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LOCALIZATION OF MAGNETIC FOREIGN BODIES IN HUMANS USING MAGNETIC FIELD SENSORS

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Abstract – A technique had been previously developed, based on magnetic field measurements using a SQUID sensor, to localise in three dimensions steel needles lost in the human body. In all six cases that were treated until now, the technique allowed easy surgical localisation of the needles with high accuracy, decreasing by a large factor the surgery time and also reducing the generally high odds of failure. The method is accurate, non-invasive and innocuous, with clear clinical importance. In this paper we present preliminary measurements performed with a fluxgate magnetometer instead of a SQUID

Keywords: foreign body, magnetic field, sensors.

1. INTRODUCTION

The accidental penetration of needles in the human body is rather frequent. Such objects usually cause discomfort or are lodged close to perforation-risky organs, leading to the necessity of surgical removal. The common methods for locating needles in humans, such as x-ray films or radioscopy, present several drawbacks and do not give accurate information about position and depth in relation to the skin. Considering these difficulties, a method that is more accurate, non-invasive and innocuous, is of meaningful clinical importance. We have developed one such technique for localisation of steel needles in humans, using a single-channel SQUID magnetometer for measuring the associated remanent magnetic field [1-3]. This technique has already been successfully applied to six patients, in which hypodermic and sewing needles were located and removed in surgeries with 10 to 30 minutes of duration, thus reducing the surgery duration by at least five times.

Despite the success of the technique, the costs involved with SQUID operation (mainly due to need of liquid Helium handling) make it prohibitive to be systematically applied on the whole health community. Thus, this paper presents preliminary measurements made with a fluxgate sensor, which has a much poorer sensitivity but is also much cheaper.

In the following section, the experimental set-up used for the clinical measurements is described, together with the localisation algorithm, which determines the relevant geometrical parameters from the measured magnetic field, and some interesting clinical results. Next, we present *in vitro* measurements performed using the fluxgate sensor.

Fig. 1: Experimental set-up used for localisation of steel needles.

2. METHODS

2.1. Experimental Set-up

Fig. 1 depicts the arrangement of the experimental set-up. The patient is laid on an X-Y moving bed placed under the magnetometer, which generally measures the normal, or vertical, component of the magnetic field. A commercial graphics tablet coupled to the bed monitors the patient's position relative to the sensor. The position of the sensor is projected over the skin by means of a laser beam guided by an optical fibre. As an example, Fig. 2 presents the magnetic field map recorded (using a LTS-SQUID system coupled to a 1.5 cm diameter 2nd-order axial gradiometer, with 4 cm baseline) at a plane 3 cm above the patient skin while moving the X-Y bed. The different grey shades correspond to the different magnetic field levels produced by the needle.

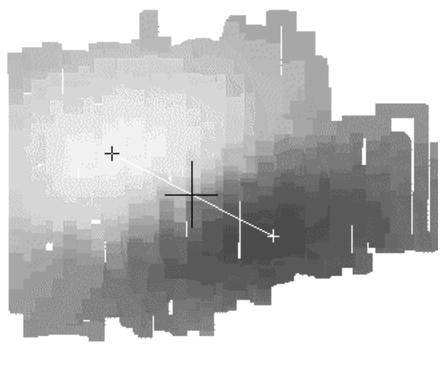


Fig. 2: Magnetic field map recorded by the SQUID sensor at a plane 3 cm above the patient skin while moving the X-Y bed. The different grey shades correspond to different magnetic field levels.

