Universitat de les Illes Balears

MASTER'S THESIS

TOWARDS THE DETECTION OF THE MAGNETIC SIGNATURE OF SHIPS FROM A SUBMARINE VEHICLE

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Master's Degree in Intelligent Systems (MUSI)

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Tutor: Gabriel Oliver Codina

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Key words:

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Towards the detection of the magnetic signature of ships from a submarine vehicle

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***Abstract*—In this thesis, the final objective is to detect military vessels from a distance of 500 metres from an underwater unmanned vehicle. This research offers a path towards that objective, reaching the election of a magnetometer, the development of software that can be integrated in the existing one and the detection of various metallic masses, including two vessels of more than 10.000 tons. The results are not completely conclusive and there is still work left to do in further research.**

***Index Terms*—Magnetometer, Magnetic signature, submarine countermeasures**

I. Introduction

For the detection of a ship with the use of technology, signals that occur naturally or artificially shall be sensed. Some early examples of vessel detection are the RADAR (RAdio Detection And Ranging) and the SONAR (SOund Navigation And Ranging). Both of these techniques use the generation of artificial signals and measurement of them after the reflection with the target to be detected. [11, 10]

Before the beginning of World War II, fluxgate magnetometers appeared to be used for the detection of submarines. Oppositely to the RADAR and SONAR detectors, magnetometers do not emit a signal to be measured after reflection. Magnetometers detect presence measuring the disturbance that an object produces in the natural Earth's magnetic field. [9]

A. Project Objectives

This work is a first approach in the research group in Systems, Robotics and Vision of the University of the Balearic Islands (UIB) to magnetic detection applied to different fields, whether scientific, industrial or strategic. Due to the limited budget of the project, a relatively low cost sensor will be used.

This aim of the project is to research a sensor that, in future projects, will be installed on board the group's Unmanned Underwater Vehicle (UUV), the Sparus II, seen in figure 1, and several experiments will be performed to assess the complexity and feasibility of using this system in future research projects.

The Sparus II UUV is a lightweight autonomous underwater vehicle for a maximum depth of 200m. It has a length of 1.6 m, an hull diameter of 0.23 m and its weight in air is 52 kg. The available energy is provided by a 1.9 kWh Li-Ion battery system. [4]

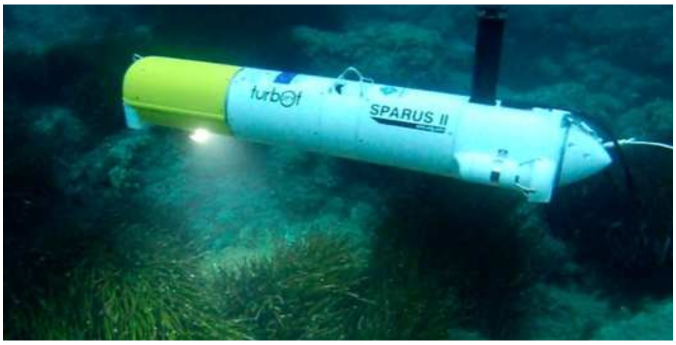

Figure 1. Sparus II UUV, available at the UIB

For the purpose of integrating the magnetometer in the Sparus II, the following tasks shall be performed:

1) Review of the characteristics of the Earth's magnetic field.
2) Study of the magnetic signature of ships.
3) Selection of a magnetic sensor that adapts to the characteristics of the project: budget, range, size, weight, consumption, power supply.
4) Integration of the sensor into a ROS node, to a later integration into the architecture of the UUV ROS architecture.
5) Test the system in a real environment.

Regarding the experimental testing, this Master's thesis presents the first steps of a larger research project, limited to free air testing of the magnetometer. Validating the sensor performance underwater is out of the scope of this project due to cost and time limitations.

II. Earth's Magnetic Field

According to [6], as it is well known, the Earth has a substantial magnetic field, which generates complex forces that have immeasurable effects on animal and human everyday lives. The Earth's magnetic field exists because of its composition, especially because of its core. The core is made up of superheated molten metals or alloys with fluctuating magnetic moments under great pressure. Since the molten metals are in electrical contact with each other, current flows between them, generating a magnetic field and creating the magnetosphere.

A. Magnetic deviation

Magnetic signatures occur because of the interaction of ferromagnetic components and conducting materials with the Earth's magnetic field. There are two different types of magnetism, which are permanent magnetism, and induced magnetism. Permanent magnetism is when an object creates its own magnetic field, whereas induced magnetism is the act of a force changing a material's ambient field into a magnet.

More specifically, induced magnetism is the combined effect of a magnetic property of the material (permeability), the Earth's magnetic field, and the shape and orientation of the object in the Earth's magnetic field. When an object's permeability is high, it is considered ferromagnetic and in the presence of the Earth's magnetic field, the two fields create a stronger magnet, which will produce a higher magnetic signature.

