Electromagnetic navigation in medicine – basic issues, advantages and shortcomings, prospects of improvement

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Abstract. This paper presents most essential problems related to electromagnetic navigation (EM) systems employed in medicine. The principle of operation of the EM navigation system, advantages of the method, requirements imposed and disadvantages of commercially available solutions have been presented. Possibilities of improvement of metrological and usable properties of such systems have been shown. The most important part of the paper is a proposal for modifications allowing significant improvement of the system operation and its capabilities. The effectiveness of these improvements has been investigated using a computer model and, partially, also the physical model of the system. The problem of distortions of magnetic field distribution caused by the presence of conducting and magnetic objects is also discussed.

1. Introduction

1.1. Description of EM navigation method and its applications

Electromagnetic (EM) navigation is a relatively new technique applied in medicine for aiding the work of physicians, mainly for improvement of precision and shortening the time of operations, as well as for increasing patient safety and also decreasing the invasive propensity of operations [1]. Just as in other systems for medical navigation, the position of an instrument used during an operation is determined by comparison with the position of the patient’s body [2]. Coordinates obtained using an electromagnetic method are often brought to three-dimensional images of the patient’s body obtained earlier with the use of computer tomography or magnetic resonance. This makes possible visualization of the actual position of the instrument in relation to anatomical structures of the patient’s body.

EM navigation is based on the relationship between the magnetic induction vector in a given analyzed position and the coordinates of this position, described by the Biot-Savart law. Knowledge of the location of the modules generating the magnetic field enables determination of the magnetic field vector in the given location of measurement and also determination of the position and spatial orientation of the magnetic field sensor placed on an instrument [2] – that is shown in fig. 1. The main advantages resulting from applying this method are connected with transparency of the human body for the EM field of low frequency, enabling measurements also inside the patient’s body. A great advantage of the presented method in comparison with optical navigation that is currently widely...
adopted is the lack of the necessity of keeping the line of sight (LOS) between the generator and sensors.

\[ B = f(R_1, R_2, R_3) \]

**Figure 1.** Explanation of the principle of position determination in EM navigation system

EM navigation is more and more widely applied in medicine. It is especially useful during endoscopic explorations and surgery (e.g. in neurosurgery [1], bronchoscopy [3], colonoscopy, tumour therapy [4], cardiological applications [5]), in situations when the operator does not see directly the farther end of the instrument placed in the patient’s body. This navigation is thus a very interesting alternative to the more expensive methods applying X-rays which can be harmful for the patient [6]. Another numerous group of applications of the method that have been described are biomechanical applications having in view the registration and description of the movement of larger parts of the patient’s body [7,8].

1.2. Requirements for electromagnetic (EM) navigation systems [2]

The wide variety of possible applications of the method entails numerous requirements for the navigation systems. The first is the requirement for comparatively good accuracy of determining the position of the end of the instrument; in some applications reaching tenths of a millimeter. The accuracy of measurement has to be kept in the operational space of relatively large dimensions, in some biomedical applications ranging up to 1 meter. Bringing together both these requirements in one system is a difficult task and a compromise is usually matched to each application. A desirable feature is the high speed of the system operation (above 50 Hz) with the simultaneous ability to control many measurement channels at the same time. This results from the required frequency of refreshing the position determination to be not lower than 2-3 per second.

Another limitation resulting from the principle of measurement itself is the need for very accurate knowledge of the distribution of the magnetic field. The acceptance of too great a simplification in the field analysis and the presence of elements disturbing the field distribution (conducting and magnetic objects) can have a crucial influence on the measurement accuracy. As previously mentioned, the sensitivity of the magnetic field distribution for the presence of conductive (metal) and ferromagnetic objects can be a serious problem in medical applications of the system. Distortions of the magnetic field lines caused by a non-magnetic conductor and a ferromagnetic element are presented in figures 2 and 3. In the case of non-magnetic conductors the alternating magnetic field produced by the emitter induces eddy currents which become the source of an additional field. For ferromagnetic materials the effect of curving the field lines also appears, connected with the difference in magnetic permeability.
From the medical point of view the possibility of the small dimensions of the sensor with the preservation of its good sensitivity is also very important. Sensors should be sufficiently small enabling them to be put easily into the farther end of the instrument placed in the patient’s body, directly near the organ which is being investigated or operated upon [9]. The small dimensions of the sensors enable application in clinical practice; also the navigation of flexible instruments which create new possibilities in branches of medicine such as. pulmonology, oncology and soft tissue surgery. Placing the sensor at the farther end of the instrument can decrease measurement errors also when tracking the position of rigid instruments (e.g. sucker, scalpel).

