XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

POSSIBILITIES OF IMPROVEMENT OF METROLOGICAL AND USABLE PROPERTIES OF AN ELECTROMAGNETIC NAVIGATION SYSTEM WITH AC EXCITED FIELD

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Abstract: One of the methods of medical navigation, applied for positioning of instruments inside the patient's body during investigation or surgery, is electromagnetic one. The great advantage of this method is a possibility of positioning inside the patient's body. Its shortcomings are: sensitivity to the presence of objects disturbing the magnetic field distribution, i.e. conducting and ferromagnetic objects in the operating space and a relatively small area of high accuracy measurement. The works presented in this paper are aimed to prevent or limit these disadvantages. The improved accuracy of measurement can be achieved thanks to the introduction of an additional reference channel and performance of numeric simulations enabling optimal choice of the system of magnetic field generation. The disturbing influence of conducting and ferromagnetic objects on the system accuracy have been simulated using the finite element method (FEM). Some methods of limiting these disturbances have been proposed on the basis of the results obtained.

Keywords: electromagnetic navigation system, medical navigation, positioning.

1. INTRODUCTION

Medical navigation is one of the auxiliary methods applied in medical diagnostics and surgery, aimed at speeding up and increasing precision of investigations and surgery, increasing safety of patients and facilitating preparation and realisation of these actions by the medical staff [1][2]. Navigation of medical instruments consists in determining spatial co-ordinates of the characteristic points of the instruments and superimposing them on the three-dimensional images of the patient's body obtained before the surgery in investigations performed using CT or NMR. During the surgery the position of the tracked instrument is located in real time on the images of the patient's body [3].

Among the medical navigation systems available on the market more and more popular become electromagnetic (EM) ones using magnetic field of low frequency. In the EM systems the position of instruments is obtained by taking advantage of the relationship between the value of magnetic induction of the field produced in a particular point of the space by the generator and the position of this point in respect of the generator, described by the Biot-Savart law. When measuring the induction of the spatial magnetic field produced by a set of three generators placed in three points of known co-ordinates, it is possible to determine the distance between the particular point and each of the generators, therefore also the spatial position of this point. The method of calculations and the suitable algorithm are described in details in [4][5][6].

Thanks to the transparency of the human body for magnetic field of low frequency the EM navigation system does not require to keep clear Line of Sight (LOS) between the field emitter (generator) and the sensor. Therefore, it is possible to track the further end of the instrument put into the patient's body which decreases the errors and enables navigation of flexible instruments. Furthermore, it makes the work of medical staff easier.

Objects made of good conductors and ferromagnetic materials can produce deformations of primary distribution of the magnetic field and, therefore, also worsen the navigation accuracy. This is the main shortcoming of the EM navigation.

2. AIMS OF RESEARCH

The main aim of research works presented in this paper is to widen the working space of the considered EM navigation system without worsening navigation accuracy. Present EM navigation systems available on the market have their working space limited to a segment of sphere about 50 cm in radius or a cube of side length 50 cm [7][8]. It is assumed to extend this space to a cube of side length about 100 cm, with simultaneous improvement of the navigation accuracy. Two procedures are proposed: (1) – widening the system working space by an optimal choice of parameters of the magnetic field generator, determining areas of convergence of the measurement algorithm and improving accuracy of measurement in the areas of low magnetic induction, and (2) – reduction of the navigation errors caused by the presence of metal and ferromagnetic objects in the operation area or its vicinity [8][9]. The second way can be complemented by introducing an additional mode of operation, of enhanced resistance to the presence of metal and ferromagnetic instruments in the operation area.

3. MEANS ENABLING IMPROVEMENT OF METROLOGICAL AND USABLE PROPERTIES OF EM MEDICAL NAVIGATION SYSTEM

A considerable improvement of the positioning accuracy in an extended working space 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 – 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.

Extension of the working space of the system can be obtained by a suitable selection of parameters of the generators of the magnetic field, improvement of convergence of the measurement algorithm and improvement of the system accuracy for the areas of very low magnetic induction.

Modifications of the generators involve a choice of dimensions of an individual emitter (source of the magnetic field) in the form of an inductor, optimal spatial distribution of the set of emitters and the method of generation of the signals exciting the emitters.

Geometric dimensions of the emitter (each emitter contains three orthogonal inductors) and intensity of the current flowing through it have been optimized on the basis of numerical computing of the signal volume and the error resulting from the assumed simplified model of the magnetic field. The mentioned parameters are chosen in such a way that the limit of the maximum permissible safe value of the magnetic field strength and the limit of the maximum admissible measurement error resulting from the assumption of non-ideal (of finite dimensions) source of the field were very close . Such solution offers the possibility to optimally utilize the working space. The value of 0.2 mm has be accepted as an admissible measurement error.

