Teaching opportunities in measurements of magnetic field

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Abstract—The measurement of magnetic fields is a complex activity, which can be of significant didactical value. The interference of the numerous sources of magnetic field around the measuring site requires a deep understanding of the fundamentals of electronic instrumentation and the particularities of the measurement of magnetic fields. The proposed experimental set-up, which makes use of a 3-axes magnetometer controlled from an Arduino board, also gives the students the chance to practice embedded programming.

Keywords—Magnetic field measurement, 3-axes magnetometer, Helmholtz Coils, Geomagnetic field, electronic instrumentation, engineering education.

I. INTRODUCTION

The proposed lab is thought for Telecommunications or Electronics Engineering degrees, but it can also be used in other science studies, like in Physics degree lab courses. In particular, the presented set-up will be included as a practical module in the *Aerospace Electronics* course of the Electronics Engineering Master of the University of Granada. The aim of the lab is to develop interdisciplinary skills of the students, preparing them for solving real engineering problems. More specifically, the objectives are:

- To put into practice the fundamentals of the electronic instrumentation and magnetic fields.
- To learn how to identify the relevant sources of information and obtain the necessary data for the experiment.
- To develop theoretical results or simulations of the problem.
- To analyze critically the results and compare them with the theory and simulations.
- To offer a contact with a real engineering project.

With regard to the last objective, the lab serves as an introduction to aerospace projects, which is a possible professional activity of the participating students after their graduation. In particular, the sources of magnetic field of interest in this case are magnetorquers, used for attitude control of satellites. Fig. 9 and Fig. 10 show the 1U and 3U embedded magnetorquers for CubeSats used in this lab as sources of magnetic field.

The measurement of magnetic fields presents a number of characteristics making it very attractive for teaching purposes. Whereas the particularities of the digital sensor, such as measuring range, digital resolution, linearity, etc. is comparable to the measurement of other magnitudes, the presence of other magnetic fields other than the source of interest must be taken into account and compensated for. The first source of magnetic interference in the measurement is the Earth's magnetic field or geomagnetic field. It varies with the geographic position and with the altitude. Fig. 1 shows a world map with an overlaying representation of the intensity of the geomagnetic field at the Earth's surface.

Fig. 1. Magnetic field at the Earth's surface [1]

TABLE I. GEOMAGNETIC FIELD RANGE [2]

Component	Range	Unit
North Component	[-4, 41]	μT
East Component	[-17, 14]	μT
Vertical Component	[-63, 60]	μT

Additionally, other sources of magnetic interference commonly present at the measurement sites are electronic devices, electric lines or ferromagnetic materials.

II. EXPERIMENTAL SET-UP

A. Helmholtz Cage

The interference of the geomagnetic field can be compensated with a Helmholtz Cage. Making use of electromagnetic coils, it is able to create the desired magnetic field inside a certain region. The coils may have a circular or a square shape, as Fig. 2 shows.

Fig. 2. 1D Helmholtz Coils [3]

With the combination of 6 coils, the three components of a magnetic field can be generated inside a certain volume (3D magnetic field). Fig. 3 shows the dimensions of the volume for the particular case of this GranaSAT's Helmholtz Cage, built following the specifications in [4]. The magnitude and direction of the generated magnetic field is determined by the current circulating on the coils in each axis. Each axis is composed of 2 coils connected in series.

Fig. 3. Place and size of the volume where the magnetic field is approximated as constant [3]

Fig. 4 depicts the feed system of the coils to obtain the desired magnetic field in this particular case. A MATLAB script controls the Agilent N6705 variable current source via its GPIB port. The current source feeds each of the axes independently using H-bridges in order to invert the direction of the current if it is needed.

Fig. 4. Connection between all the used elements [3]

Fig. 5 shows the Helmholtz Cage in the GranaSAT lab. In order to place the magnetometer and measured components in the region with constant magnetic field without producing additional interference, a non-ferromagnetic support is used, in this case a wood stand.

Fig. 5. Helmholtz Coils, current source, H-bridges and Matlab control program

B. Magnetometer

The magnetometer used in the experimental set-up is a HMC5883L 3-axis digital compass, shown in Fig. 6. Among the different magnetic field ranges available, ± 0.88 Gauss ($88 \mu\text{T}$) gives the smallest sensitivity of $0.230 \text{ LSB}/\mu\text{T}$ at 12-bit ADC. Its maximum sampling frequency 160 Hz must also be taken into account for measuring varying magnetic fields, but for steady magnetic fields, as in this case, this parameter has minor relevance.

The digital pressure sensor BMP180 is also integrated in the same box in order to obtain further climatic physical magnitudes, which can be relevant for the measurement.

