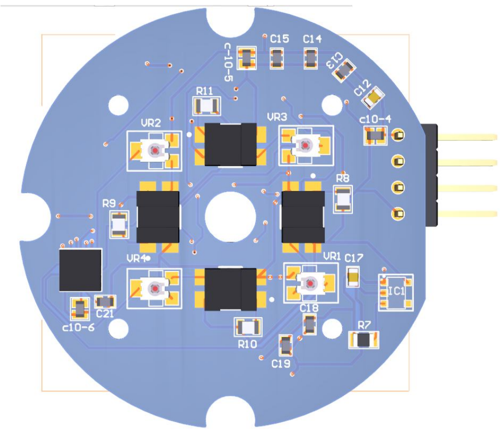
(a) Top layer view of PCB Routing



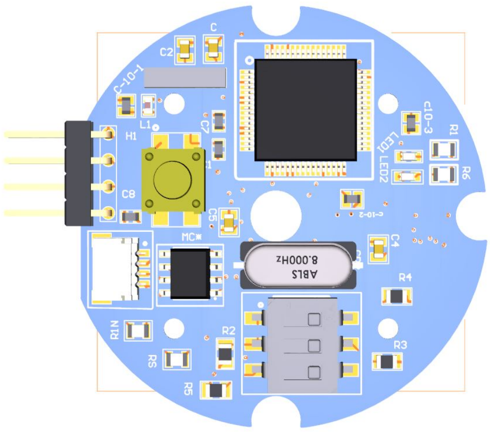
(b) Bottom layer view of PCB Routing

Figure 4.5: 2D Layout of the PCB design

As altium has feature to show the elements in 3D view, so final look of the board in 3D would be like this in figure 4.6



(a) Top 3D view of PCB board



(b) Bottom 3D view of PCB board

Figure 4.6: 3D view of the PCB design

4.2 Mechanical design of the sensor

We have designed the electrical part of the sensor for electrical signal conditioning and measuring. This is not enough for our design as we need to introduce the obstacle for each sensor, these obstacles have been designed in the form of mechanical design. Also, mechanical design is used to pack the sensor for safety TO applying the force. The mechanical design contains the following part.

4.2.1 Software

The Solidwork is CAD design software used to design mechanical design of different objects, particularly for automation applications. This software let us design and sketch our idea quickly. We can add features and dimensions and detailed drawings to it. Solidwork is used to generate the 3D model by designing 2D sketches. We can also design the different components inside it and assemble them like real objects. For the design of the sensor, the latest version of Solidwork 2020 is used in this work.

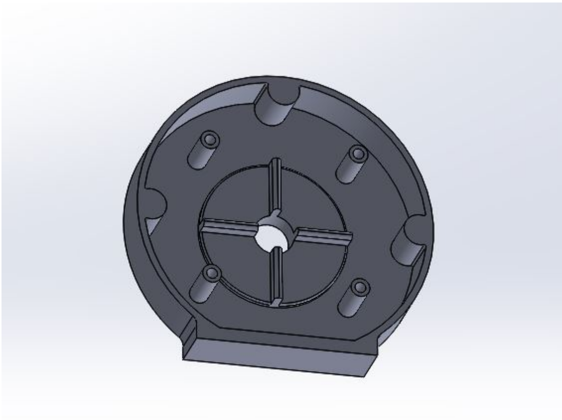
4.2.2 Obstacle's design of the sensor with upper design

The Cap of the sensor is part, which is used to introduce the obstacle for the sensor. It has been designed in circular form. And there are four obstacles to it. When force is applied on the top of the sensor these obstacles move down between LED and PD. Their distance is linear to the applied force . The dimension and lengths of the obstacle design are given in the following table IV

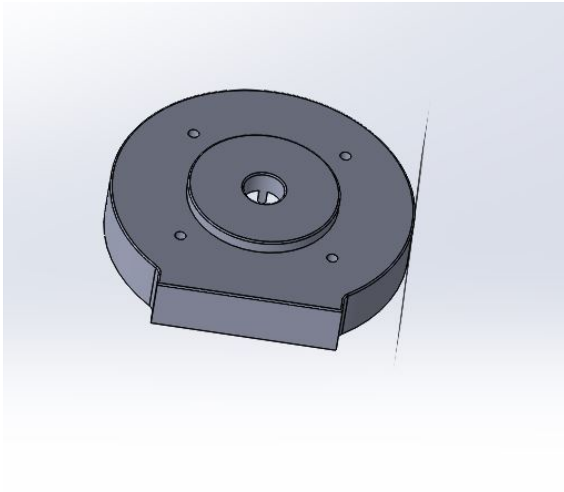
Solidwork design can be seen in the following diagram 4.7