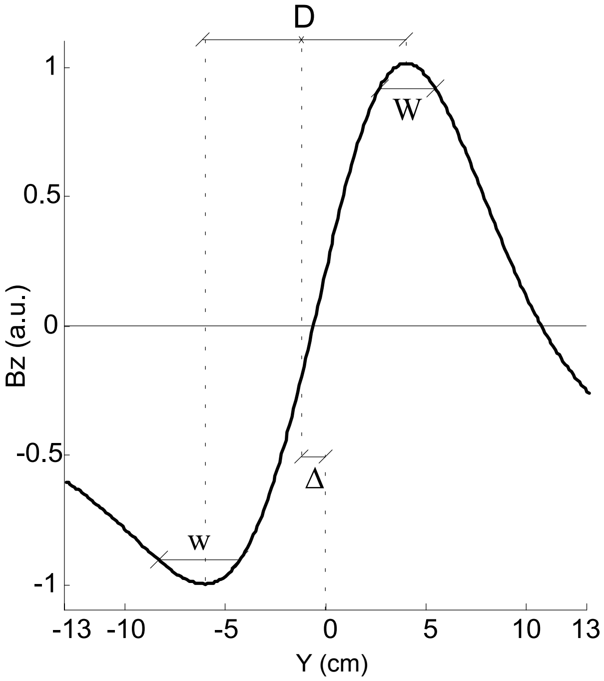


Fig. 3: Normalised magnetic field generated by a 4 cm needle, with $\alpha = 40°$ and $h = 12$ cm. D is the distance between magnetic field extrema, and Δ is the displacement of the midpoint between extrema from the needle centre. The parameters W and w are the widths of the regions that contain the points that fall above +0.9 or below −0.9.

2.2 Localisation Algorithm

The localisation algorithm initially determines the regions for which the magnetic field is greater than 95% of the maximum value, or less than 95% of the minimum value.

After that, the positions of the extrema, marked by small crosses on Fig. 2, are defined as the averaged positions of the points contained in each such region, weighted by the magnetic field values.

The positions of these crosses are also marked on the patient skin, and used as references to the surgical procedure, giving information about the position of the needle centre and its orientation.

Fig. 3 presents the normalised magnetic field measured along a line $h = 12$ cm over a 4.5 cm length needle, with an inclination $\alpha = 40°$. Also shown are the distance D between magnetic field extrema, and the displacement Δ of the midpoint between extrema from the needle centre.

Furthermore, two other parameters are indicated, W and w, defined as the widths of the regions that contain the points that fall above +0.9 or below −0.9, respectively. The ratio $R = W / w$ is related to the inclination angle α.

Three plots are generated relating each of the desired parameters (h, α, Δ) with R and D, by varying the inclination α of the needle for various depths (h).

Figures 4 through 6 present the plots relative to depth h, inclination α and displacement Δ, generated from in-vitro magnetic field maps.

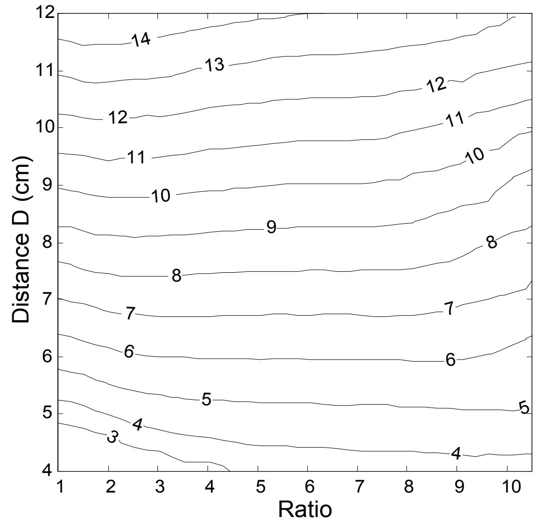


Fig. 4: Depth h of the needle in relation to the sensor as a function of the distance D and of the ratio R.

