Analysing the Magnetometer Capabilities in Pololu 3pi+ Robot: A Study on Precision Measurement and Directional Detection of Neodymium Magnets

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***Abstract*—A magnetometer is designed for the detection of magnetic fields in an environment. The Polulu 3pi+ 32U4 robot is equipped with a magnetometer that is able to provide data about the presence of a magnetic marker in the environment. This provides a field of investigation. The study deals with recognizing the performance characteristics of the magnetometer, investigating the various filters and conducting a comparative study of the filters. The raw data received from the magnetometer is noisy. The filters are applied to deduct the noise from the data. We have designed an experiment where the filters are applied to the magnetometer and the data received as output is analyzed. Another experiment entails a hypothesis where the robot is used as a magnetic marker detector. The robot is made to move and then stop in a direction pointing to the magnetic marker, demonstrating the usability of the magnetometer in the system as an effective method to localize the magnetic marker.**

I. Introduction

The magnetometer is a device that detects and measures the polarity and strength of a magnetic field. The working of a magnetometer is based on various principles. The magnetometer used in Pololu is based on the principle of the Hall Effect as it allows for a reasonably good magnetometer to be encased inside an IC chip LIS3MDL thereby reducing the size of the overall IMU unit [1].

In the realm of robotics and inertial measurement units (IMUs), the integration of magnetometers plays a crucial role in providing insights into the surrounding magnetic field. This is exemplified in the Pololu 3pi+ 3U24 Robot, where a magnetometer, leveraging the Hall Effect principle, is encapsulated within the compact LIS3MDL integrated circuit (IC) chip. This strategic integration not only facilitates the measurement of magnetic field strength and polarity but also contributes to the overall reduction in the size of the IMU unit. You can find the position of the magnetometer on the robot at the link provided for this reference: [2].

However, the precision of the magnetometer (Fig. 1) in the 3pi+ 3U24 Robot is not without its challenges. Magnetic fields generated by the robot's motors, coupled with potential distortions from hard-iron interference in the batteries, introduce complexities to the accuracy of the readings. Remarkably, for the sake of focused analysis, certain factors are deliberately overlooked in this context. The magnetic fields emanating from the robot itself and the influence of friction on the wheels are temporarily set aside, allowing for a streamlined exploration of the magnetometer's outputs as absolute readings.

Fig. 1. Location of the magnetometer in Pololu 3pi+.

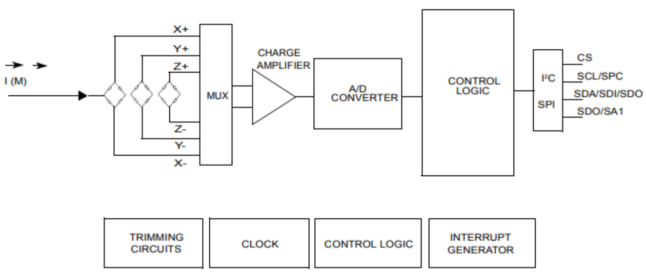

Fig 2 - Circuit diagram for the magnetometer

With this intricate interplay of technology and simplification, the Pololu 3pi+ 3U24 Robot opens avenues for magnetic field measurement, encouraging a deeper understanding of its surroundings despite the inherent challenges. This amalgamation of principles and practical considerations sets the stage for a nuanced exploration of robotic mobility and magnetic field sensing.

You can find the circuit diagram for the magnetometer at the link provided for this reference: [2] and [3].

A. Hypothesis Statement

Listed below are the hypotheses that we sought to investigate during the paper:

There are three sets of data that we have worked with: not calibrated (raw readings), calibrated, and lastly, the one passed through an Exponential Moving Average (EMA) Filter. The variation in data processed by the magnetometer is the highest in the not calibrated (raw data) and lowest in the Exponential Moving Average filter. So, in theory, the standard deviation of the uncalibrated data should be the highest, that of the calibrated data should be lower than that of the uncalibrated data and the standard deviation of the EMA filter data should be the lowest.