Feature	Dimension
Wdith of single obstacle	1.20mm
Lenght of Obstacle	2.50mm
Diameter of circular part	25mm
Width of circular part	3mm

Table IV: Feature of obstacle's mechanical design



(a) Top Module with obstacle design

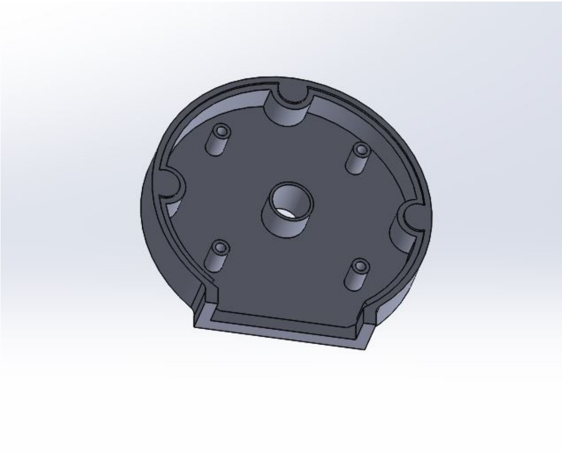


(b) upper view of sensor

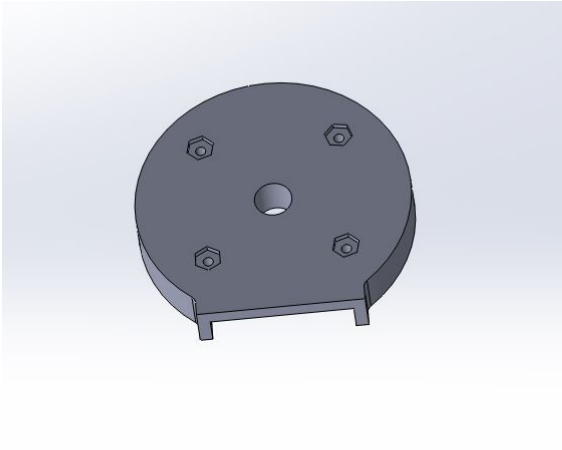
Figure 4.7: Mechanical Top case design of the sensor

4.2.3 Mechanical design for base of the sensor

For proper alignment of the obstacle and safety of the sensor mechanical case has been designed in which our PCB board is completely packed and aligned with the cap of the sensor. Only electrical wires come outside which makes its complete design. Solidwork design in has been given in the following figure 4.8.



(a) Base of sensor inner design vie

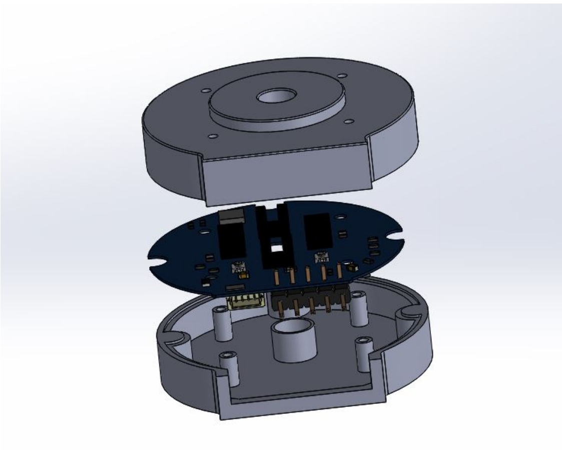


(b) Base of sensor with bottom view

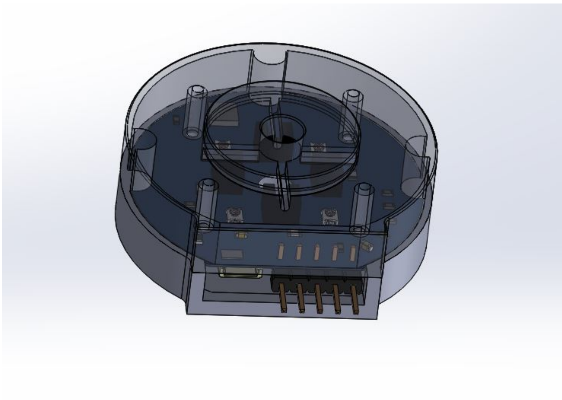
Figure 4.8: Mechanical case design of base of the sensor