Both sensors are controlled from an Arduino Mega 2560 board using the I2C protocol. A serial connection between the Arduino board and MATLAB permits receiving the samples on a PC as well as sending commands with the appropriate settings for each particular measurement.

Fig. 6. HMC5883L magnetometer and BMP180 barometer

1) Calibration

A compensation for magnetic interferences other than the geomagnetic field can be performed using a soft-hard iron technique. Since the magnetic interferences depend on the material and equipment close to the experimental site, the calibration process must be performed in the same spot and with the same distribution of components as during the measurement. The soft-hard iron calibration process is summarized below:

- Retrieval of samples with the uncalibrated magnetometer. The sensor is rotated in *yaw*, *pitch* and *roll*, while it retrieves periodical samples in its 3 axes X, Y and Z. A three degrees of freedom platform like the one in Fig. 7 can be used as support for the magnetometer.
- Calculation of the coefficients of the soft-iron matrix W_{cal} and the hard-iron offset V_{cal} [5].
- The calibrated values B_c are obtained by applying the calibration soft- and hard-iron correction to the uncalibrated samples B_p .

$$B_c = W_{cal}^{-1}(B_p - V_{cal}) \quad (2)$$

Fig. 7. Three degrees of freedom calibration platform

A polar representation of the samples has the shape of an ellipsoid. A compensation matrix translates the samples into a sphere centered at the origin, as Fig. 8 shows.

Fig. 8. Magnetometer calibration ellipsoid

To check whether the magnetometer calibration has been correctly done, each of its axis can be oriented to one of the components of the geomagnetic field: North, East and Vertical, respectively. The values of the measured magnetic field should now be the same as the geomagnetic field at that geographical coordinate, which can be obtained using the World Magnetic Model (WMM) or the International Geomagnetic Reference Field (IGRF). For convenience, online tools like the NOAA's Magnetic Field Calculator can be used [6]. After calibrating, a certain residual field is still present but it can be neglected if its value is small. Table II gives the values of the geomagnetic field in the experimental site.

TABLE II. GEOMAGNETIC FIELD VALUES

Component	Value ^a [μT]	Residual field [μT]
North Component	27.38	-0.05
East Component	-0.30	-0.12
Vertical Component	33.70	-0.09

^a Values at the GranaSAT Lab. Granada, Spain (Lat.: 37° 08' 38" N, Lon.: 003° 36' 24" W, Altitude: 675m). Date: November 28th 2017. [6]

C. Magnetorquers

The process described can be used for the measurement of any source of magnetic field fitting in the Helmholtz Cage. In the case of this lab, embedded magnetorquers for 1U and 3U CubeSats were chosen. They are coils embedded in PCBs with squared and rectangular shapes, respectively, complying with the CubeSat design specifications [7]. The PCBs are then used as holders of the solar panels of the satellite. Fig. 10 shows a 1U embedded magnetorquer with its solar cells mounted and the magnetometer on top. The advantage of this type of magnetorquer, in comparison with non-embedded models, is the reduction of size and space.

Fig. 9. 3U embedded magnetorquer

Fig. 10. 1U embedded magnetorquer with solar cells mounted

III. MEASUREMENT

The procedure to measure a magnetic field is described in the following steps:

1) Alignment of components

The magnetometer must be placed inside the volume in the Helmholtz Cage with uniform field. The magnetometer axes must be aligned with the axes of the Helmholtz Cage, as shown in Fig. 11. The aim of this lab is to determine the intensity of the magnetic field in the center of the magnetorquer. Therefore, the magnetorquer is also placed in the center of the volume shown in Fig. 3 and the magnetometer centered on its top or its bottom. Fig. 12 shows a photo of the components inside the Helmholtz Cage, with the magnetometer placed under the magnetorquer board.

Fig. 11. Layout for the measurement process [3]

2) Cancellation of the geomagnetic field

The power source, controlled by MATLAB through a GPIB interface, feeds the coils of the Helmholtz Cage. Each axis is fed from a different channel, as it can be seen in Fig. 4, so that each component of the geomagnetic field is cancelled independently.

The MATLAB routine retrieves periodic samples from the magnetometer and the value of the current in each axis is changed until the measured value of each component of the magnetic field is as close as possible to zero.

Fig. 12. Magnetometer and 1U magnetorquer inside the Helmholtz Cage

3) Measurement

Fig. 13 shows the MATLAB GUI, which allows to control the input of the magnetorquer as well as to visualize the measured values of the magnetic field as the samples from the magnetometer are retrieved.

Once the appropriate currents in each axis for cancelling the geomagnetic field have been found, the magnetic source of interest can be measured. The values can be seen in the *Calibration Current* panel and the residual geomagnetic after cancelling is displayed as *Residual B_x*, *Residual B_y* and *Residual B_z*.