Most metallic structures, independent of their shape and size, are mainly built from ferromagnetic materials, causing them to disturb the Earth's magnetic field and make up the so-called magnetic signature. [6]

III. Ship detection

Magnetic signature consists of the Electric and Magnetic Signature Components of various sources, added together using the principles of superposition and vector addition, when evaluated at a distance far enough away from the hull of the vessel to be considered "far field". There is a "standard" distance that is of interest and use to naval military vessel signature systems design, which is called the "reference depth". This depth is far enough away from the vessel to be considered far field, yet close enough to the hull to be considered a dangerous distance for electrically and magnetically activated and triggered weapons such as mines and torpedoes. The various sources contributing to magnetic signature at reference depth are [5]:

A. Static magnetic signature due to Earth's magnetic field

This SM signature arises from the disturbance of the earth's magnetic field when a vessel with significant ferrous content (ship) is placed in the earth's field. There are two major components to this SM field source: induced magnetism from the ferrous content of the ship and permanent magnetism of the ship that was created inadvertently during construction of the ship, changed inadvertently during rough traveling and combat operations, and/or changed purposefully during deperming treatments.

B. Alternating Magnetic Signature due to Earth's magnetic field

This AM signature arises from the disturbance of the earth's magnetic field when a vessel with significant continuous conductive surface areas is moving in the earth's field in such a way as to change the conductive area perpendicular to the direction of the earth's magnetic field. There are two major contributors to this AM field source: The rolling, pitching, and yawing of the ship and the orientation and location in the earth's magnetic field (ie, latitude, longitude, and heading).

C. Static and alternating electric and magnetic signature due to stray fields

These sources from Stray Fields are propagating sources (not sources that are injecting current into the seawater) that arise from various equipment inside or outside the hull of the vessel.

D. Signatures due to galvanic corrosion and corrosion control

Static and alternating electric and magnetic signature components arise from the effects of corrosion and corrosion control.

IV. Magnetometers

Magnetometers can measure magnetic fields. They can measure the direction, strength, or relative change of a magnetic field at a particular location. This is why magnetometers can be used as metal detectors: they can detect only ferromagnetic metals, but can detect such metals at a much larger range than conventional metal detectors, based on oscillators producing an alternating current.

The Earth's magnetic field can vary depending on location, and magnetic field variations due to magnetic anomalies can be found. The detection and characterization of those anomalies is the technique used in metallic object detection using magnetometers. [9]

A. Magnetometer types

There are laboratory and survey magnetometers. Unlike survey magnetometers, laboratory magnetometers require the sample to be placed inside the magnetometer. And survey magnetometers can be divided into two basic types: scalar magnetometers, that measure the total strength of the magnetic field and vector magnetometers, that have the capability to measure the component of the magnetic field in a particular direction.

Among survey vector magnetometers, there are fluxgate magnetometers. They consist of a small magnetically susceptible core wrapped by two coils of wire. An alternating electric current is passed through one coil, driving the core through an alternating cycle of magnetic saturation. This constantly changing field induces an electric current in the second coil, and this output current is measured by a detector [9]. The operating principles of fluxgate magnetometers are shown in figure 2. The output signal becomes modulated by driving the soft magnetic core into and out of saturation. The shaded regions indicate the regions of operation.

B. Selection criteria of the magnetometer

Selection criteria of the magnetometer involved several requirements. Those are described below.

1) Budget: Due to the limited budget of the project, a relatively low cost sensor will be used. The maximum budget of the magnetometer at established in 5000€.

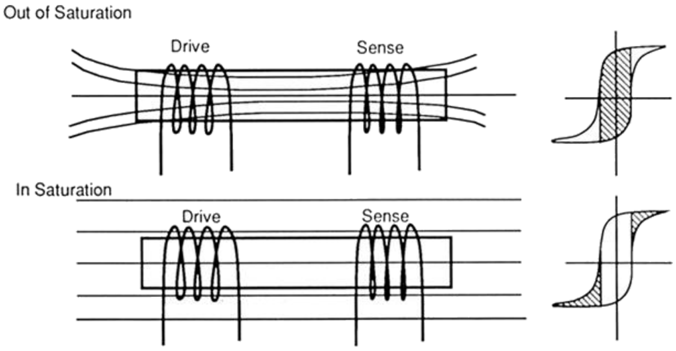

Figure 2. Operating principles of fluxgate magnetometers. [7]

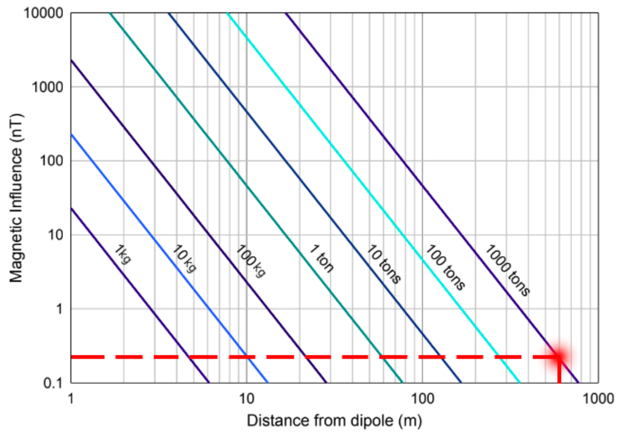

Figure 3. Magnetic influence if iron (T) from 1 to 1000 metres

2) Range: The magnetometer shall be capable of detecting vessels of at least 1000 tons at a distance of 500 meters. In order to satisfy the requirement, it is necessary to calculate the magnetic influence in Tesla unit (T) of ferromagnetic metals at a given distance.