Uncalibrated Data: The standard deviation of the uncalibrated (raw data) magnetometer data is expected to be the highest. Calibrated Data: The standard deviation of the calibrated data should be lower than that of the not calibrated data. EMA Filter Data: The standard deviation of data passed through an Exponential Moving Average (EMA) filter should be the lowest.

Magnet Detection and Localization Hypothesis:

The magnetometer in the robot is capable of detecting the magnetic field emanating from a Neodymium magnet. The robot, programmed to rotate on its axis, stops when pointing toward the direction where the magnetic field is the strongest at its front. Distance Estimation Hypothesis:

The magnetometer provides an output indicating the magnitude of the magnetic field strength. When the robot is pointing toward the direction of the magnet, the magnitude of the magnetic field strength can be utilized to estimate the distance of the magnet from the robot.

These hypotheses collectively form a comprehensive set of inquiries, delving into the intricacies of data processing, magnet detection, and the potential for estimating distances based on magnetic field strength. The results and analyses stemming from these hypotheses will likely contribute valuable insights into the performance and capabilities of the magnetometer-equipped robot in various scenarios.

Section II describes the system we have design and used.

II. Implementation

The magnetometer is employed to collect data about the magnetic field emanating from the Neodymium magnets. To start with, we take the uncalibrated (Raw) readings of the magnetic field strength. Subsequently, we proceed towards the calibration of the magnetometer which involves a series of steps to smoothen the readings by eliminating noise from hard iron and soft iron distortions and thereby giving better processed, lesser variation data which is more reliable to work with. Additionally, we employ the Exponential Moving Average (EMA) filter for further smoothing of data.

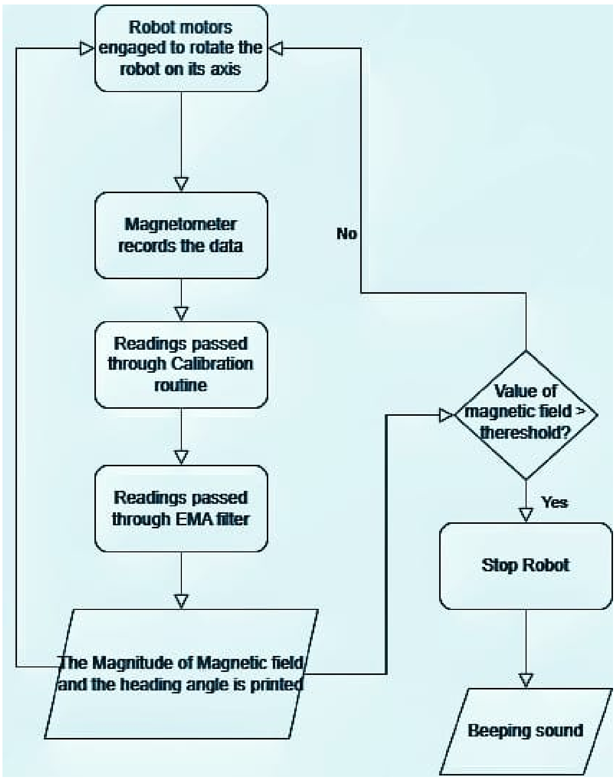

Fig 3 - Flowchart entailing the experiment procedure

A. Calibration

For calibration of the magnetometer, we have to calculate two correction factors for each axis, namely an offset, which ensures that the readings are centered around zero, and a scale correction, which ensures all axes have the same range of response.

