Increasing Magnetometer Performance in a Mobile Robot Setup by Noise Reduction Filtering

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***Abstract*—There is a large amount of noise present when a magnetometer is connected to a mobile robot, this causes reduced magnetometer performance. It was discovered that by using different noise filtering techniques the performance of a magnetometer can be improved. In this report, three different noise reduction methods are compared to see which yields the greatest improvement.**

I. Introduction

With mobile robots developing further, more and more robots enter the world outside of the laboratory, opening doors to new opportunities. With extensive use of magnetometers in a diverse range of applications across multiple disciplines such as geographical surveys, space exploration, coal mines, and within nuclear environments [1], mobile robots can be utilised to perform *Dull, Dirty* or *Dangerous* jobs [2]. Ultra-low-power, high-performance magnetometers can quickly and efficiently detect ferrous metals, minerals, or other objects in environments inhospitable for humans. However, combining highly-sensitive magnetometers and mobile robots presents a wide range of domains to consider. One of these is the reliability of the readings. While in motion, the accuracy of these magnetometers can be compromised due to noise produced by the components actuating the robot. To investigate this, in this report, the characteristics of a three-axis magnetic sensor (LIS3MDL) are analysed by looking into how the readings from the magnetometer are affected by noise produced from the robot components (Pololu Romi 32U4). This is done at different distances between a magnetic object and the magnetometer. By solely looking into this problem could lead the way into a new era of mobile robotic exploration. This report proposes possible noise reduction filters to increase the overall performance in a mobile robotic system.

II. Background

A. Magnetometer history

The simplest magnetometer is a compass, where a needle points in the direction of a magnetic field. It was discovered towards the end of the 18th century that the intensity of the field is proportional to the squared frequency of the compass needles oscillation [3]. The intensities however were not absolute, the first instrument used to measure the absolute intensity of magnetic fields was created in 1833 by Carl Friedrich Gauss. This setup required a second measurement immediately after the first where the magnetic moment would be measured [4]. Along with this new way of measuring, Gauss also introduced a new unit of his namesake, this is a unit of measurement of magnetic induction. One Gauss is equivalent to one maxwell per square centimeter [5]. The Gauss is the unit of measurement that will be used in this report. The discovery of the Hall effect in 1879 by Edwin Hall made much more precise magnetometers possible. The Hall effect is when a magnetic field creates a potential difference across a component which acts perpendicularly to the flow of current. The potential difference can be measured across a component and it will be proportional to a magnetic field [6]. This potential is however very small and must be amplified. These are the magnetometers that are used today, including the LIS3MDL magnetometer used in this report which consists of three Hall sensors.

B. LIS3MDL Magnetometer

The magnetometer investigated in this study is the LIS3MDL, which is a three-axis magnetometer and gives an intensity of magnetic field along with the direction. This sensor is made up of three perpendicularly placed Hall sensors where each sensor measures the magnetic field intensity for an axis. These three sensors are then amplified and fed into a logic chip which connects to the outputs [7]. This sensor is very suitable for mobile robotic applications as it is highly sensitive as can be seen in [8] where it is used to detect the slight changes in the magnetic field caused by a car being near the sensor. The ease of use is also shown in the paper. In addition, the low cost makes it very attractive to those wanting to test research ideas. The high sensitivity of this sensor however raises the question, will it be highly susceptible to noise that arises when it is combined with a mobile robot?

C. Mobile Robot

The LIS3MDL magnetometer is connected to a Polulu Romi 32U4 mobile robot which is based on the Arduino Leonardo microcontroller. Arduino is the most popular open-source hardware prototyping platform, meaning that anyone can build and sell the Arduino design of microcontrollers and that there is a lot of software and other resources available online [9]. Arduino microcontrollers are also low cost which is ideal for this application and many others where funding is limited [10]. However, using a microcontroller as a measurement device is not as reliable as more traditional scientific instrumentation, but the small size and cost make up for the drawbacks [11]. The mobile robot is actuated by sending a pulse-width modulation signal programmed onto the microcontroller. The elapsed distance can be determined by the quadrature encoders.

III. Initial Hypothesis

Magnetometers have become sufficiently sensitive that it is now possible to use a magnetometer as a digital compass that orients the robot based on the earth's magnetic field [12] [13]. However, this high sensitivity also means signals can be obscured by irrelevant data, thus for this experiment, the constant error is filtered out by a zeroing process described in Section IV-B. This sensitivity also becomes problematic when combining magnetometers with a mobile robot as this indisputably leads to a higher level of noise, possibly causing unreliable results. The main cause of this noise are the two DC-motors with quadrature encoders. In order to perform a delicate measurement task, a clear signal is necessary [14].