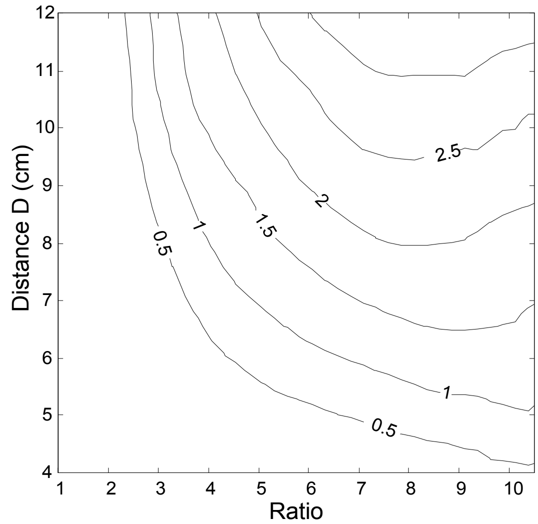


Fig. 5: Inclination α of the needle in relation to the sensor as a function of the distance D and of the ratio R.

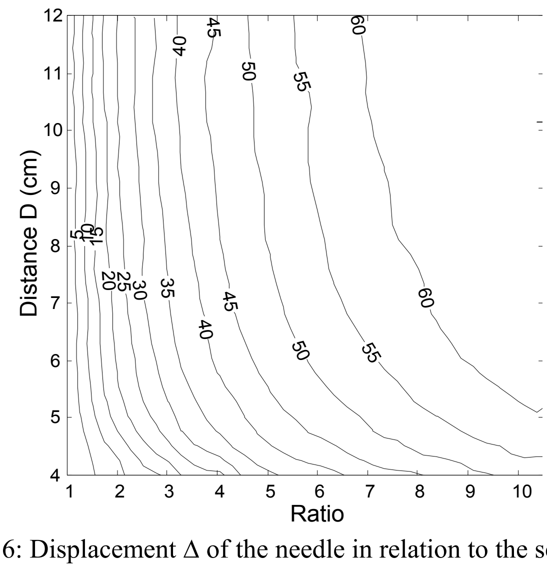
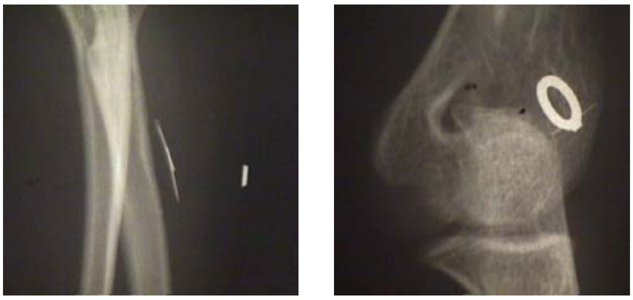


Fig. 6: Displacement Δ of the needle in relation to the sensor as a function of the distance D and of the ratio R.



(a) (b)

Figure 7: *X-ray films taken from a youngster with: (a) two fragments of a broken needle in the forearm; (b) small fragment from another needle in the elbow. A single surgery based on the marks determined by the magnetic field technique, shown by radio-opaque markers above, was performed to remove all three needle fragments.*

2.3 Clinical Results

Until now, six cases (all children of various ages) have been treated by the localisation technique, in which hypodermic and sewing needles were located and removed in surgeries with 10 to 30 minutes of duration (a reduction of at least five times).

In the last case studied by our group, probably the most interesting one, a fifteen-year old child had a needle broken into two fragments lodged in the left arm (Fig. 7a), and had already been subjected to an unsuccessful removal surgery. During the magnetic field measurements, a complex configuration was observed, suggesting the presence of another magnetic field source located about 5 cm centimetres above the referred broken needle. By examining meticulously the X-ray films taken on the patient, a small fragment (1 cm length) of a very thin needle was detected (Fig. 7b). Two separate magnetic field maps had to be performed, in order to define distinct mapping areas for each needle.

The broken needle was located in the forearm, at a depth of about 4 cm. The scar produced by the previous non-successful surgery was several centimetres away from the calculated reference points. The smaller fragment, located about 3.5 cm deep, was lodged 2 cm above the child's elbow. A single successful surgery was performed to remove all three needle fragments.

Despite the success of the technique, the costs involved with liquid Helium for SQUID operation make it prohibitive to be systematically applied on the whole health community. Next section presents measurements performed with a fluxgate sensor (much cheaper than the SQUID), in order to investigate the feasibility of employing less sensitive sensors in the localisation technique.