To execute the process of calibration, it is required to collect as many data points as we move the robot through multiple orientations. Upon collection of this data, a range of the data is found for each of the axes. The maximum and minimum values of each of the axes are stored and calculated according to the formulae:

$$range_x = (max_x - min_x) \tag{1}$$

Upon recording the range of data for each axis, we calculate the centre point offset. It is at the half the range from the minimum reading on the axis. It is calculated according to the formulae:

$$Offset_x = min_x + (range_x/2.0) \tag{2}$$

Now the average range is calculated across all the axes. This is done by using the formula:

$$\text{avg range} = (range_x + range_y + range_z)/3.0 \tag{3}$$

A scale factor adjusting each axis range by the average range recorded is calculated. It is done by using the formulae:

$$Scale_x = \text{avg range}/range_x \tag{4}$$

A calibrated reading is then calculated for each of the axes. This is done by using the formulae:

$$Calibrated_x = scale_x(reading_x - offset_x) \quad (5)$$

We can implement the following algorithm using above equations:

Algorithm 1 Collect & Report Samples

Input:
Output: Array of sensor readings, XR and YR

$SamplesTaken \leftarrow 200$
for $i \leftarrow 0$ to $SamplesTaken$ **do** ▷ Collect Samples
  do Equations 1,2,3,4 and 5
  $X[i] \leftarrow Singlereadings\ of\ X\ axis$
  $Y[i] \leftarrow Singlereadings\ of\ Y\ axis$
  delay(200)
end for

while true **do** ▷ mag readings
  Serial.print("Readings: ")
  for $i \leftarrow 0$ to $SamplesTaken$ **do**
    Serial.print($X[i]$)
    Serial.println($Y[i]$)
  end for
  delay(200)
end while

Now, we calculate the heading angle of the robot. We assume that our robot is at level to the horizon on a two-dimensional plane. The heading angle is the parameter that is able to localize the direction in which the magnet is placed. The value of the angle is calculated by the following formula:

$$heading = atan2(calibrated_y, calibrated_x) \quad (6)$$

Here the readings of the z-axis are not taken into account as the robot rotates on the x-y plane about the z-axis and thus the readings on the z-axis remain constant.

In the above Algorithm, the readings are taken using calibrating equations.

B. Exponential Moving Average filter

In order to get a more useful signal out of the sensor, we apply a filter to reduce the noise further. In the case of the accelerometer and magnetometer, the noise is mostly at high-frequency, and so we can remove this by applying a simple low-pass filter.

A simple form of low-pass filter well suited for implementation on a micro-controller is the Exponential Moving Average (EMA) filter. This produces an output according to the equation:

$$output_t = (\alpha \times reading) + ((1 - \alpha) \times output_{t-1}) \quad (7)$$

This filter provides data that is somewhat of a combination of the past data and the present data at a time t. The co-efficient alpha controls how much weight is put on the current reading versus how much we put in the past reading. To implement this filter, we need to design a code that would run on the following algorithm.

Algorithm 2 Localisation of the Magnet

Input:
Output: The Bot will stop once it is facing towards the magnet

$SamplesTaken \leftarrow 200$
for $i \leftarrow 0$ to $SamplesTaken$ **do** ▷ Collect Samples
  do Equations 1,2,3,4 and 7 ▷ We are using EMA
  $X[i] \leftarrow Singlereadings\ of\ X\ axis$
  $Y[i] \leftarrow Singlereadings\ of\ Y\ axis$
  delay(200)
end for

if x-axis matches threshold **then** ▷ stop robot
  Serial.print("Readings: ")
  Serial.print($X[i]$)
  Serial.println($Y[i]$)
  Motor stops x-axis gets normal readings
  rotate bot with controlled encoders
  delay(200)

In the above algorithm, our code is rotating the robot every 3 degrees (which is configurable). If the magnetometer detects the given threshold of magnetic field strength in it's X-Axis, it will stop heading towards the Neodymium magnet.

Comprehensive details regarding the formulation of the equation and algorithm can be found at the link provided for this reference: [4].

III. Experiment Methodology

The experiment involves setting up an environment where the robot has been tested, apart from uploading a designed code for the detection of the position of the magnetic marker. The environment in which the robot was deployed for the test was meticulously planned in such a way that the experimental setup was far away from any objects that could somehow introduce any external hard or soft iron distortions in the working of the system.