A. Preliminary test

A preliminary test was performed to investigate how much of an effect the components actuating the robot have on any readings from the magnetometer. This test involved simply taking measurements from the magnetometer, which is zeroed using the process described in Section IV-B, with no magnet present. The motors are initially off for this test, the motors are then turned on and more data is taken. The data is visualised in a scatter plot in units of Gauss. As can be seen in Figure 1 the spread of the points increases significantly once the motors are actuated after 100 arbitrary units.

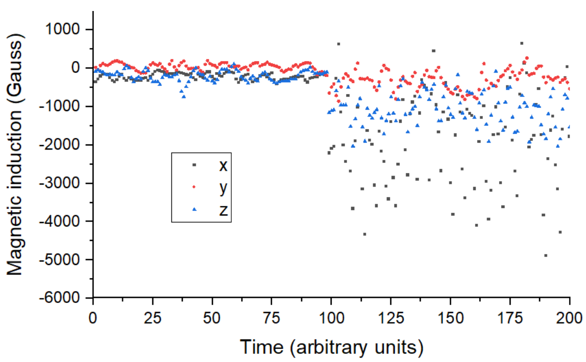

Fig. 1. Effect of actuators on readings

B. Hypothesis

The problem discovered by the preliminary test might be that the noise limits the ability of the magnetometer to read the desired data. This would mean that if the Romi is moving, the data from the magnetometer is not entirely reliable as the noise from the robot's components appears to be large. This results in the following hypothesis:

> *It is hypothesised that the magnetometer combined with a mobile robot is accurate and sensitive enough to detect a magnetic object up to a metre when the robot is stationary. However, when the robot is moving, the noise produced by the components actuating the robot will lead to a higher level of noise and fail to reliably detect magnetic objects, ultimately resulting in inaccurate measurements.*

IV. Baseline Implementation

A. Data Capture

In this report, the I^2C communication protocol is used to communicate the captured data. This means that instead of connecting to an individual pin for each value to be read (analogue), multiple values can be transmitted through just two pins (digital). These pins are called the Serial Data (SDA) and Serial Clock (SCL) pins. The data itself is transferred through the SDA-pin, the SCL-pin is used to make sure the devices are in sync. Using this system it is possible to connect several sensors to the microcontroller or vise versa. In the experiment described in Section V there are three sensors connected, although they are all within the same board. More about the I^2C communication protocol can be read in the LIS3MDL datasheet [7]. The open-source LIS3MDL library is used to establish digital communication and extract the reading of each axis. The raw values are converted by a class into Gauss values. According to the datasheet of the LIS3MDL magnetometer [7], the Gaussian values are achieved by multiplying the raw data by *6.842*. The x-axis of the magnetometer is aligned with the forward direction of the wheels. The Romi setup with the magnetometer sensor attached can be seen in Figure 2.

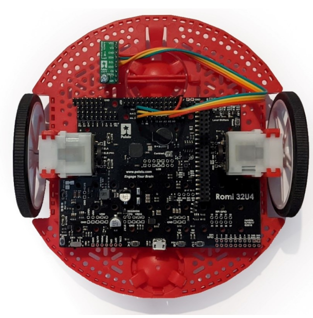

Fig. 2. Romi Setup

B. Zeroing process

It was realised that the earth's magnetic field should first be removed from the readings before conducting any experiments. This is because any reading of the magnet would have a zero error if the earth's magnetic field was not subtracted from the readings. At a large enough distance the reading of the earth's magnetic field would also be larger than the readings that are of interest in this report. A zeroing process was added in order to eliminate the readings of the earth's magnetic field and any other consistent background noise by subtracting this magnitude from the readings. The method works by subtracting a constant offset from each reading which is determined by an average of 50 values without magnetic objects present. The zeroing sequence is programmed to run when the C-button of the mobile robot is pressed. This removed the readings from the earth's magnetic field, which in the case of this experiment, were considered to be undesired. However, it should be noted that any movement of the magnetometer would require the zeroing to be run again. The graph seen in Figure 3 simply shows how the earth's magnetic field is eliminated at 100 arbitrary units by pressing the trigger button. The vertical axis on the graph shows the readings from the magnetometer for all three axes, the horizontal axis is in arbitrary units of time as this is just a visualisation of the zeroing procedure.

