Automatic system for locating magnetic foreign bodies using GMI magnetometer

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Abstract. The development of systems capable of characterizing the positioning and inclination of metallic objects inside the human body is seen with great interest by health professionals who are responsible for their extraction. A surgical procedure can be shortened from a few hours to minutes with a system that provides accurate positioning data. Thus, the present work aims at the construction of a measurement system of magnetic fields originated by ferromagnetic objects, based on magnetoimpedance (GMI) sensors. The developed system is capable of positioning a ferromagnetic object to be measured with 5 degrees of freedom, being 3 linear (X, Y, Z) and 2 angular (θ, Φ), and measure the magnetic flux density of this source in an automated way. Three tests were performed with a steel needle, varying the angles of inclination to the measurement plane (θ) and rotation angles in the same plane (Φ). The obtained results yielded records of the magnetic patterns formed by the needle, which can be later processed in order to create a localization software.

Keywords. Automated Measuring System, Metrology, Giant Magnetoimpedance, Ferromagnetic Foreign Body, Magnetic Flux Density

1. Introduction

The high incidence of metallic foreign bodies inserted in the human body, which requires surgical extraction, points to the need for developing methods for providing information about the position and spatial orientation of such objects [1,2].

The available methods for foreign body localization, such as radiography, computed tomography, and radioscopy, do not present adequate resolution, which often makes them ineffective. In addition to its long duration, surgical procedures may require the use of radioscopy, exposing the medical staff and the patient to ionizing radiation [1].

Using Superconducting Quantum Interference Devices (SQUID) sensors, a technique for locating ferromagnetic [1,2] and non-ferromagnetic [3] metallic foreign bodies in the organism was developed by mapping the spatial distribution of magnetic flux density [1-3]. The technique developed for locating ferromagnetic objects in patients has promoted the surgical success for removal of sewing and hypodermic needles of various dimensions, reducing the duration of surgical procedures to about 10 minutes [1]. Although SQUID magnetic sensors are the most sensitive available, they operate at cryogenic temperatures and represent a costly procedure, making their clinical application difficult.
More recently, through research carried out in the Post-graduate Programme in Metrology of PUC-Rio, high sensitivity and low-cost magnetic field sensors have been developed based on the giant magnetoimpedance (GMI) and giant magnetoresistance (GMR) effects [4-9]. These sensors operate at room temperature, and their sensitivities have been enhanced to be able to locate metallic objects (ferromagnetic or not) in human organisms, among other applications [4-8].

The present work aims at developing an automatic measuring system for mapping static magnetic flux density generated by ferromagnetic bodies positioned at several degrees of freedom, using a low-cost GMI-based sensor configured to detect time-varying magnetic fields.

2. Materials and Methods

2.1. Positioning System

An automatic magnetic measurement system was designed and built, having a sample holder of non-magnetic material, which can be oriented with 5 degrees of freedom, being 3 linear (X, Y and Z) and 2 angular (θ and Φ). Figure 1 shows the schematic drawing of the measuring system. The system was constructed so that the sample holder could be moved on a horizontal plane through rails oriented in the X and Y directions of the Cartesian axis. Thus, it was possible to position the specimen over different positions in the XY plane.

The dimensions of the measuring plane were defined in such a way as to allow a sample holder positioning range of 20 cm along the X axis and 14 cm along the Y axis. The X = 10 cm and Y = 7 cm coordinates correspond to the central position of the measuring plane, as shown in Fig. 1.

Figure 1: Schematic of the automatic magnetic measurement system showing the 3 linear degrees of freedom of orientation of the sample holder (X, Y and Z).
As the system has 2 further angular degrees of freedom (Figure 2), the specimen could be oriented to represent any desired inclination condition. Angle \( \Phi \) is the rotation in the horizontal plane, ranging from 0º to 360º, and angle \( \theta \) is the inclination in relation to the horizontal plane, ranging from -30º to +30º, with 0º being the horizontal orientation.

![Figure 2: Schematic view of the two angular degrees of freedom (\( \theta \) and \( \Phi \)) for sample orientation.](image)

To automate the sample holder positioning process a stepper motor (located outside the measurement plane) was connected to the sample holder through a belt and pulley system. An Arduino controller, powered by an external 12 V power supply (Figure 3), was used to control the speed and direction of engine rotation so that the sample holder moved at constant speed along the X axis direction.

![Figure 3: Step motor controller of the engine rotation at constant speed along the X axis direction.](image)

The speed of the sample holder has been set to be 0.17 m/s. The movement of the sample holder in the Y-axis direction was not automated, requiring manual displacement by an operator. Centered on the XY plane and at a vertical distance of 7 cm from the center of the sample holder, a bracket for mounting
the magnetic sensor was installed. The position \( Z = 0 \), position occupied by the sample holder when \( \theta \) is null, was adopted as a reference.

2.2. \textit{GMI Magnetometer}

This work used a magnetic transducer previously developed by our lab [5-6] as a magnetometer to measure the magnetic flux density generated by ferromagnetic foreign bodies. This transducer consists of two uniaxial giant magnetoimpedance (GMI) sensor and an associated electronic circuit.

One of the characteristics of this transducer is the existence of a high pass filter with a cutoff frequency of 0.1 Hz. This feature cancels static magnetic fields, such as that generated by geomagnetism, and responds only to time-varying magnetic fields with high sensitivity.