The primary apparatus used in this experiment is the Polulu 3Pi+ 32U4 robot. It comprises an ATmega32U4 AVR microcontroller and has been programmed with the C/C++ variant as developed in the Arduino community. Of the varied components that contribute to its versatile use, we are concerned primarily with the magnetometer.

Apart from the robot we used four Neodymium magnets that were stacked upon one another for a stronger field and mechanical stability as it was observed that upon using a single magnet it flips upon bringing it close to the robot and does not have mechanical stability. Also, it does not have a strong magnetic field and readings become unreliable.

A. Overview of Method

The Polulu 3Pi+ robot was placed in a setup where, for better magnetic performance, the setup was aligned along the north-south axis of the Earth. The robot was made to face the geographical North and the magnet was placed such that the south pole of the magnet faces the robot.

The workspace was divided into angular segments, as shown in Figure 3. The angles varied from 50° to 150° and distances were marked from 4cm to 16cm thereby making a partial 2D Polar Coordinate System. The robot was placed with the Inertial Measurement Unit (IMU) at the origin.

The magnet was mounted on top of a non-magnetic material as a platform so the readings could be recorded more reliably and four magnets were stacked upon one another for a stronger magnetic field and for magnetic and mechanical stability while taking readings.

It was observed that the readings were unreliable beyond a radius of 16 centimetres and also sometimes unreliable at very close distances, less than 4 centimetres.

The whole family of readings was taken by running the program multiple times and only those readings that maintained consistent behaviour, which were coming up close to each other over the cluster were taken up for further consideration and were used in the study.

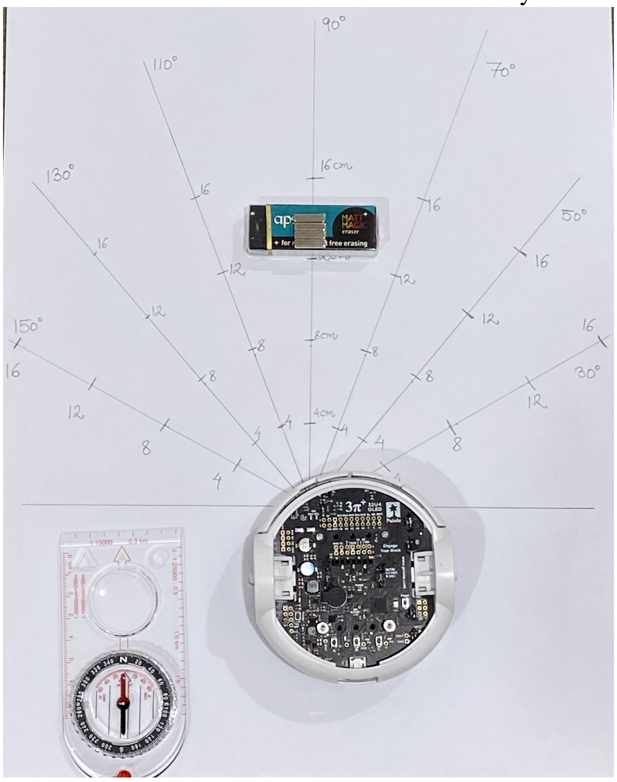

Fig 4 - Experimental Setup for Magnetic Field Strength Measurement

In the detection of the magnetic marker, the robot was made to rotate slowly on its axis. A magnetic marker was placed at a distance of 6 centimeters from the robot. The robot rotates slowly and when it detects the magnetic marker, it stops and starts emitting a beeping sound. Feel free to check out this video [5].

B. Discussion of Variables

The experiment involves the use of multiple variables. These variables affect how the experiment progresses and how the outcomes shall turn out to be.