4.2.4 Assembly of the design

After designing the mechanical part of the sensor. Solidwork allows assembling all components to check the perfection of design and to figure out any error before the manufacturing. As Altium design provide the 3D model of the sensor, so we can assemble all three parts, Cap, PCB board, and a case of the senor, the visual Assembly can be seen in the following figure 4.9



(a) Component of for assembly



(b) transparent view of design

Figure 4.9: Assembly design of the sensor

Final design can be seen in the following fig 4.10

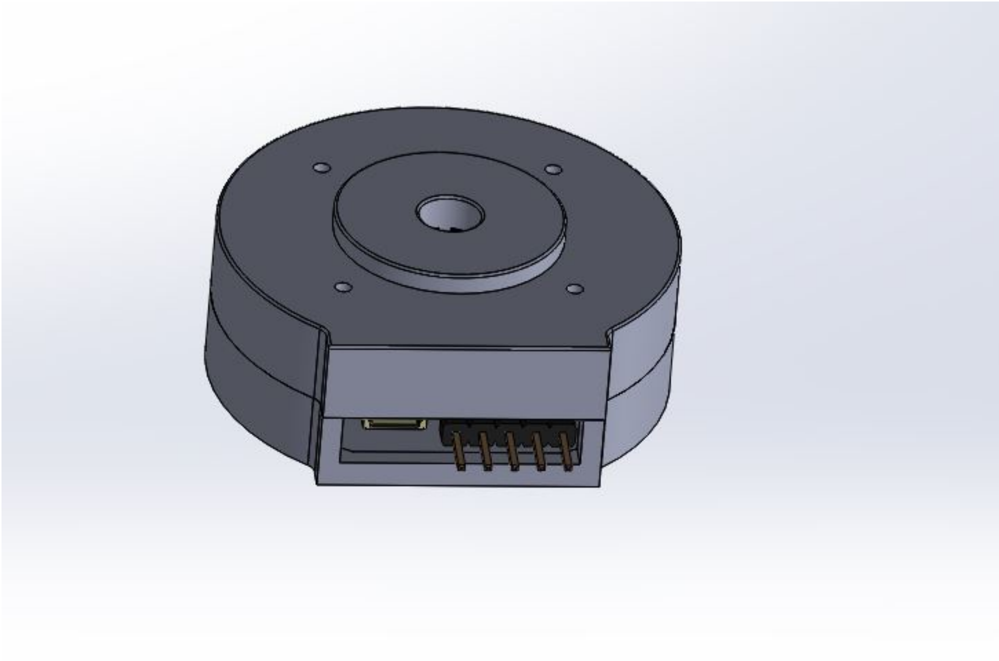


Figure 4.10: Final assembly of design of Force sensor

4.2.5 Manufacturing the Mechanical parts

Mechanical parts have been manufacturing using a 3D printer available in the LAB. Solidwork can generates and save the 3D parts in form of STL file. This file is used by the 3D printer software to manufacturer the mechanical part.

4.3 Process of Calibration

After the design of any sensor which is used for measuring force, torque, or load, there is a need for calibration. It is a process to configure the instrument which provides the output result of the device within an acceptable range. The main purpose of our calibration is to measure the force when force is applied. The Process of calibration contains the following the steps

- Reading the sensor's data.
- Applied known force.
- Calculation of the force.

4.3.1 Reading the sensor's data

At the initial stage, a raspberry pi3 has been used as MC to read the data from all four sensors. First, there is no force applied to the sensor, the value of all sensors has been set to zero.

4.3.2 Applied known force

To apply the known force, i have used the weight bar with mass (1kg,1.25kg,2.50kg), using these mass known force can be calculated as:

$$F_{known} = mg \tag{4.1}$$

After that saved the data from all sensors in the .csv file for more than 1000 iterations for each weight bar.