Simplifying the metal as a monopole spherical object, the Biot–Savart law [8] can be applied. The equation of the electric current density throughout conductor volume is expressed in equation 1.

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \iiint_V \frac{(\mathbf{J}\, dV) \times \mathbf{r}'}{|\mathbf{r}'|^3} \tag{1}$$

Where B is the the resultant magnetic field at position $\mathbf{r}'$, $\mathbf{r}'$ is the vector from dV to the observation point $\mathbf{r}$, μ_0 is the magnetic constant, dV is the volume element, and $\mathbf{J}$ is the current density vector in that volume (in SI in units of A/m²).

Considering that $(\mathbf{J}\, dV) \times \mathbf{r}'$ represents the magnetic moment, and utilizing the representation of the magnetic moment in equation 2, the electric current density throughout conductor volume can be represented as in equation 3.

$$\mathbf{M} = \frac{B_i \cdot V}{\mu_0} \tag{2}$$

$$\mathbf{B}(\mathbf{r}) = \frac{B_i \cdot V}{4 \cdot \pi \cdot r^3} \tag{3}$$

Where B_i i is the material's internal flux density, obtained by multiplying the material's susceptibility by the value of the ambient flux density, and V is the material's volume.

Using the equations given above, we estimate the magnetic influence of iron of different masses in the chart shown in figure 3, considering a density of 7.86g/cm³, assuming no permanent magnetization of the object, a susceptibility of 100, and an ambient field of 50,000nT. The chart is a log-log plot, which shows the third-order relations as straight lines.

Having this chart in consideration, using a magnetometer with resolution capabilities of 0.1nT and a noise of 500pT, the criteria for detection range will be satisfied.

3) Size: The size of the magnetometer has to be small enough to be transported by the Sparus II, along with the rest of its attached instrumentation. A limit of 5cm x 5cm x 25 cm is established.

4) Weight: Similar to the size, the limit of the weight is established considering the Sparus II capacities. A complete system of 1kg is considered to be limiting the integration.

5) Consumption: Consumption is not only limited by the capacities of the Sparus II batteries, but also because high consumption implies high temperature. A power consumption of 1W is considered in order to not have issues with both battery capacity and dissipation.

6) Power supply: Compatibility with the voltages available at the Sparus II is a factor to consider as an incompatible voltage requirement by the magnetometer would imply additional hardware to be implemented in the integration in the form of a voltage converter.

7) Magnetometer type: The magnetometer type shall be a survey vector magnetometer, as mobility of the device and the capability of reading the direction of the field are required. According to [7], among the survey vector magnetometers, the fluxgate is suitable for the purpose of this thesis. A magnetometer with similar sensitivity might be considered as well. In the figure 4, a comparison between different types of magnetometers in terms of sensibility is shown.

C. Magnetometer options

In this subsection, several options for a Fluxgate Magnetometer will be shown. A small description of the observed item will precede a normalized table with the following information:

- Manufacturer
- Model name
- Magnetometer type
- Resolution
- Noise
- Size
- Weight
- Consumption
- Power supply
- Price

1) Stefan Mayer: This German-based manufacturer is a Sensys partner company. By agreement with Sensys, they do

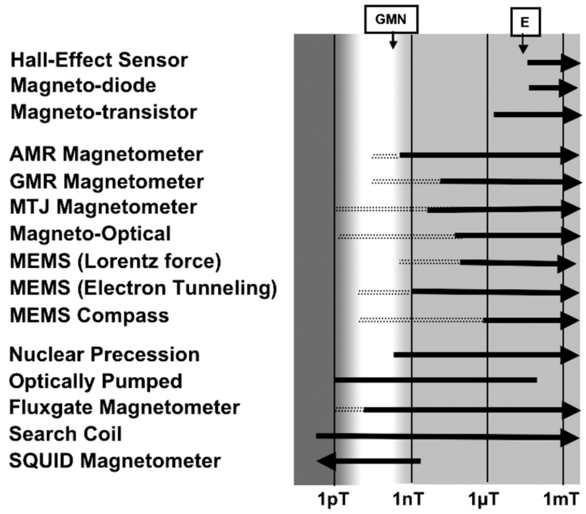

Figure 4. Estimate of sensitivity of different magnetic sensors. The symbols E and GMN are used to indicate the strength of the Earth's magnetic field and geomagnetic noise, respectively. [7]

not manufacture magnetometers with more than one axis. A photograph of the magnetometers can be seen in figure 5.

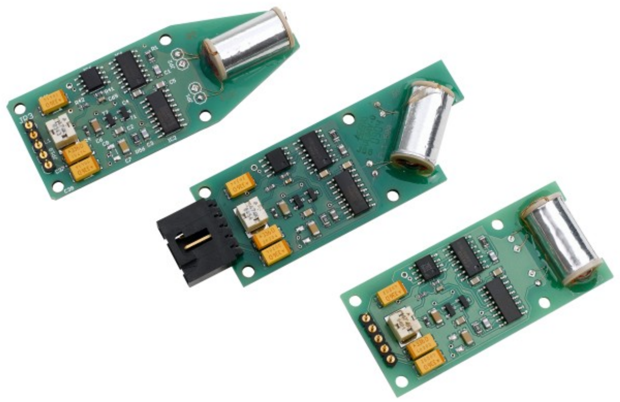

Figure 5. Stefan Mayer FL1-100 magnetometers

The advantage of the Stefan Mayer magnetometers is the price, but on the other hand the analog nature of the devices adds complexity to the system, as a separate ADC shall be researched. Also, the limitation to only one axis is not convenient for our research purposes and aligning three of them with precision would require a high-end CNC machine.