- **Controlled Variables**: These parts of the experiment have been controlled by carefully designing the experiment. The environment where the experiment was conducted, was kept at a distance from any kinds of iron bodies that can cause any kinds of distortion in the system. The surface chosen was as such that would impart a minimal amount of friction to the wheels of the robot. The magnets chosen were strong enough so that the readings were reliable.
- **Independent Variable**: This is the part of the experiment that we control to observe a change in the output of the system. Here we are changing the position of the magnet concerning the robot. First, we are varying the angle from 50° to 150° of the magnet for the robot to detect the change in the intensity of the field. We expect a change in the heading angle of the robot's output. The next change is where we change the distance of the magnet from the robot, varying it from 4 centimeters from the robot to 16 centimeters from the robot.
- **Dependent Variable(s)**: This is the part of the experiment where we record the change in the output parameters. The dependent variables are the heading angle of the robot and the intensity of the magnetic field recorded by the magnetometer of the robot. These values change when there is a change in the independent variables. The data generated is interpreted through multiple statistical data interpretation procedures.

C. Discussion of Metric(s)

The performance of the experiment was measured through the following metrics:

- Magnetic field intensity versus Angle: We placed the neodymium magnets at angles from 50° to 150° with interval of 20° as shown in Figure 4. As per theory we should get a peak at 90° which is what was observed for distances of 10cm and 12cm. However, the peak for the distance of 8cm occured at around 71°.
- Magnetic Field vs Distance for Alpha = 0.55 and Alpha = 0.8: The detected magnetic field strength decreased with an increase in the distance of the magnet from the Pololu robot as shown by the Box plot of Figure 6. The magnet was placed at distances of 4cm, 8cm, 12cm and 16cm.
- Observations regarding the standard deviations between Uncalibrated (Raw) data, Calibrated Data and EMA Data: The measure of the standard deviation is an indicator of the variation of data within an observation/experiment. The larger the standard deviation, the larger is the variation in the data. Theoretically, the variation in the data of the EMA should be lesser than that of the Calibrated data which in turn should be lesser than that of the Raw data. Our experiments have shown that there has been a marked improvement from Raw to Calibrated data with 69.1% decrease in variation. However, the standard deviations of Calibrated and EMA are comparable with just a decrease of 6.8% in variation from Calibrated to EMA.

IV. Results

The robot was placed in an experimental environment, and trials were carried out. The resulting data was recorded, and observations were made. Based on the data, graphs were created and examined to reach conclusions about the magnetometer's performance metrics and its operation within the robotic system.

The magnet was placed at different distances from the robot as shown in the table. The magnetic field strength