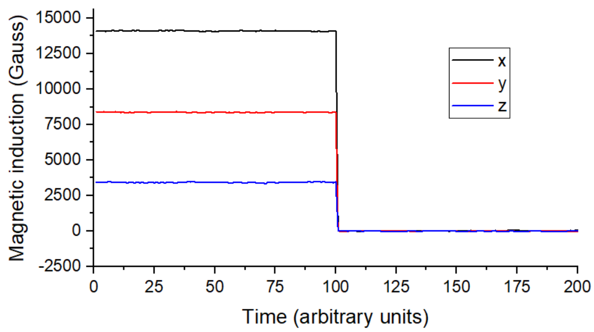

Fig. 3. Zeroing

V. Experiment Methodology

A. Overview of Method

After the zeroing process to eliminate the earth's magnetic field from the readings as mentioned in Section IV-B, the magnet is placed so that it is positioned on the x-axis of the magnetometer as seen in Figure 4 where the red rectangle represents the position of the magnetometer in relation to the Pololu Romi. The magnet is orientated so that positive measurements are received on the serial plotter of the mobile robot. Measurements are taken with the magnet at several locations along the x-axis starting with the magnet 100 cm away and decreasing this gap, with a 5 cm interval, to 15 cm. It was found that if the gap was smaller than 15 cm the sensor would be fully perturbed. As the magnet is being moved along the forward direction and thus will mostly affect the magnetometers x-axis, it was decided that the values from the magnetometers x-axis will be most important to focus on. First, this experiment is conducted without the use of the motors, it is then repeated, with the motors turned on.

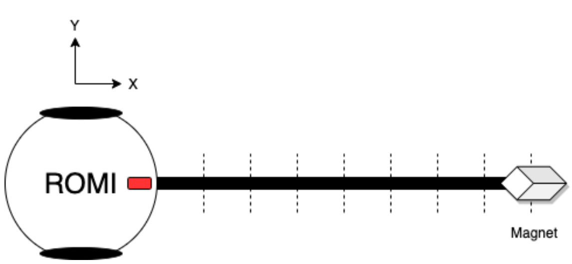

Fig. 4. Experimental setup

B. Discussion of Variables

- **Controlled Variables**:
  $Environment$:
  - *Surface*: Flat, no underlying metal
  - *Magnetic env.*: Neutral, far away from large metal objects, electronic devices or pipes

  $Hardware$:
  - *Magnet*: Neodymium (S-10-10-N) [15]
  - *Robot*: Polulu Romi 32U4
  - *Sensor*: LIS3MDL Magnetometer
  - *Placement*: Specified in Figure 4
  - *Batteries*: Six new AA batteries
  - *Pin usage*: SDA and SCL using I^2C

  $Software$:
  - *Motors PWM*: 0/25 out of 255
  - *Reading interval*: 50 milliseconds
  - *Prerequisite*: Zeroing process (Section IV-B)

  $Task$:
  - *Distance x-axis*: 100 – 15 cm (5 cm interval)
  - *Distance y/z-axis*: 0 cm
- **Independent Variable**: The distance between the mobile robot and the magnet is altered between 15–100 cm along the x-axis during the experiment with an interval of 5 cm.
- **Dependent Variable**: The measurements from the magnetometer in Gauss are taken and the variance in these values is found.

C. Procedure

The following steps are performed as the experimental process:

- The zeroing method is first used, with the mobile robot in the starting position, to eliminate the earth's magnetic field from the readings as been specified in Section IV-B. Note that the magnet isn't present at this stage.
- The magnet is introduced, placed 100 centimetres away from the magnetometer. Note that the magnet is lined up with the magnetometers x-axis as visualised in Figure 4.
- The following is performed until the distance between the magnet and the magnetometer is equal to the final distance of 15 cm:
  - Motors are turned off
  - Fifty readings as values of Gauss are recorded
  - Motors are turned on with a PWM value of 25
  - Another fifty readings in Gauss are recorded
  - The magnet is moved closer to the magnetometer by 5 centimetres

The interval distance is determined by balancing the experiments execution time and precision necessary to find the furthest distance where the magnet can be detected within the range. High intervals would lead to a lower precision whereas small intervals increase the execution time significantly. An interval 5 cm is determined as an optimal balance between the two.