4.3.3 Calculation of the force

Then combined all values and using the least square and find the coefficient for each sensor used to calculate the force as described in the methodology chapter.

$$F_{unknown} = \lambda_1 \; V_1 + \lambda_2 \; V_2 + \lambda_3 \; V_3 + \lambda_4 \; V_4 \tag{4.2}$$

Chapter 5

Evaluation and Discussion

In this section, we evaluate the performance of the force sensor in a number of different experiment to evaluate the working accuracy of our design. The following section will demonstrate the experimental procedure:

- Experimental setup.
- Calibration Using weight bar.
- Calibration Using industrial Futek sensor.
- Finite element analysis of Mechanical design

5.1 Experimental setup

Raspberry pi3 is used as a controller which is connected with a laptop using SSH connection. And sensor module is connected with raspberry through ADC module.The futek sensor is also connected with MC through amplifier which operate at 20v. The experiment setup can be seen in the fig 5.1.

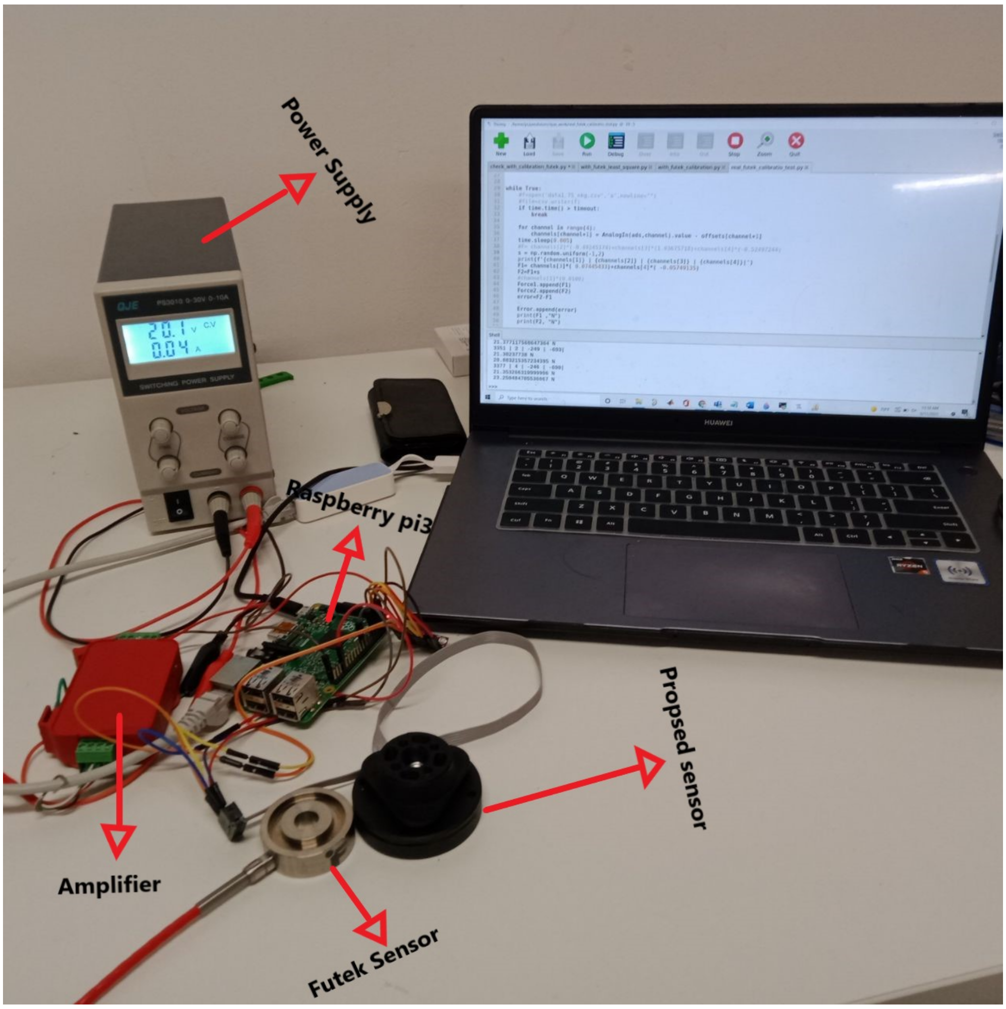


Figure 5.1: Experimental setup

5.2 Calibration Using weight bar

First, there is a need of the known force. I have used the weight bar with mass (1kg,1.25kg,2.50kg), using these mass known force can be calculated as:

$$F = mg \tag{5.1}$$

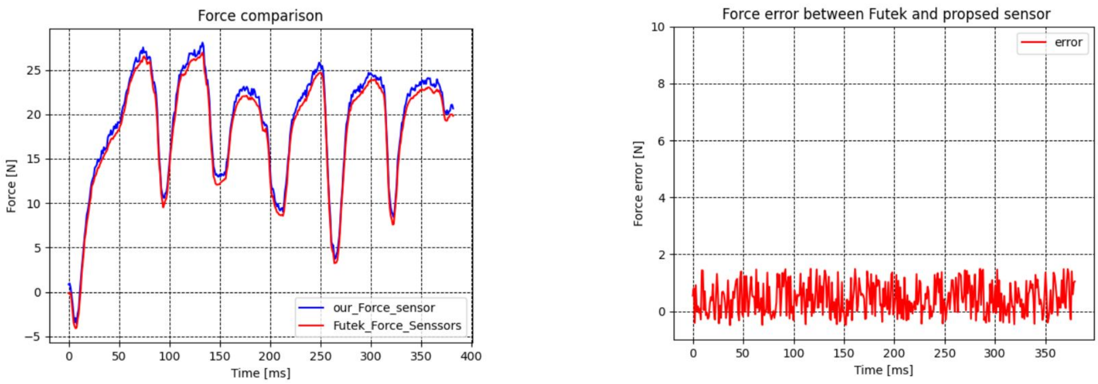
After that data from all sensors is saved in the .csv file for more than 1000 iterations for each weight bar.

5.2.1 Calculation of the force

Then combine all values and using least-square and find the coefficient for each sensor that is used to calculate the force.

5.2.2 Comparison with Futek sensor

To evaluate the results,whether proposed sensor is working correctly and measuring the force accurately ,I have applied the same force on both (my proposed and futek) sensors and record the result. In first experiment, the applied force is similar to sinusoidal and error is in form of noise that are given in 5.2

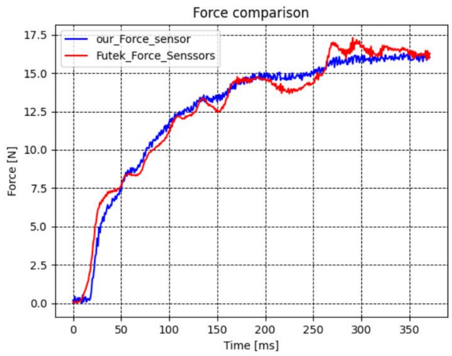


(a) First comparison with futek sensor

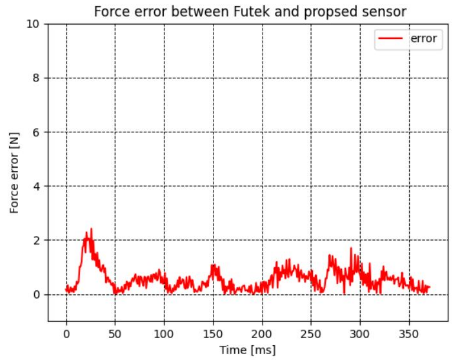
(b) magnitude of the error

Figure 5.2: weight bar calibrated sensors comparison with Futek sensor

Another experiment with in which applied force is increased continuously.In this experiment our proposed sensor show the little large error with maximum magnitude 2N.The results are given in fig 5.3



(a) second comparison with futek sensor



(b) magnitude of the error

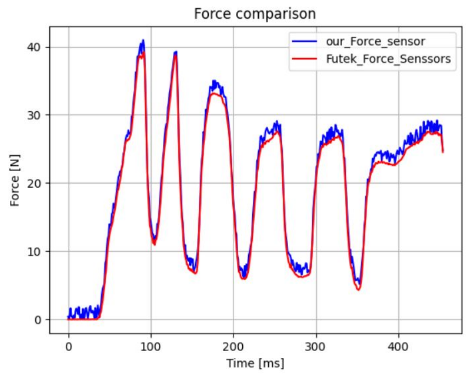
Figure 5.3: weight bar calibrated sensors comparison with Futek sensor