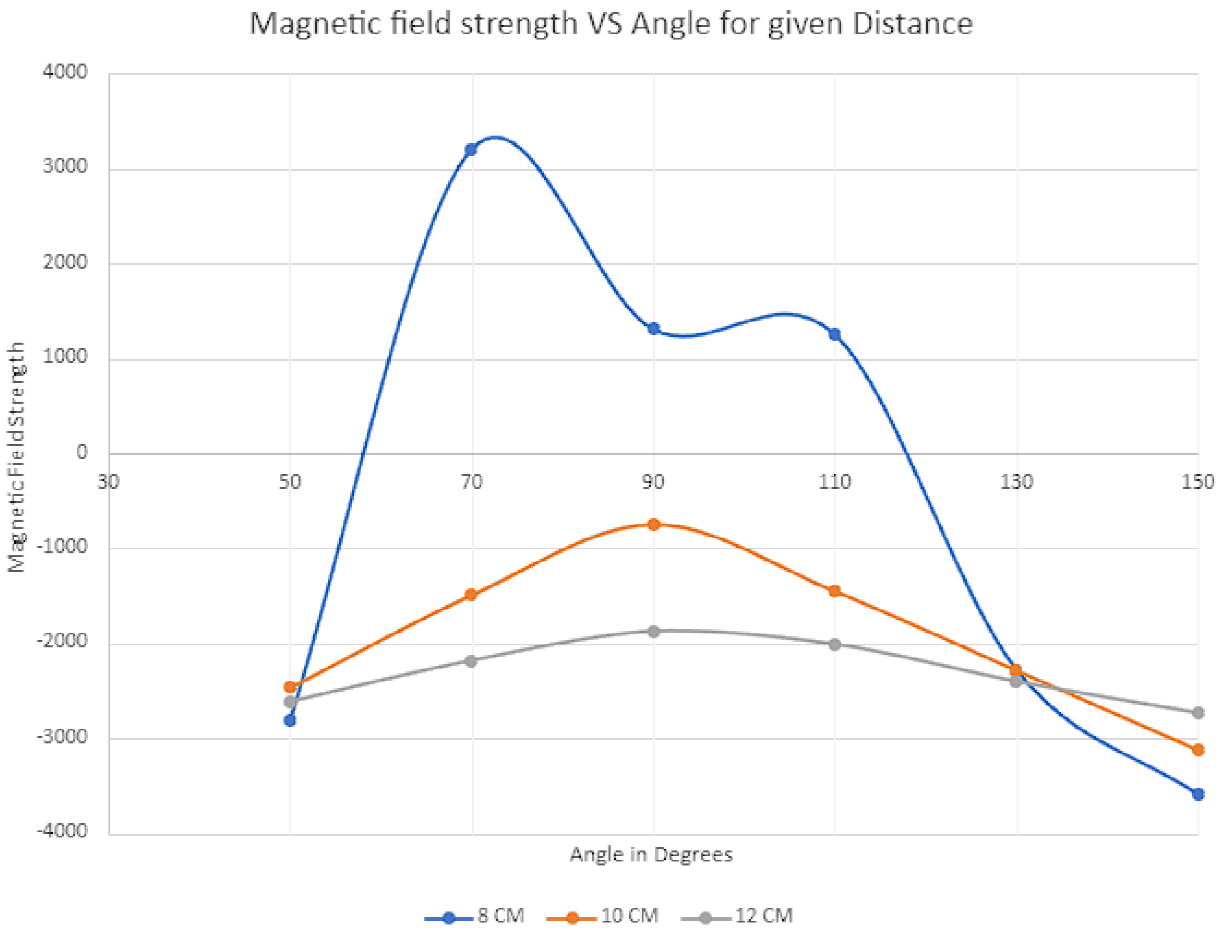

Fig 5 - Magnetic Field Strength Vs Angle at three different distances

was observed to decrease as the magnet was moved away from the robot, as observed from the readings of the table. The value of the magnitude of the magnetic field strength

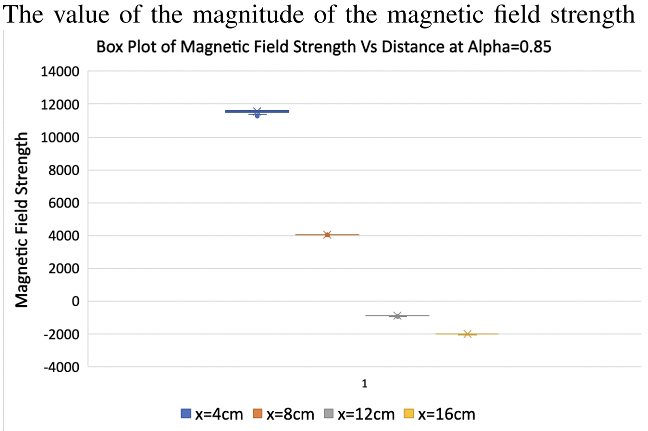

Fig 6 - The Box Plot has no variation and so appears as a horizontal line.

is predicted to decrease by a factor of 4 for every doubling of the distance. However, in our observations it was noted to be decreasing by a factor ranging between 3 to 5.

Table I presents the matrix of EMA readings corresponding to different angles at three distances from the robot's magnetometer.