D. Limitations

There are a few things that need to be taken into account when running this experiment: first of which is that the magnet used is quite powerful. According to the datasheet [15], this magnet has a pulling force of 38.2 Newton, as such if they are brought within around 15 cm of the sensor they will cause it to be perturbed. Once the sensor is perturbed it can take seconds or minutes to return to normal. In addition, the mobile robot is being actuated while not physically moving. It should be taken into account that this is not the case in a real-world application.

VI. Final Hypothesis

Taking the preliminary test into consideration and looking at the results when the baseline experiment is run as shown, the noise appears to have a significant impact on the measurements, decreasing their accuracy. As the noise is caused by the components driving the mobile robot, such as the motors, quadrature encoders, and possibly conductivity in the wires. Hypothesised in this paper is a software-based approach to reduce the noise, improve the performance, and increase the reliability of the readings.

> *It is hypothesised that the magnetometer combined with a mobile robot is accurate and sensitive enough to detect a magnetic object at a distance of 80 to 20 centimetres when the robot is stationary. In addition, with the use of a software-based reduction filter, the noise produced by the components actuating the robot will not lead to a significant decrease in performance. Making the mobile robot accurate in a stationary and actuated state.*

VII. Improved Implementation

In order to reduce the noise that comes about when the motors are activated, various software-based solutions were considered. These approaches were tested by simply rotating a magnet near the sensor and recording the data. Note that for these tests only the x-values were filtered as these are the values investigated in the experiment.

The first filter used was a fraction based approach. The filter works by adding a fraction of the newly read measurement to the existing value in order to get a reading that does not fluctuate as much. This works well to remove high-frequency noise while still allowing quick alternations, it does however lead to the readings being somewhat distorted. Another limitation with this approach is that it is only comparing to one previous value which allows noise to have more of an effect than if more values were used. Equation 1 is used for this filtering technique.

$$x\_filtered = (x\_filtered * 0.9) + (mag.x * 0.1) \quad (1)$$

The effectiveness of such a technique can be seen in Figure 5.

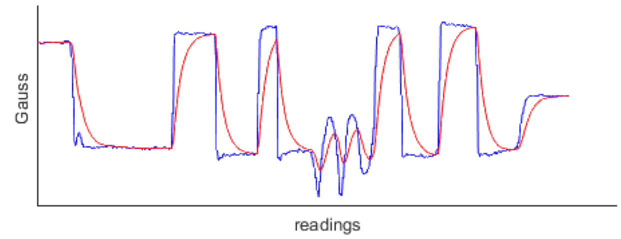

Fig. 5. Test with fraction filter

Another approach of filtering out noise is by using a moving average method. This method gives out a value that is equal to the average of the previous 50 values read from the sensor [16]. It is possible to change the size of the window used but in this case 50 readings was considered to give rather good results as can be seen in Figure 6. Due to having a constant sample size, the high-frequency noise has been removed more successfully than the first approach. Alas, there is also predominant distortion. This approach also gives a significant delay to readings, which in the case of the fractional filter is less significant.

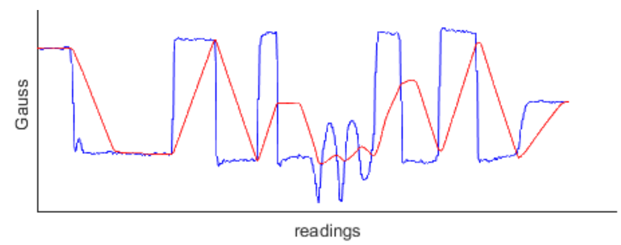

Fig. 6. Test with averaging filter

The final approach attempted is a much more advanced method and as such, unlike the other methods, it was not performed within the microcontroller itself. This method used a low-pass filter; what this does is to attenuate the higher frequencies in a signal and to pass the lower frequencies [14]. Using this method it is possible to eliminate certain frequencies from the data. This process performed in MATLAB uses the *Fir1* function to create the filter, the function runs a convolution which is based on the initial readings. To do this in MATLAB, an external package called "Signal Processing Toolbox" must be installed. The advantage of such a filter is that a specific threshold can be chosen meaning specific frequencies can be attenuated giving rather good results.