2) Marine Magnetics: This American manufacturer proposes a system consisting of a magnetometer dragged by a submarine using a long cable, so that the sensor is at such a distance that the interferences from metallic elements of the submarine do not affect the measurements. A photograph of a submarine with the magnetometer attached by a cable can be seen in figure 6.

Marine Magnetics magnetometer is an excellent choice because of the noise reduction of their system. On the other hand, the integration with the available AUV would not be

Table I
STEFAN MAYER MAGNETOMETER

Manufacturer	Stefan Mayer
Model name	FL1-100
Magnetometer type	Analog 1 axis fluxgate
Resolution	0.1 V/μT
Noise	$< 20pT/Hz^{1/2}@1Hz$
Size	55 mm × 25 mm × 11 mm
Weight	10 g
Consumption	+30 mA @ ± 12 V
Power supply	±12 to 16 V
Price	380€

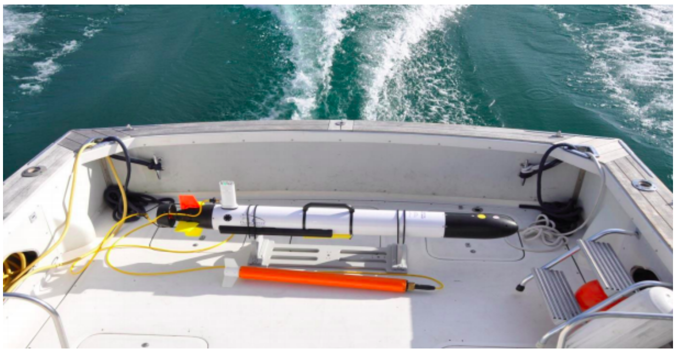

Figure 6. Marine Magnetics SeaSPY2 magnetometer

simple. Also, the manufacturer operates in the United States of America, so the logistics to transport the magnetometer gain complexity over the options within Europe.

3) Bartington Instruments: This UK manufacturer has a wide variety of instrumentation. It designs and manufactures high precision fluxgate magnetometers, gradiometers, magnetic susceptibility instruments, Helmholtz Coil systems and associated data acquisition equipment. A photograph of the magnetometer proposed by Bartington Instruments can be seen in figure 7.

Figure 7. Bartington Instruments Mag-13MSS magnetometer

Bartington has a wide range of magnetometers with great specifications. This manufacturer is located in the European continent, so the logistics are not as complex as if it was in another continent. The downside is that the proposed magnetometer is analogic and, in order to get the readings,

Table II
MARINE MAGNETICS MAGNETOMETER

Manufacturer	Marine Magnetics
Model name	SeaSPY2
Magnetometer type	Digital 3 axes overhauser
Resolution	1pT
Noise	$< 20pT$
Size	865 mm × 76 mm × 76 mm
Weight	3700 g
Consumption	2W
Power supply	9-30 VDC or 100-240 VAC
Price	Unknown

Table III
BARTINGTON INSTRUMENTS MAGNETOMETER

Manufacturer	Bartington Instruments
Model name	Mag-13MSS
Magnetometer type	Analog 3 axes fluxgate
Resolution	166 mV/µT
Noise	$< 6pTrms/Hz^{1/2}$
Size	30mm ø × 250 mm
Weight	250 g
Consumption	+65mA, -30mA ±1.4mA/100µT
Power supply	±12 to ±17V DC
Price	3009€

an ADC shall be configured.

4) Sensys: This German manufacturer is associated with Stefan Mayer and offers 3-axis fluxgate magnetometers, consisting of a submersible module and an analog-to-digital converter. A photograph of the magnetometer proposed by Sensys, next to the submersive ADC can be seen in figure 8.

Figure 8. Sensys FGM3D/100 UW II magnetometer

Sensys is an excellent choice. It has great specifications and the sensibility and noise levels are suitable. Unfortunately, the immense weight of the system, more than five kilograms, and the price starting at 10000€, immediately discarded this option.

5) Applied Physics: This US-based manufacturer supplies several digital magnetometers that are very close to our requirements. Mainly, they have three options: one small, another with a very high sampling frequency and the third that prioritizes resolution. The one that Applied Physics proposed is the Digital Magnetometer that prioritizes resolution. Its photograph can be seen in figure 9.