Table II clearly shows that the variation of data as captured by standard deviation decreases from Uncalibrated (Raw) data to EMA data. The trend, as predicted, is thus:

Angle (degrees)	Distance (cm)		
	8	10	12
50	-2816	-2471	-2613
70	3201	-1496	-2180
90	1307	-749	-1871
110	1253	-1453	-2008
130	-2278	-2287	-2400
150	-3592	-3125	-2732

TABLE I
EMA READINGS ANGLE-WISE AT DIFFERENT DISTANCES

Distance (cm)	Raw	Calibrated	EMA
8	19.8	6.1	5.9
12	23.1	7.2	5.2
16	18.5	5.7	6.6
Average SD	20.5	6.33	5.9
Percentage Decrease in SD from Raw to Calibrated		69.1	-
Percentage Decrease in SD from Calibrated to EMA		-	6.8

TABLE II
STANDARD DEVIATION COMPARISON FOR RAW, CALIBRATED, AND EMA VALUES AT DIFFERENT DISTANCES

$$\text{Raw Reading} \gg \text{Calibrated Reading} > \text{EMA Reading} \tag{8}$$

As expected, the robot which was using localisation algorithm can nearly head towards the magnet.

Further guidance on compass heading is available in the reference provided at [6] and [7].

V. Discussion and Conclusion

A. Discussion

The LIS3MDL magnetometer being used was engaged to find data readings and the following points were hypothesised

- Three sets of data are being used: one raw, one calibrated, and one that has been filtered using an exponential moving average. The uncalibrated filter has the largest fluctuation in the data processed by the magnetometer, whereas the Exponential Moving Average (EMA) filter has the lowest variation. Thus, theoretically, the uncalibrated data should have the largest standard deviation, the calibrated data should have a lower standard deviation than the uncalibrated data, and the EMA filter data should have the lowest standard deviation.
- The robot's magnetometer is capable of detecting the Neodymium magnet's presence. We programmed the Pololu 3pi+ robot to rotate and seek the direction of strongest magnetic field along the magnetometer's x-axis and and align itself facing the magnet.
- The output of the magnetometer indicates the strength of the magnetic field. The magnitude of the magnet that is received as output can be utilized to localize the estimated distance of the magnet from the robot when the robot is pointing in the direction of the magnet.

The observations that have been made in the course of the experiment support the hypotheses stated. The observations second the hypotheses, where the uncalibrated data has the noisiest readings. The application of the calibration shows a distinct change in the readings, wherein the data is more equivalently distributed as compared to the raw data. Upon application of the EMA filter we observe a further improvement over the calibrated data. This translates to a smoother curve and more normalized readings to interpret the data.

The value of the magnetic field is inversely proportional to the squared of the distance. The results obtained support such a trend. Moreover, the doubling of the distance should reduce the magnetic field strength by a factor of 4. However, in our setup, this factor ranged between 3 and 5.

Due to the reduction in variation in EMA filter, the Box Plots we got in the graph in Fig 4 are see as horizontal lines due to the fact that the variation is very low with respect to the absolute data reading.

Another experiment was set up was to make the robot detect and stop in the direction of the magnet. This has been demonstrated successfully by programming the Pololu 3pi+. The robot, whilst rotating on its axis, stops with a beep while facing the magnet right in front of it.

This idea can be extended where the robot can be used as a system that detects magnetic markers. Future work can be done to develop a system that is able to move towards a magnetic marker by triangulating its position.The implementation of the magnetometer in the robotic system to move towards the magnetic marker would involve the system engaging the motors to move in the direction of the magnet. This work can be accomplished by coding the encoders in the robot, where the magnitude of the magnetic field can be used as a parameter to infer the distance of the magnetic marker from the robot, utilizing a pre-gathered dataset. Additionally, implementing advanced filters such as the Complementary filter and G-H (Kalman) filter can enhance the reliability and performance of the magnetometer readings.

B. Conclusion

In this work, we have amply demonstrated that the magnetometer in the Pololu 3pi+ robot can be used to reliably measure and effectively localize the strength and the source, respectively, of a magnetic field in the robot's vicinity when both the source and the robot are on the same plane. The LIS3MDL has been identified as an effective sensor with some limitations and on application of EMA filtering to it we could negate distortions and noise, and a measurable improvement of the sensor was observed while it was subject to varying conditions.

VI. Acknowledgement

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