The magnetorquer is fed from an additional channel of the Agilent N6705 source. In the *Source parameters* panel, the input source can be configured as current controlled (CC) or as voltage controlled (VC). A step function can be set, introducing the initial input voltage, the end input voltage and the voltage increase in each step. In this case, it was of interest to feed the magnetorquer with 3.3 V and 5 V, which are usual power values in CubeSats. The *Magnetorquer Input Current* graphic shows the values of the input voltage and input power.

The *Magnetometer – Order of Magnitude* panel allows to configure the field range of the magnetometer. In this case, the smallest range ± 0.88 Gauss ($\pm 88 \mu\text{T}$) is sufficient to measure the generated magnetic field and is the optimal for obtaining the smallest resolution [8].

The graphics in the bottom half of the GUI display the values of the measured magnetic field in real time as the samples are received. In the center of the magnetorquer, where the magnetometer is placed, the generated magnetic field has a direction perpendicular to the PCB panel. Therefore, the values in the X and Y axes are close to zero, whereas in the Z axis the values of the magnetic field correspond to the contribution of each segment of the measured coil. A high value of the

magnetic field in the X or Y axes indicates a misalignment of the components.

The magnitudes at the bottom of the GUI are obtained from the BMP180 digital pressure sensor. Their function is to complement the magnetic field measurement with ambient information.

Fig. 13. Matlab GUI

IV. MAGNETIC SIMULATION

The results can be compared with the theoretical expected value, obtained from the Biot-Savart equations, and with a magnetic solver, like ANSYS Maxwell. The second has the advantage to be suitable for complex geometries of the magnetic source. The model can be built directly on the program or imported from a compatible CAD file. For the case of the embedded magnetorquers, which were designed using Altium Designer, they can be exported to AutoCAD files and then imported directly to ANSYS Maxwell.

A magnetostatic simulation allows to obtain the value of the magnetic field at any desired point and also to plot the field directly in the 3D model. Fig. 14 shows a vectorial field plot.

Fig. 14. ANSYS Maxwell simulation with field vector lines plotted

The following list summarizes the preparation of the simulation:

1. Import the geometry from the CAD file.
2. Join the terminals using the geometrical blocks available on the program.
3. Change the material properties of all objects to copper.
4. Define the voltage source.
5. Define the room where the simulation will be executed. Change its material to air.
6. Define the simulation parameters.

7. Simulate and plot the desired results.

The calculated values of the magnetic field can be obtained at any desired position. In this case, it is of interest to determine it at the center of the coil for different distances from the magnetorquer plane (in the Z axis). This simulates the separation of the magnetometer and the magnetorquer plane. The value of the magnetic field at the center of the magnetorquer as a function of the distance from the plane are given in Fig. 15 for inputs voltages V_{in} of 3.3 V and 5 V.

Fig. 15. ANSYS Maxwell simulation linear magnitude B values.

V. FURTHER DEVELOPMENT

There are additional elements with didactical value that could be introduced in the course.

A. Solar simulator

It is interesting to determine the effect that the power generation of the solar cells has on the generated magnetic field. For this, the panels can be illuminated with a spotlight acting as a Sun simulator. Fig. 16 shows a photo the spotlight illuminating the magnetorquer board, which is inside the Helmholtz Cage.

Fig. 16. Sun simulator illuminating a magnetorquer in the Helmholtz Cage

B. Air bearing testbed

The force produced by the interaction between the magnetorquer and the geomagnetic field could be measured using an air bearing testbed. It provides a friction-free environment in 2 axes, allowing to measure the angular speed generated by the magnetorquers in the presence of an external magnetic field. It can be placed directly inside the Helmholtz Cage too, since its materials are non-ferromagnetic and do not interfere with the magnetic field. A 3D representation of an air bearing testbed is shown in Fig. 17.

Fig. 17. Air bearing testbed [9]

VI. CONCLUSIONS

The presented lab intends to provide engineering and science students with a global view of the process to solve a real problem. A background in different disciplines is therefore necessary to accomplish the proposed tasks: electronic instrumentation, theory of magnetic fields or embedded programming are some of the fields of knowledge that the participants have to put into practice to successfully complete the course. A simulation is also proposed in order to compare its results with the ones obtained experimentally. To conclude, two additional experiments are proposed as an extension of the measurements of the magnetic field. All these activities are expected to reinforce the student's knowledge of the theory in the mentioned disciplines as well as to provide them with a procedure to accomplish the characterization of an electronic component, more particularly, a satellite actuator.

The characterization of embedded magnetorquers for 1U and 3U CubeSats also serves as an example of a practical application of electronics in space missions. This field is usually very attractive to the students and this project aims to take advantage of that to boost their motivation.

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