Table IV
SENSYS MAGNETOMETER

Manufacturer	Sensys
Model name	FGM3D/100 UW II
Magnetometer type	Analog 3 axes fluxgate + ADC
Resolution	6pT
Noise	$< 15pTrms/Hz^{1/2}$
Size	98 mm ø × 300 mm
Weight	5000 g
Consumption	10W
Power supply	10..32 VDC
Price	+10000€

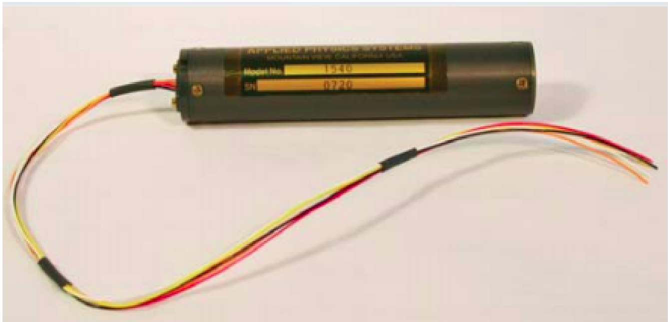

Figure 9. Applied Physics magnetometer

Table V
APPLIED PHYSICS MAGNETOMETER

Manufacturer	Applied Physics
Model name	Model 1540
Magnetometer type	Digital 3 axes fluxgate
Resolution	50pT
Noise	$0.5nT$
Size	25 mm ø x 120 mm
Weight	<200 g
Consumption	55 mA
Power supply	+4.95 VDC to +9 VDC
Price	3000€

The sensor offered by Applied Physics has suitable specifications, as well as a built-in ADC that simplifies the operation. The power supply range and consumption are adequate, as well as the size. The only downside is that this sensor is manufactured in the United States of America and, if chosen, a company that can import the sensor shall be found.

D. Final decision

Despite being a manufacturer located in the United States of America, Applied Physics Systems proposed a magnetometer that is perfectly suitable for the purposes of this thesis.

- The manufacturer location makes necessary the search for a provider in Europe that can import the product and sell it in our continent.
- The magnetometer type ended up being a fluxgate, as it was expected.
- The nominal resolution is ten times more than the required.
- The size, weight and consumption are suitable for the Sparus II.
- The power supply is compatible with the Sparus II voltage availability.
- The price is lower than our budget.

V. Integration

As the purpose of the thesis is to make an approach towards the integration of the magnetometer to the Sparus II, a ROS driver will be developed. This ROS driver will be configured to read a RS232 serial port where the Model 1540 magnetometer will be connected and will provide data in a format that the ROS Software Architecture already implemented in the UUV will easily read and process using the additions of future work regarding this project.

The ROS version to be used is Melodic Morenia, primarily targeted at the Ubuntu 18.04 Bionic Beaver release, being this the operative system used for the development of the ROS driver.

A. ROS driver

The ROS driver consists of a publisher ROS node. The node uses an interface to communicate with the Model 1540 through RS232, publishing then throught a ROS topic the information.

The main operation mode is to request data to the device, either by configuring it to send a continuous flow of data, known as continuous sampling mode, or requesting the message with a given frequency set by a parameter, known as sampling mode.

The driver is also capable of modifying the baud rate configuration of the magnetometer.

In order to run the node, it shall be imported inside the catkin workspace, compiled with catkin and run using the command "rosrun" followed by the node name and the launch file.

1) Published ROS message: Once the information given by the magnetometer is read by the node, it shall be published so other nodes can process the information. When published, this information can also be plotted in real time using the ROS plotting tool named "rqtplot", just by running the command and configuring the tool to plot the desired information.

The published topic is a PointStamped Geometry message. This message has two fields: one is the header, which contains a counter, a description and a time stamp; the other is a point containing three coordinates corresponding with the measured field in Gauss (G) read by the Model 1540. Table VI contains a brief description of the message elements.

Table VI
ROS MESSAGE ELEMENTS

Name	**Type**	**Description**
seq	Integer	Number of times the topic has been published.
stamp	Time	Exact date of the message generation.
frame_id	String	A generic string with a message.
x	Float	Measured field in Gauss by the x axis.
y	Float	Measured field in Gauss by the y axis.
z	Float	Measured field in Gauss by the z axis.

Table VII
ROS DRIVER LAUNCH PARAMETERS

serialDevice	Location of the serial port.
Model name	Model 1540.
period	Frequency of sampling in Hz.
sampling	Modes are POLLING and CONTINUOUS.
connectBaudrate	Connection baud rate.
newBaudrate	New baud rate.

2) ROS launch file: The launch file defines parameters that are used during execution. A brief description of the parameters found in the launch file is described in table VII.

The valid values for the baudrate are contained in the following set: $\{300, 1200, 2400, 4800, 9600, 19200, 38400\}$.

B. Software architecture

Software architecture of the ROS driver is divided into three modules, following an onion architecture. Every layer of the architecture is described below.

1) Serial reader: This layer is the core of the ROS driver. It is the interface to the serial communication through any serial port available.

2) Communications interface: This layer uses the serial reader to communicate with the Applied Physics Systems Model 1540 magnetometer. It has specific sets of commands that the device can understand and also manages a buffer where the magnetometer readings are stored.

3) ROS Publisher: This layer is the outer one of the software architecture. It uses the communication interface to configure the magnetometer, if needed, and to receive the data from it. After reading the data, the message is parsed and sent through the ROS system in the form of a ROS message.

VI. Experimental Testing

For testing the magnetometer, shown in figure 10, there are three factors that are considered. First, the characteristics to be tested; then, the target of evaluation and finally, the testing environment.

The characteristics to be measured are static and alternating magnetic signature. For this, a big mass of ferromagnetic material shall be positioned at known distances, static or moving at a constant speed.