The sensor element is 13.5 mm long and 2 mm wide, detecting the longitudinal magnetic field along its length. The magnetic field measurement range is \( \pm 1 \mu T \), with a sensitivity of 5 V/\( \mu T \) and a frequency range of 0.1 to 10 kHz, with linearity \( \leq 2\% \) and a noise spectral density of 10 pT/Hz at 1 Hz. The output voltage has an offset of approximately 7.0 V, ranging from 2 V to 12 V for the \( \pm 1 \mu T \) measurement range. The analog high pass filter integrated in the sensor allows to cancel static magnetic fields with magnetic flux densities up to \( \pm 30 \mu T \), above which electronics saturation occurs.

2.3. \textit{Experimental Tests}

Three tests were carried out to measure the magnetic flux density generated by a 3.3 cm long needle, naturally magnetized during its manufacturing process. The GMI magnetometer was positioned so that the sensor element closest and furthest to the needle were, respectively, at the coordinates \( Z = 7.5 \) cm and \( Z = 10.0 \) cm. In all tests the needle was moved from coordinate \( X = 0 \) cm to \( X = 20 \) cm, keeping the \( Y \) coordinate fixed at values manually changed from 1 cm to 14 cm with 1 cm intervals. The speed along the \( X \) axis was kept constant and equal to 0.17 m/s (automated measurement). Thus, the relationship between needle positioning (along the \( X \) axis) and that recorded on the magnetometer had to be calculated from the time instants.

Each test began with a command on the Arduino controller that started the stepping motor torque. Simultaneously, the magnetic flux density measured by the GMI magnetometer generated an input to an A/D converter board, which transformed the measured analog signals into digital signals. These were processed in a LabView environment, which saved both the test time instants and the magnetic flux density of the 2 sensor elements in a spreadsheet.

In the first test, the needle was positioned at angles \( \theta = 0 \) and \( \Phi = 0 \). The second test angles were \( \theta = 0 \) and \( \Phi = -90^\circ \). The last test was performed with \( \theta = -20^\circ \) and \( \Phi = 0 \).

3. \textit{Results}

Using the developed automatic measuring system (Fig. 1 and 2), magnetic flux density mappings of a 3.3 cm long ferromagnetic foreign body (sewing needle) were performed for different positions concerning the GMI sensors, angles \( \Phi \) and \( \theta \), as detailed in Section 2. Figures 3, 4, and 5 show the magnetic flux density maps generated by the sample positioned at three distinct conditions:

- parallel to the X-axis (angles \( \Phi = 0^\circ \) and \( \theta = 0^\circ \)), in Fig. 3;
- parallel to the Y-axis (angles \( \Phi = -90^\circ \) and \( \theta = 0^\circ \)), in Fig. 4; and
- parallel to the X-axis, but tilted \(-20^\circ\) to the horizontal plane (\( \Phi = 0^\circ \) and \( \theta = -20^\circ \), with the needle eye positioned closest to the GMI transducers), in Fig. 5.

Figures 3a, 4a, and 5a show the field configuration detected by the transducer located closest to the sample (GMI 1), at a distance of 7.5 cm, for the three measuring conditions. The results using the GMI transducer positioned farther away (GMI 2), at a distance of 10 cm from the sample, are shown in figures 3b, 4b, and 5b. Magnetic flux density maps, in microteslas (\( \mu T \)), show measurement results with the object moving from left to right (LR).

The correspondence of the magnetic flux density distribution with the location of the ferromagnetic object, considering its positioning in the horizontal plane and its tilt angle, is shown in Figures 4, 5, and
6. The effect of the distance of the metal object to the magnetic sensor is evident by comparing maps of Figures 4a, 5a, and 6a to Figures 4b, 5b, and 6b, respectively.

Figure 4: Magnetic flux density maps of a 3.3 cm needle positioned parallel to the X-axis (angles $\Phi = 0^\circ$ and $\theta = 0^\circ$), for LR motion measurements. In (a), magnetic isofield map ($\mu$T) detected by GMI 1, the nearest sensor; and, in (b), by GMI 2, the farthest sensor.

Figure 5: Magnetic flux density maps of a 3.3 cm needle parallel to the Y-axis (angles $\Phi = -90^\circ$ and $\theta = 0^\circ$), for LR motion measurements. In (a), magnetic isofield map ($\mu$T) detected by GMI 1; and, in (b), by GMI 2.

Figure 6: Magnetic flux density maps of a 3.3 cm needle (angles $\Phi = 0^\circ$ and $\theta = -20^\circ$), for LR motion measurements. In (a), magnetic isofield map ($\mu$T) detected by GMI 1; and, in (b), by GMI 2.
The maps configurations present some features associated with their acquisition in motion, which differs from those employing a stationary procedure for detecting each point of measurement. Thus, the inverse problem solution must incorporate the specificity of the methodological approach developed to measure the spatial distribution of static magnetic flux density by using sensors that detect only time-varying fields. The elaboration of an algorithm to solve the inverse problem considering the acquisition specificities associated with the automatic system developed constitutes future work, which is in progress.

4. Conclusion
The present work developed an automatic system for continuous measurement, in a constant velocity, of static magnetic flux density using a low-cost GMI-based sensor that detects time-varying magnetic fields. The system allows the positioning of the field source with five degrees of freedom, three of them linear (X, Y, Z) and two angulars (θ, Φ).

By using the developed system, it was possible to characterize the configuration of the magnetic field generated by a ferromagnetic metallic object, consisting of a 3.3 cm sewing needle, positioned at different angles of rotation (Φ) and inclination (θ) in relation to the horizontal plane.

The results point to the success of employing the automatic system, to analyze the distribution of DC magnetic flux density generated by metallic objects, using low-cost GMI sensors designed for AC measurements. The study, therefore, characterizes the potential for clinical application of the developed system in the pre-surgical location of foreign bodies inserted in the human body, essential information for outlining a successful removal procedure.

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