5.3 Calibration Using Force value from Futek sensor

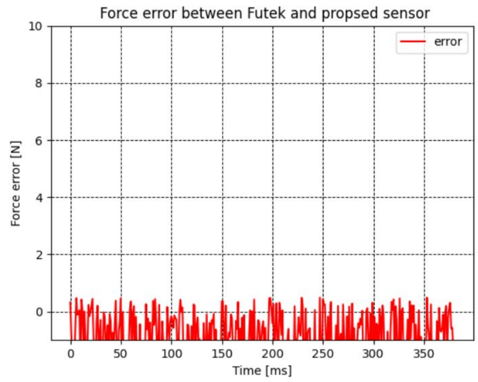
Futek LTH350 is the industrial sensor with high accuracy and precision.These sensor measure the force very accurately. In this calibration first,combined the both sensor and apply the force on them. During this process, force value from futek sensor and digital values of four optoelectronics sensors are saved in csv file.This will give more accurate force data.

5.3.1 Comparison with Futek sensor

After calibration,two experiment are conduct, the first experiment in5.4, there is small errors on the point, where force change abruptly. Second experiment in 5.5 show less error as compare to weight calibration.

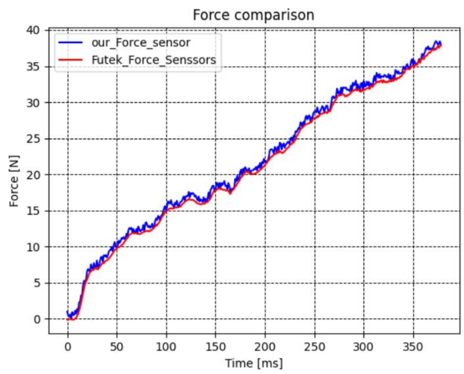


(a) First comparison with futek sensor

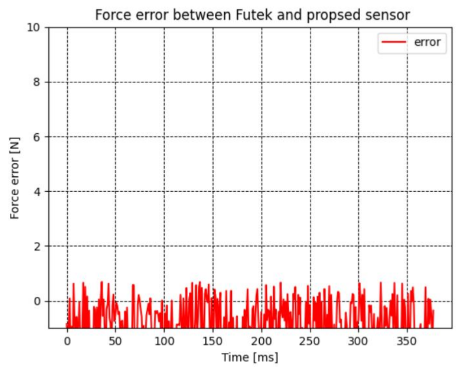


(b) Magnitude of the error for sensors

Figure 5.4: Futek sensor based calibration and comparison with Futek sensor



(a) First comparison with futek sensor

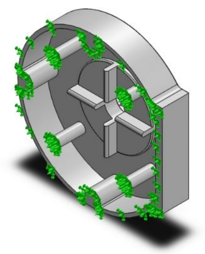


(b) Magnitude of the error for the sensor

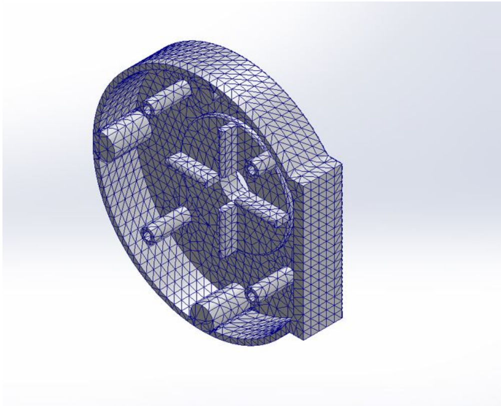
Figure 5.5: Futek sensor based calibration and comparison with Futek sensor

5.4 Finite element analysis(FEA) of for obstacle

Finite element analysis has been performed for the obstacle part of the sensor.To put The maximum force on the obstacle, the statics points has been selected which can be shown in fig 5.6a and mesh generated in fig 5.6b



(a) Selection of Statics points



(b) Solid mesh for sensor cap

Figure 5.6: Finite element analysis of obstacle

20N force is applied and after analysis we can see that maximum deformation is 0.63mm.and this sensor can bear upto 60N force withstand.We can increase the force limit with increase of width of the top cover.