1.3. Imperfections of available EM navigation systems
Commercially available EM navigation systems often do not fulfill all the requirements that have been presented. This relates to the accuracy of measurement (typically 1–2 mm RMS) as well as the size of the operating space (maximum dimension is 60–70 cm) [1,7,9]. Also dimensions of the sensors are problematic; in most systems they are too large to be put inside the body. Sensors usually are placed at the near end of instruments, just as in optical navigation systems. This precludes full use of the advantages of EM navigation systems (LOS not required, possibility of using flexible instruments). A better situation is from the perspective of the maximum frequency of the position determining, which in most of commercial solutions can reach tens to hundreds per second [1,7,9].

In the majority of commercially available systems of a similar type, the problem of errors resulting from the magnetic field distortions caused by conducting and ferromagnetic objects generally has not been solved [1, 7], despite it being essential in all operating rooms, where usually plenty of metal
instruments and auxiliary equipment are in use. Some of them are used directly in the operating area and, which is worse, they can be introduced there and removed rapidly. In the literature there are proposals for limiting the influence of the objects disturbing the magnetic field consisting in eliminating them from the operating room equipment, introducing screening of metal objects [9], applying calibration and tables of corrections for a given instrument [11], applying mathematical methods of compensation [12] or changing the shape of the exciting field [9]. However, all mentioned methods have some shortcomings.

2. Method of measurement and its proposed modifications – iterative algorithm applied in EM navigation system

The designed system for determining the 3D position on the basis of the magnetic induction measurement makes use of the iterative algorithm described in [10]. Such an approach, although in principle is less accurate than the analytical solution, essentially accelerates the operation of the system because it does not require complicated and troublesome calculations. In the EM method the position of any point $P$ in the 3D space can be determined from its distance $R$ to at least three points $G_i$ of known positions (Figure 4). A pair of solutions, $P$ and $P'$, is thus obtained. $P'$ is an erroneous one, however, though it is easy to detect and ignore.

![Figure 4](image)

Figure 4. Determination of the co-ordinates of the point $P$ from its distances $R_i$ to the reference points $G_i$.

According to [10] the magnitude of the magnetic induction vector in point $P$ of the field produced by a square coil of $N$ turns, placed in the origin of coordinates, when $b<<R$ (Figure 5), is equal to:

$$ |B| = \frac{k_G}{R} \sqrt{\cos^2 \alpha + 1} $$

(1)

where:

- $R$ – distance from point $P$ to the centre of the coil generating the field,
- $K_G$ – coil constant, dependent on its shape and dimensions, number of turns and current,
- $\alpha$ – angle between the coil axis and the leading vector of point $P$. 


Equation (10) cannot be used directly because it describes the case of application of the magnetic field of isotropic spatial characteristic, which does not exist in practice. As the voltage signal induced in a real field sensor is the scalar product of the magnetic induction vector $\mathbf{B}$ and the sensitivity (spatial orientation) versor $\hat{\mathbf{s}}$, correct determination of magnitude of the magnetic induction $\mathbf{B}$ requires additional information.

The simplest solution consists of determination of the components of the magnetic induction vector by use of three independent, orthogonal magnetic field sensors located at point $P$ and calculation of the induced signal magnitude. However, more practical is the application of three sets of orthogonal magnetic field sources located in the reference points $G_i$ (Figure 4). Both the principle of operation and the equations presented earlier remain valid.