The target of evaluation (ToE) shall be then metallic and be able to move.

The chosen ToE, the Volkswagen Golf Plus 1.9 TDI DSG, is a car with 105 hp and 1502kg of weight when empty, translated in about 1 ton of steel [3]. The human load is not considered because it does not contain a significant amount of ferromagnetic material. This car model is chosen for its availability.

The testing environment is a prepared test trail at a parking lot situated at 39.63704N, 2.64241E, that is shown in figure 11. The magnetometer is going to be situated in the position A and the measured points are labeled as 1, 2, and 3, being the distance between every point and the position A: 8, 25 and 42 meters respectively.

Figure 10. Test set-up at the UIB

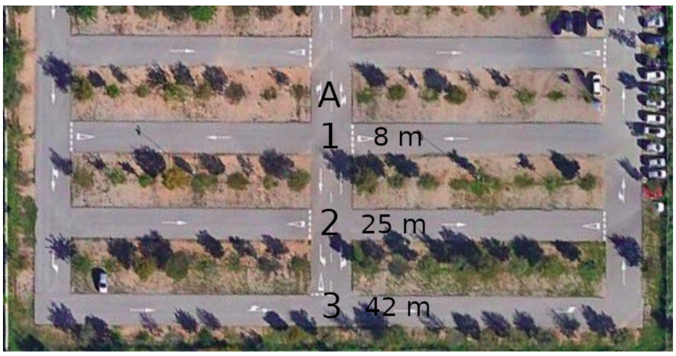

Figure 11. Test trail prepared for the tests

A. Tests

In order to measure the static and alternating magnetic signature of the car, two separate tests are going to be run.

1) Static magnetic signature test: For this test, the car will be situated in the points 1, 2, 3 and back to 2 and 1, staying five seconds in every position. Each position will be labeled as a, b, c, d and e respectively. A graph with the output of the magnetometer will be plotted, as well as a table reflecting the oversampled measure of the magnetometer for every position.

2) Alternating magnetic signature test: For this test, the car will pass at two different speeds by the points 1,2 and 3. The first run will be at 20 km/h and the second, at 40km/h. Those speeds are equivalent to 10 and 21 knots respectively, which are nautical speed magnitudes common in vessels. Each position will be labeled as f, g, h, i, j and k respectively. A graph with the output of the magnetometer will be plotted, as well as a table reflecting the oversampled measure of the magnetometer for every position at the given speed.

B. Results

1) Static magnetic signature test results: The results of this test can be seen in figure 12. Table VIII gives information about the data in each point. The timestamp will be provided in Unix epoch, which is the number of seconds that have elapsed since January 1, 1970 at midnight UTC/GMT.

Table VIII
STATIC MAGNETIC SIGNATURE TEST POINTS

Point	Timestamp (s)	Distance	Measurement (G)
a	1631874775	8 metres	346236
b	1631874794	25 metres	346128
c	1631874813	42 metres	337116
d	1631874870	25 metres	347721
e	1631874906	8 metres	346753

The measures are coherent with the test case steps. The valley that starts at point c occurs at the same moment the car stays at a distance while making a reverse maneuver. Also, every timestamp coincides with a local minimum of the measures. This makes complete sense as, when the car is in movement, it is supposed to have alternating magnetic signature as well, so when it stops the total signature is diminished.

2) Alternating magnetic signature test results: As can be seen in figure 13, there are local maximums when the car passes through points 1, 2 and 3 for each speed. Table VIII gives information about the data in each point.

The magnetic influence at the samples at 8 metres, for 20 km/h and 40 km/h, the positions known as f and i, are clearly visible. The samples at the rest of the positions are positioned at local maximums, but not as accentuated. The oversampling factor has a role, as for longer distances and greater speeds, the magnetic influence is detected for a smaller amount of time.

VII. Real environment tests

Tests in real environment consist of measuring the magnetic signature of ships from land. Testing environment is shown