4. MEASUREMENTS WITH FLUXGATE SENSOR

A series of *in vitro* measurements have been performed, using a fluxgate sensor [4,5] to detect the magnetic field. Fig. 8 presents one such measurement, at a depth $h =$ 7 cm. In this case, the needle originally did not present a remanent magnetic field strong enough for the fluxgate sensitivity, but a permanent magnet was employed to magnetise the needle and allowed the detection and measurement.

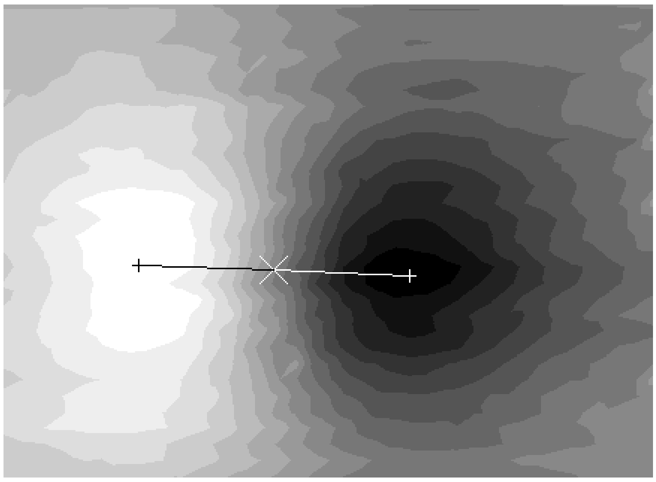


Fig. 8: Magnetic field map recorded by the fluxgate sensor at a plane h = 7 cm above the needle, after magnetisation of the needle with the aid of a permanent magnet.

The preliminary measurements have indicated the need of enhancing the needle magnetisation in some cases. Also, it could be observed that the resultant needle magnetisation depends both on the time of exposure to the permanent magnet and on the distance to the needle. So, a systematic study was performed, aiming to optimise the magnetisation procedure, as explained in the next section.

4.1 Magnetisation of the Needles

Evidently, in practice the minimum distance obtainable from the magnet to the needle is limited by the depth of the needle in relation to the patient's skin.

Thus, we fixed the magnetisation distance at 5 cm (a reasonable value, based on the former experience), and progressively increased the exposure time. After each cycle, a tape demagnetiser was used to remove the needle magnetisation to the maximum extent possible.

For each magnetisation cycle, a different final magnitude was obtained, due to the randomness associated with the magnetisation/demagnetisation processes.

Fig. 9 presents the results obtained for three distinct cycles. Despite the noise and variability, it can be noticed that after 20 minutes the needle magnetisation tends to stabilise.

4.2 In-vitro Measurements

Once the optimum exposure time has been defined as 20 minutes, a series of *in vitro* measurements was performed, by varying the depth h of the needle in relation to the fluxgate sensor position, from 5 cm to 15 cm.

For each magnetic field map, the distance D between magnetic field extrema was calculated, as depicted in Fig. 3. The data obtained from the series of measurements is presented in Fig. 10.

In Fig. 10, it can be clearly seen that the distance D increases monotonically with the depth h. This plot has a similar function as the one shown in Fig. 4, that is, it allows the inference of the depth of the needle from the magnetic distance measured from the experimental data, thus performing an inverse problem solution.