Then the signal induced in the magnetic field sensor is the vector:

$$\mathbf{V} = [U_x, U_y, U_z]$$

(2)

where:

$U_x$, $U_y$, $U_z$ – signals induced in the magnetic field sensors, coming from the corresponding orthogonal sources, from where we obtain:

$$|\mathbf{V}| = \sqrt{U_x^2 + U_y^2 + U_z^2}$$

(3)

The magnitude of the magnetic induction $B$ at a given point $P$ can be calculated from the magnitude of the voltage induced in the sensor located at this point:

$$|B| = k_s |\mathbf{V}|$$

(4)

Comparing equations (1) and (4) we obtain:

$$k_s |\mathbf{V}| = \frac{k_G}{R^2} [\sqrt{3 \cos^2 \alpha + 1}]$$

(5)

$$R = \sqrt{\frac{k_G}{k_s |\mathbf{V}|} [\sqrt{3 \cos^2 \alpha + 1}]}$$

(6)
Equation (6) contains a variable \( \alpha \) (angle) of unknown value which theoretically precludes determination of the distance \( R \). Since the element with \( \alpha \) takes its value from the interval 1 to 2 only, it is possible to obtain the approximate value of the distance \( R \) substituting at the beginning of the calculations any value of \( \alpha \).

Knowing the approximate distances between the sensor and the three reference points (centres of the exciting coils) it is possible to calculate the approximate coordinates of point \( P \), and later also a more accurate value of the angle \( \alpha \). In this way, in consecutive iterations, it is possible to obtain a more and more accurate approximation of the distance \( R \), and hence more accurately determine the coordinates of point \( P \).

Iterations should be repeated until a sufficiently accurate result is obtained or until subsequent iterations do not improve accuracy of calculations.

2.1. Possibilities of improvement of metrological and usable properties of EM medical navigation system [2]

The potential of designing the EM navigation system under consideration with the required features and possibly free of shortcomings was analyzed in [2] where a number of improvements were proposed. Improvement of accuracy of the system can be obtained in two ways. A considerable improvement of the positioning accuracy can be achieved by introducing an additional reference channel, with its sensor situated at a point of exactly known coordinates. Such a solution provides continuous testing changes of the field produced by the emitter and the negative feedback ensures correction of these changes and therefore improves the stability of the exciting field, which directly improves the metrological features of the system.

The second way of improving system accuracy consists in modification of the algorithm for determining position. In the systems available at present on the market, the generation of the magnetic field pattern distribution is performed making use of a simplified model of the magnetic dipole, which seems to be overmuch of a simplification for small distances – this is a shortcoming of this method. Calculated in this way, the distribution of the magnetic field for small distances between the emitter and sensor differs significantly from the real magnetic field distribution determined from the Biot-Savart law. This is presented in Figure 7 for a typical cross-section line. This simplification not only worsens accuracy of measurement but also confines the operating area in which the measurement could be performed correctly from the physical point of view. The assumption of a less simplified model of the field can give simultaneously two advantages: a possibility of improving the accuracy and widening the operating area of the system. The most accurate solution would be elaboration of a new algorithm based directly on the Biot-Savart law. However, considering the great complexity of the calculations, such a solution could be too slow. A compromise solution consists in the application of the simplified algorithm, however, with the inclusion of corrections determined from the Biot-Savart law (a table of such corrections can be mapped). These corrections should be introduced after preliminary position determination with the use of the simplified algorithm. Another solution can consist in finding a relationship between the value of correction and the sensor position determined by the simplified method.
The next improvement proposed enables the speeding up of the system for many parallel driven measurement channels. The first of the solutions proposed consists of applying simultaneous measurement of the fields emitted by all generators (each generator operates at different frequency, i.e. frequency division multiplexing), instead of the traditionally applied sequential measurement of the magnetic induction from particular generators (time division multiplexing). Such a solution requires good spectral purity of the excitation signal, such that the amplitudes measured for subsequent frequencies could be easily discriminated. This intensifies the requirements in proportion to the
physical realization of the generator. Introduction of the presented solution enables a very large (even three orders of magnitude) increase in the speed of the system operation.