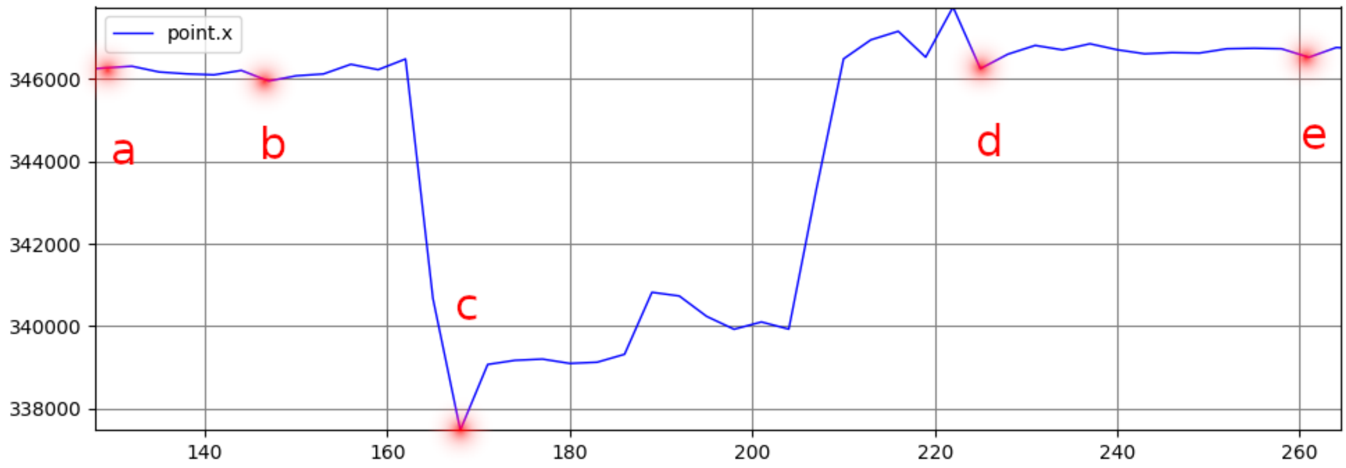

Figure 12. Plot with the X axis measurements of for the static magnetic signature test, in Gauss (y axis) over sample number (x axis)

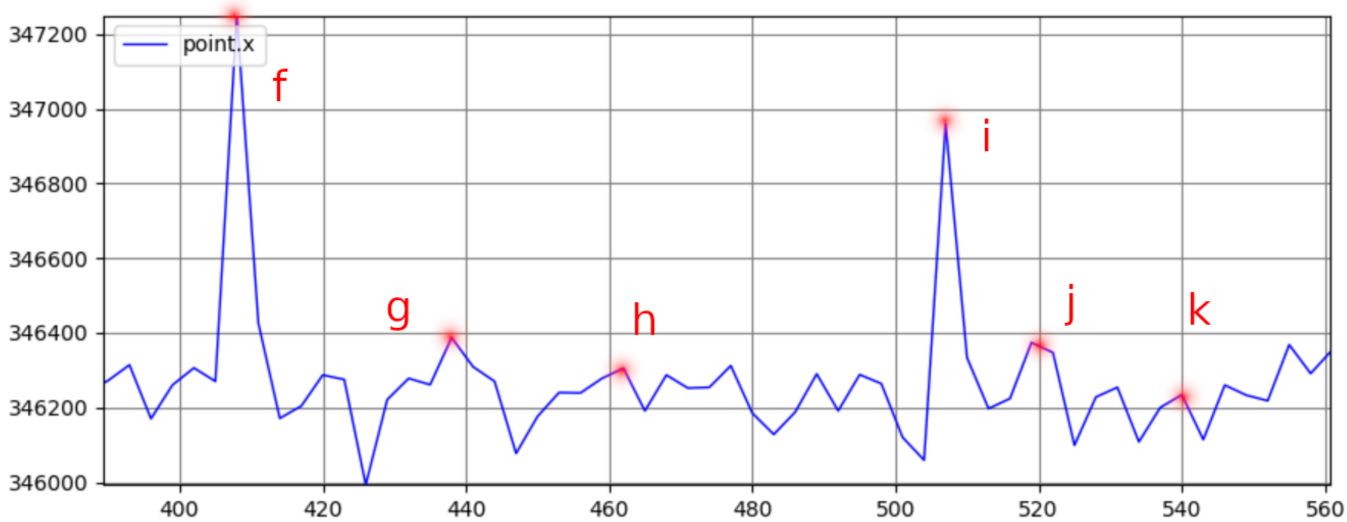

Figure 13. Plot with the X axis measurements of for the alternating magnetic signature test, in Gauss (y axis) over sample number (x axis)

Table IX
ALTERNATING MAGNETIC SIGNATURE TEST POINTS

Point	Timestamp (s)	Distance	Speed	Measurement (G)
f	1631875054	8 metres	20 km/h	347497
g	1631875080	25 metres	20 km/h	346380
h	1631875103	42 metres	20 km/h	346366
i	1631875153	8 metres	40 km/h	346960
j	1631875168	25 metres	40 km/h	346245
k	1631875183	42 metres	40 km/h	346233

in figure 14. Accuracy of these tests is diminished as in real environment the quantity of noise is significant and not predictable.

Magnetic signature of two ships is measured from a distance of 365 metres, being the magnetometer situated in the coordinates 41.333N, 2.165E and pointing to 105º, as shown in figure 15. The measured ships are named Eurocargo Cagliari, shown in figure 16 and MSC Virtuosa, in figure 17.

A. *Eurocargo Cagliari*

Eurocargo Cagliari is a cargo ship that was built in 2012 and is sailing under the flag of Italy. It's deadweight tonnage is 10780 tons and her current draught is reported to be 7.2 metres. It's length is 200.63 meters and it's width is 26.5 metres [1].

In figure 18, the magnetic field of The Earth rises gradually when the ship starts to be measured, marked in the graph as A, from an average of 140500 Gauss to an average of 140700 Gauss. In point B, the ship has already passed and the magnetic field gradually recovers.

B. *MSC Virtuosa*

MSC Virtuosa is a Passenger Ship that was built in 2021 and is sailing under the flag of Malta. It's deadweight tonnage is 19610 tons and it's current draught is reported to be 8.5

Figure 14. Testing set-up in the port of Barcelona

Figure 15. Testing coordinates in the port of Barcelona

meters. Her length overall is 331.43 metres and her width is 43 metres [2].