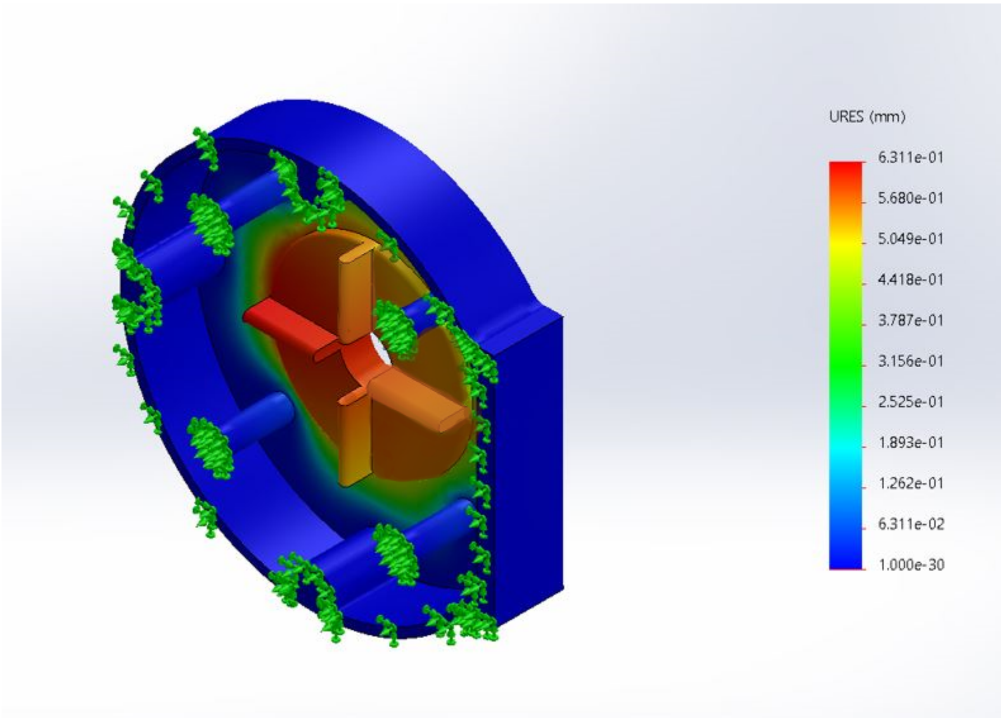


Figure 5.7: Final finite element analysis of obstacle

5.5 Discussion

The experiment to measure the force show that deformation of mechanical obstacle are dependent on the material. We can see the measurement graph shown in figure 5.2 and 5.3, when force change from on the sensor its take some more time to restore the deformation. The results in 5.4 and 5.5 are calibrated with help of industrial futek load sensor and produce the better results. These experiment are performed on the prototype of the electrical design, there is also some noise due to loose connection. Overall performance of the sensor is good. Optoelectonics sensors shows good linear and sensitivity properties.This proposed design is cheap and can be good subsitute for expensive sensors.The source files for electrical and mechanical design and calibration source code are given in [18]

Chapter 6

Conclusion

This work presents the development of low-cost and easy-building design of the force sensor using optoelectonics sensing component, which is called light fork and embedding the LED (light source) and PD (phototransistor).This special structure of optoelectronics device OMRON EE SX1108 and its characteristics like light fork and allowing the compact flexible implementation make this deign easy without considering particular design or care during component assembly. This design allow to change the mechanical structure according to requirement of the system.The mechanical structure for the sensor can be easily design using the 3D printer according to requirement of design.Further electrical design has its own Flash memory to save the calibration data in it.The result show that they produce the good result with minimum error with compare to very expensive commercial sensors.

Future work will be devoted by designing the special mechanical structure like for legged robot ect.. to evaluate the application of this proposed force sensor model. Futher using this light fork optoelectronics sensor, the multi-axis force/-torque sensor can be proposed .These multi-axis sensor will require a special mechanical design to measure the deformation from different side to measure the force from different axis.

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