In the performed computations the magnetic dipole was assumed as the source of the magnetic field. In the vicinity of the set of generating coils this assumption is fulfilled only approximately what causes the occurrence of a position measurement error in this area. The value of this error was computed by comparing the real coordinates of the grid of the control points with the coordinates obtained as a result of numerical computations. At first, for each point of the grid, the Cartesian components B_x, B_y and B_z of the magnetic induction vector were computed using Biot – Savart's law. Then the values of the components were used to compute the location of the control points using the magnetic dipole model. The position measurement error is the distance between the real position vector of the control point and the position vector computed for the same point using the magnetic dipole model.

The geometry of a single generating module used in the developed system, containing three orthogonal coils is shown in fig. 1. The diameter of the winding wire equals to 0.9 mm. The electric current value used in computations is 1.6 A which is the maximal allowed limit related to the thermal effects estimated for that diameter. The distribution of the position measurement error in the vicinity of each of the orthogonal coils is shown in fig. 2. The error distribution was compared with the contour corresponding to the value of magnetic field intensity equal to 10 A/m which is considered to be safe for a human.

The obtained results show that for the magnetic field generator with the geometry used in the developed system both the acceptable value of the position measurement error and the maximal admissible value of the magnetic field intensity appear in the distance of several centimeters from the middle of the set of generating coils. It is also visible that the asymmetry of a single generating coil decreases the agreement between distribution of the generated field and the magnetic dipole model.

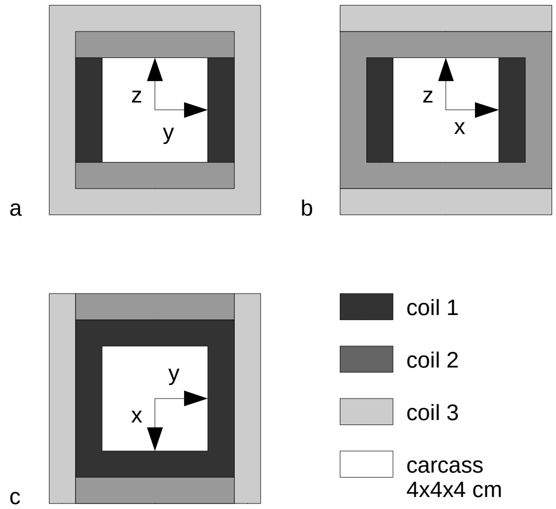

Fig. 1. Geometry of a single set of generating coils used in the developed system – the cross-section through the set of coils in three orthogonal directions. The proportions are not respected.

A proper arrangement of the set of three magnetic field emitters has been chosen on the basis of numerical simulations of convergence of the measurement algorithm. Signals exciting the emitters are produced using a generator system of high spectral purity and high stability, which improves the accuracy of measurement in the points distant from the sources, in which the signal to noise ratio is low.

Modifications of the path of signals coming from the sensor coils consist in application of low noise and high gain amplifiers, introduction of an additional amplifier stage of controllable gain, depending on the signal volume and automatically controlled, and application of an ADC of higher than typical resolution. Algorithms for calculation of the voltage induced in the sensor coils, consist in determining the signal volume for a given exciting frequency with application of FFT or phase-sensitive detection.