The second solution lies in implementation in the system of one of the simplified algorithms of spectral analysis, like the Goertzel algorithm or a simplified DFT algorithm. Application of expensive, dedicated DSP modules or the necessity of performing a larger part of the calculations by a computer connected to the system can be substituted by a hardware signal analysis module operating in parallel, realized by the use of a programmable logic FPGA circuit. Implementation of the improvements obtained will result in further increase of the system operations. This will be especially noticeable in multichannel measurements, where the simultaneous performing of many complicated calculations is necessary.

The final proposed modification refers to the magnetic field sensor. Investigation of various types of sensor indicates that the best solution is a small coil wound on a ferromagnetic core. It has the smallest dimensions and acceptable sensitivity. A shortcoming of a sensor of this type can be, in some applications, its relatively high sensitivity for mechanical damage. In cases where extremely high mechanical resistance of the coils is required (e.g. examination of patients with Parkinson’s disease, biomechanical tests) the coils can be substituted by magnetoresistive elements. Unfortunately, this entails unavoidable reduction of sensitivity and an increase in the sensor’s dimensions.

3. Investigations of the system operation

Having in view the verification of the algorithm for the determination of position and its proposed modifications consisting in application of a more accurate magnetic field model, a series of tests of this model were carried out adopting a Matlab programming environment. They served to test the space of convergence of the algorithm and estimate the systematic error of the whole system, resulting from the simplified magnetic field model assumed in the algorithm. All these tests were performed considering a cube of 2 m side as the operating area of the system. The excitation coils were located in the cube basis according to Figure 8.

Calculations were performed for a network of test points located every 20 mm in chosen planes XY, XZ and YZ. Taking advantage of equations 1 and 3, the signals induced in the magnetic field sensors, coming from corresponding excitation coils, were calculated. Then, applying the algorithm tested, these signals were applied for determination of the sensor position. The difference between the position of a chosen test point and coordinates obtained from the algorithm is presented in plots shown in Figures 9 and 10.

![Figure 8. Location of the exciting coils in the system](image)
3.1. Determination of the convergence space and estimation of random error of the algorithm
In the first stage of tests, the convergence space was checked and random error of the algorithm was estimated assuming an ideal measurement path (lack of errors of magnetic field measurement). Typical results of simulation are presented in Figure 9. The areas for which it is impossible to determine the sensor position because of lack of the algorithm convergence (white area, colourless) are readily visible. In Figure 9, for comparison, the range of operation of the existing system manufactured by John Bladen Medical Systems is distinguished using a darker colour.

![Figure 9](image)

**Figure 9.** Error of the algorithm used for determination of position in XZ plane for x=0mm. For comparison, darker colours are used to distinguish the operating area of the system manufactured by John Bladen Medical Systems.

3.2. Determination of the error of the modified algorithm
In the next stage a series of simulations was performed in which the results obtained using the algorithm based on the simplified model of the field were compared with the results calculated from the algorithm applying the Biot-Savart law (Figure 10). It is clearly seen how large errors result from the assumption of too simplified a model of the field and why the application of corrections is necessary in the algorithm for the determination of position. Introductory experiments carried out with the use of the partially built up physical model of the system confirmed the results of the simulations.
4. Summary
Considerations presented in this paper indicate that the metrological and usable properties of the EM navigational system can be considerably improved in order to widen its range of medical applications. Most of the modifications proposed do not significantly complicate the system, neither do they increase its cost. The improvements proposed have been initially tested using computer simulations and partly also experimentally. The results obtained confirm their effectiveness. Further work will involve design and construction of the physical model of the whole system, including all the improvements proposed. Tests performed on this model and on phantoms of the human body will enable verification of the effectiveness of the improvements applied. Investigations on the disturbing influence of metal and ferromagnetic objects on the system accuracy will be carried out in parallel. Elaboration of the method enabling elimination or compensation of this influence would considerably enhance the metrological properties of the EM navigation system.

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