In figure 19, the magnetic field of The Earth decreases gradually when the ship starts to be measured, marked in the graph as C, from an average of 141000 Gauss to an average of 139000 Gauss. In point D, the ship has already passed and the magnetic field gradually recovers.

There can be seen a noise in the samples after point D in figure 19. It corresponds with a freight truck passing behind the magnetometer, at a distance less than 15 metres. Freight trucks weight an average of 10 tons.

Figure 16. Picture of the vessel Eurocargo Cagliari

Figure 17. Picture of the vessel MSC Virtuosa

VIII. Conclusions

After testing the magnetometer both in experimental and real environments, we can conclude that the objects of evaluation are detected successfully. Changes in the magnetic field are coherent with what is expected. It is true that, even if the experimental environment was prepared for the testing, there was a high amount of noise in both environments. The test with the MSC Virtuosa was the most successful one because of the size and weight of the ship. The magnetic field was altered clearly and the alteration remained some minutes after the ship passed the line of sight of the magnetometer.

Admittedly, the experiments carried out seem to indicate that we are on the right track, but they are not conclusive. Adjusting the sampling frequency or filtering the raw data might be a way to get a more identifiable passing mark. The module and direction of the magnetic field vector must also be taken into account, not just the X axis. Ultimately, testing both in air and water shall be continued. For air tests, it will be necessary to work in an isolated area from unexpected noises like passing trucks, high voltage lines, etc. Finally, the sensor will have to be waterproofed and tests carried out at sea, also in an area far from the coast and with little maritime activity.

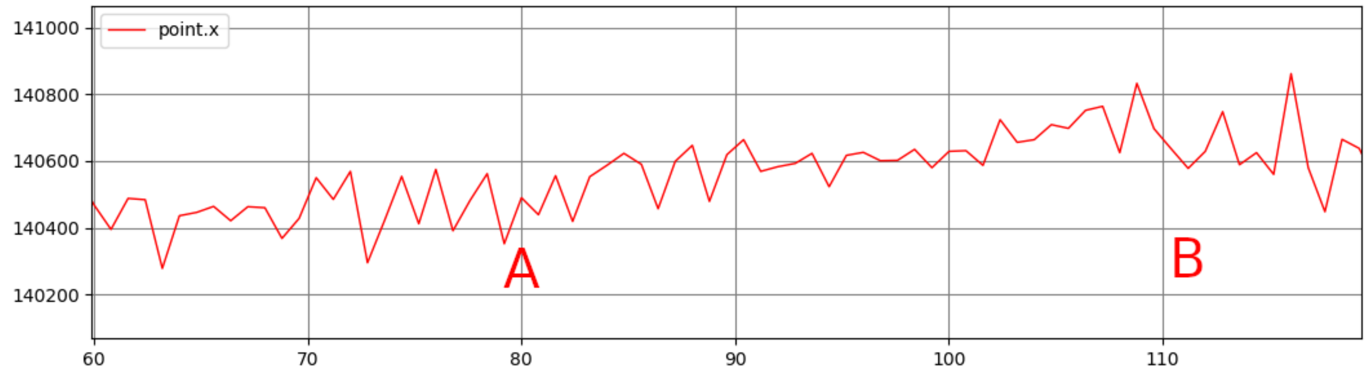

Figure 18. Plot with the X axis measurements of the Eurocargo Cagliari, in Gauss (y axis) over sample number (x axis)

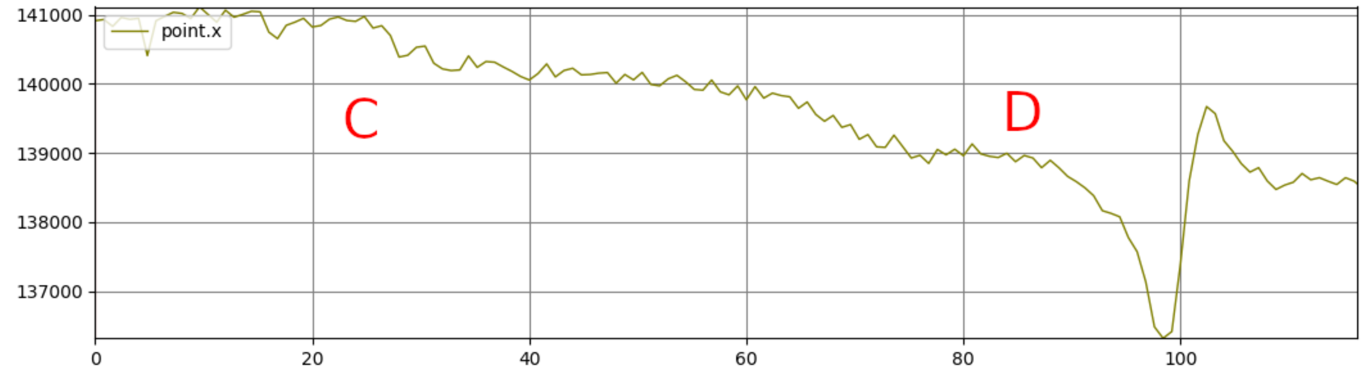

Figure 19. Plot with the X axis measurements of the MSC Virtuosa, in Gauss (y axis) over sample number (x axis)

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