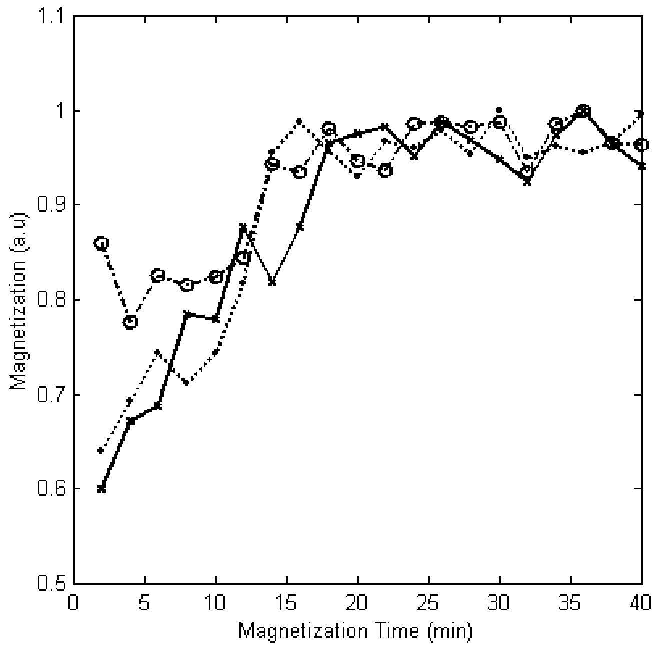


Fig. 9: Normalised magnetisation of the needle as a function of exposure time. Three distinct measurements have been performed with the same needle, and each curve was normalised by its maximum value.

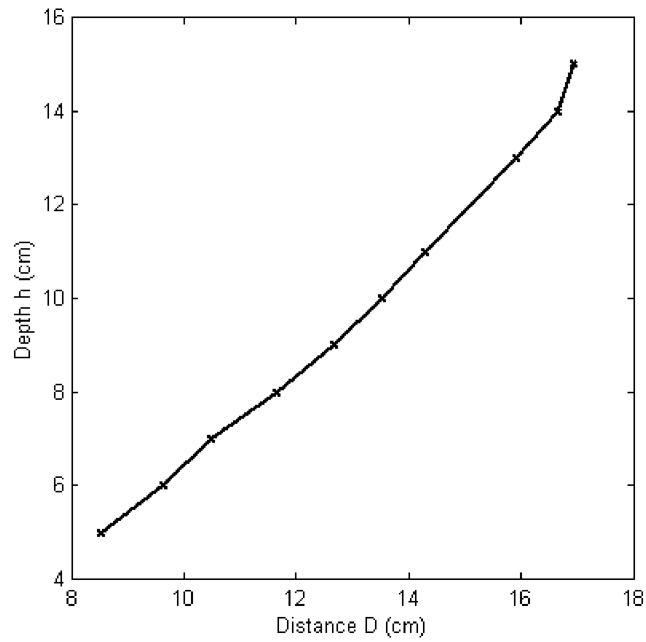


Fig. 10: Depth *h* of the needle in relation to the fluxgate sensor as a function of the distance D, measured from the magnetic field map.

4. CONCLUSIONS

The *in-vitro* measurements performed with the fluxgate sensor have shown that it is possible to replace the highly expensive LTS SQUID system by less sensitive systems.

Further experiments have confirmed such possibility, yielding the fluxgate or other magnetic sensors as possible magnetometers to be employed for magnetic foreign body localisation.

One option could be the fluxgate itself, but it is very difficult and expensive to obtain a differential (gradiometric) configuration, which is of foremost importance for regular use of the sensor, as it allows cancellation of a large amount of environmental magnetic noise.

An affordable option presently available commercially is the HTS SQUID, which employs liquid nitrogen instead of liquid helium.

Another interesting possibility is the newly developed giant magnetoimpedance (GMI) magnetometer [6], which is much cheaper and simpler than the other options above referred. Our research group at PUC-Rio is presently working with this last option, aiming to enhance the sensitivity of a GMI magnetic sensor already available, and used for nondestructive testing of oil pipelines (thus presenting a much larger magnetic field strength).

Future work also includes an adaptation of the technique for localisation of firearm projectiles, the most prevalent foreign bodies in the modern society. It is generally composed of lead, a paramagnetic material, thus not presenting a remanent magnetic field as steel needles do. However, as lead is a good conductor, eddy current techniques can be employed. A theoretical study has already been accomplished about this subject [7], also indicating the possibility of employing less sensitive sensors.

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