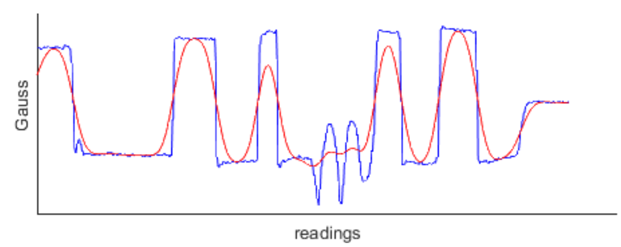

Fig. 7. Test with low-pass filter

VIII. Results

After conducting the experiment according to Section V, the results have been plotted in the following Figures 8 and 9. The graphs represent the magnetometer measurement in Gauss on the vertical axis and the distance of the magnet to the sensor in centimetres on the horizontal axis. Only the x-axis has been measured and represented on the graph as the y and z-axis of the magnetometer are considered equal to zero in the experiment. Four series are plotted: in green the baseline data measured by the magnetometer sensor without any post-processing, in yellow the data after applying the moving average filter, in red the data after applying the low-pass filter, and in blue the data after applying the fractional filter. It is noted that the Gauss measurement for all of the plots increase sharply when the magnet is closer than 30 centimetres away from the magnet, because of this the vertical axis has been truncated between 16000 and 32000 as well as between 32000 and 70000 Gauss to display all the relevant values. The scale however remains constant.

A. Motors Off

The experiment without the motors actuated can be seen in Figure 8. The experimental data can be used as a control to see how the magnetometer and the applied filters perform in the absence of noise, in contrast to a moving mobile robot. The illustrated graph uses boxplots to highlight the scattering of data collected at each position. With these conditions, the variance of the data with motors off is considered very small as shown by the interquartile range and remains constant throughout the experiment. The distance does seem not to affect the variance. The result from the three filters visualised in yellow, red, and blue have the same trend as the baseline data with no filter. However, the variance appears to be slightly smaller when the filters are applied. The overall trend of the four data-sets can be considered to be identical and the filters do not add a significant improvement.

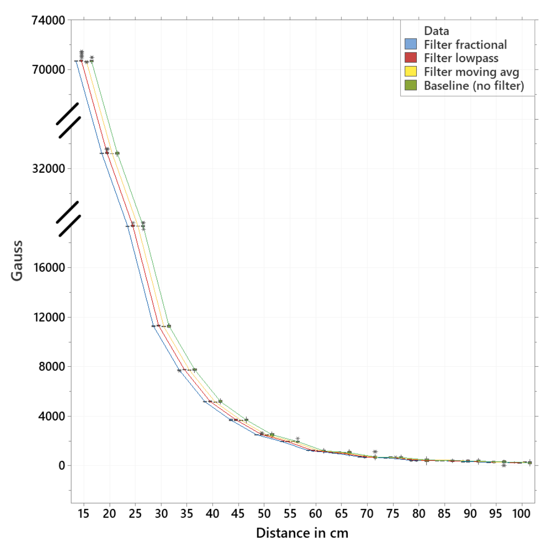

Fig. 8. Boxplot of experimental results with the motors off

B. Motors On

The results of the magnetometer measurement of a magnet regarding distance with the noise produced by actuating the mobile robot are visualised in Figure 9. Comparing these to the previous results with the motors turned off, several differences can be noted The variance of the baseline data capture has significantly increased, the added noise shows a direct influence on the standard deviation which is plotted separately (Figure 10), confirming the preliminary test. The standard deviation remains relatively consistent throughout the entirety of the data. Nonetheless, a constant increase of the standard deviation can be seen as the sensor is further away from the magnet. On the other hand, the three datasets with the filters applied as been described in Section VII results in a significant improvement of the standard deviation. Visualised by Figure 10, the fractional and low-pass filters have been able to reduce between 5 and 7 times the standard deviation of each data point, and the moving average filter by up to 15 times. The results of the filtered data indicate a much more significant trend than compared to the baseline without any filter.

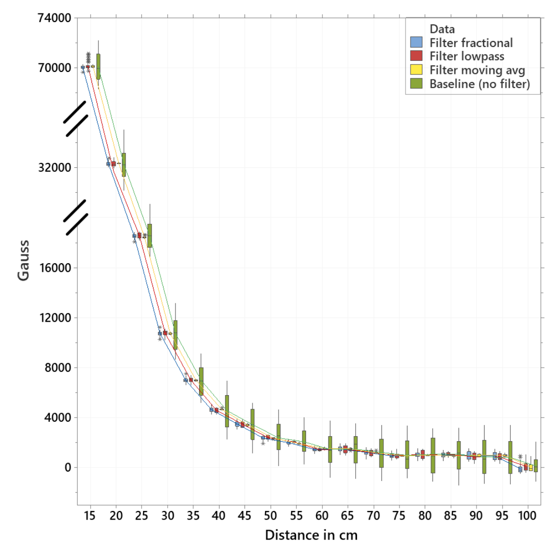

Fig. 9. Boxplot of experimental results with the motors on

C. Variance

The main improvement of the filters regarding the data capture can be seen in the standard deviation Figure 10. While the low-pass and the fractional filter manage to reduce the standard deviation with motors on, they do not improve the quality of the captured data enough to eliminate the noise. The captured results are also of a lesser equivalent to the standard deviation than those with the motors off. On the other hand, the moving average filter can reduce the standard deviation to a lower level than the baseline data, even with the motors off and thus, results in more precise measurement. Adding the moving average filter when the robot is in motion, allows the standard deviation to remain constant regarding perturbation from its motors and encoders. This directly affects the accuracy of the sensor and thus its maximum range detection.

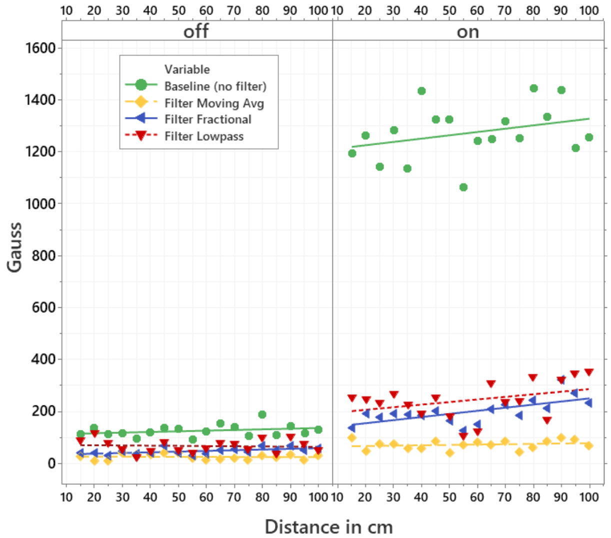

Fig. 10. Standard deviation

IX. Discussion and Conclusion

The conducted experiment and the interpreted results have confirmed the final hypothesis on several key points:

> *It is hypothesised that the magnetometer combined with a mobile robot is accurate and sensitive enough to detect a magnetic object at a distance of 80 to 20 centimetre when the robot is stationary ...*

The results from the test with motors off visualised in Figure 8 have shown a very confident trend on the measurement from the sensor between 15 to 100 centimetres. However, when the magnet is more than 95 cm away, the standard deviation becomes larger than the measurement. At this distance, there can be no confidence in the ability to detect a magnet. The standard deviation on the Figure 10 is low enough to have precise numbers in Gauss from distance values from 15 to 85 centimetres. In other words, the sensor combined with a stationary mobile robot seems to have no issue detecting the magnet on the distance hypothesised.

Nevertheless, when the robot is actuated, the standard deviation sharply increases. When the magnet reaches 65 centimetres away from the sensor, the standard deviation is higher than the value measured. At 40 cm, the boxplot of the variance in Figure 8 starts to overlap and precise measurement of the Gauss values is not possible. The improved implementation Section VII proposed three possible solutions to decrease the noise and thus the standard deviation. As seen in the results Section VIII, the three filters all significantly increase the precision of the data captured. The reliability of the readings is also improved by the filter removing any irregularities in the data. The results express a standard deviation that is almost as low as the control test with motors off for all distance values. The standard deviation becomes higher than the measurements at 90 cm and thus values can be precise up to 80 cm.

This confirms the next and final part of the hypothesis:

> *... with the use of a software based reduction filter, the noise produced by the components actuating the robot will not lead to a significant decrease in performance. Making the mobile robot accurate in a stationary and moving state.*

Finally, the experiment was not able to confirm the fractional and low-pass filter with enough confidence. Although initially, they seemed very promising, the variance reduction was not sufficient when compared to the test without motors actuated in these experimental conditions. A limitation of this study is that there has been no investigation into whether the current setup will function correctly when the Romi is in motion. It is also true that the filters can slow down readings thus reducing the practicality of implementation. Future research could examine the optimisation of the filter properties and map the earth's magnetic field in three axis for any orientation of the robot making the current zeroing process obsolete. It should be taken in account that with a small sized magnet the maximum distance measured cannot exceed one metre.

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