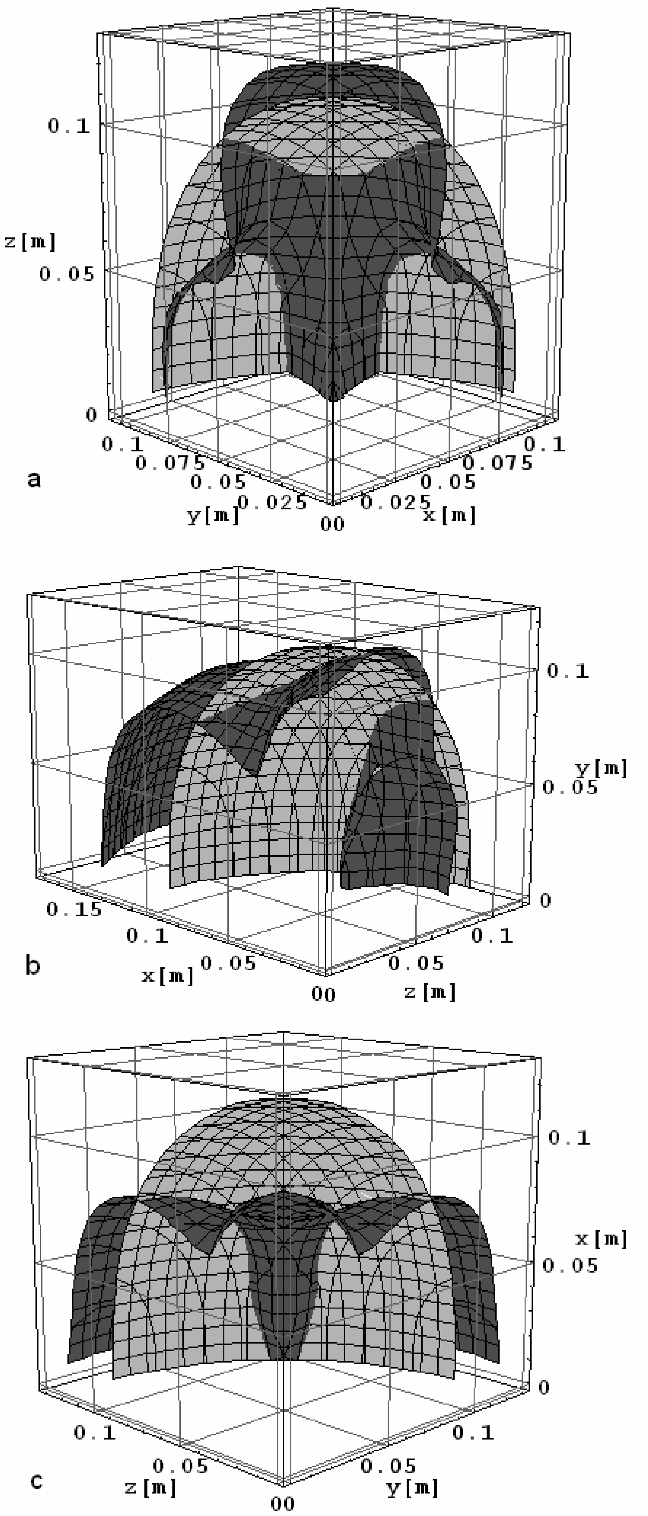

Fig. 2. The distribution of the acceptable position measurement error (the **dark-gray** contour corresponds to the value of 0.2 mm) and the maximal admissible magnetic field intensity (the **light-grey** contour corresponds to the value of 10 A/m) for three orthogonal coils (a, b and c, respectively).

4. REDUCTION OF THE INFLUENCE OF CONDUCTING AND FERROMAGNETIC OBJECTS PRESENT IN THE OPERATING AREA

4.1 Estimation of distribution of the position measurement error introduced by conducting objects

The first stage of works aiming to improve the electromagnetic navigation system immunity to the presence of conducting and ferromagnetic objects in the working space of the system or in its vicinity involves quantitative description of the distortions produced by such objects having geometry and dimensions corresponding to typical objects usually present in the operating room or surgery [10]. Computer modeling has been applied for this purpose. Deformations of the magnetic field distribution in the vicinity of the disturbing objects mentioned have been determined through the application of FEM (finite element method) for the sinusoidal alternation of magnetic field of different frequencies and, for comparison, also for the commuted DC field (rectangular waveform). On this basis a distribution of the positioning error caused by the presence of the conducting and ferromagnetic objects has been determined. Simulations were performed for the models corresponding to small, steel instruments located directly in the operating space as well as for the models of large conducting and ferromagnetic objects placed outside the operating space of the system but still in the operating room. Exemplary results obtained for the model of a long, slender instrument (e.g. chisel, blade or applicator) are presented in fig. 3 [11].

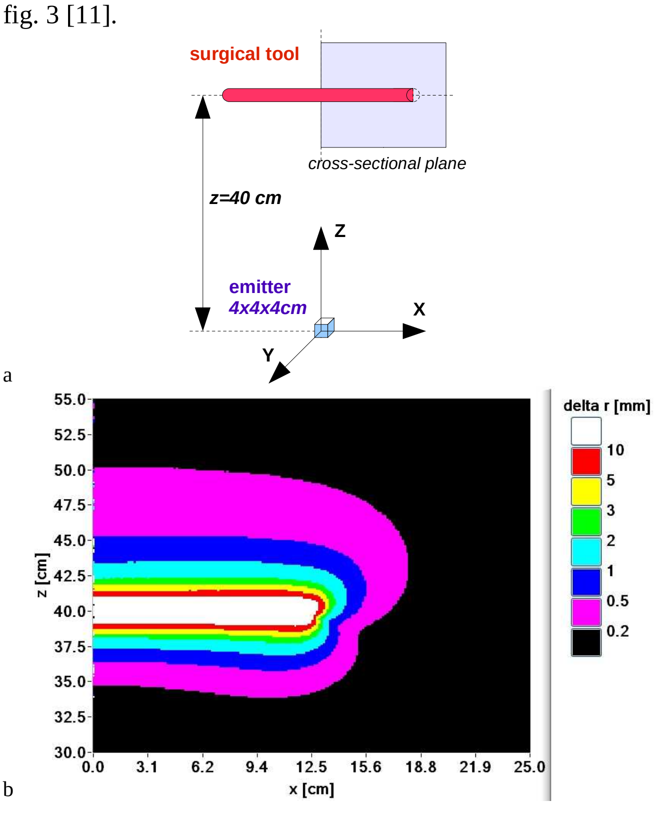

Fig. 3 Exemplary distribution of the navigation error caused by a long, slender surgical instrument: geometry of the arrangement (a) and the error Δr of determining the distance (b) – AC sinusoidal field of frequency 20 kHz applied.

4.2 The proposal of method of decreasing the influence of large objects on the position measurement error's distribution

On the basis of results of the conducted simulations, the methods of correction of disturbing influence of the objects of different size and shape, inserted inside the working space of the system and outside it have been proposed. In the case of large objects placed outside the working space, a simple and effective method seems to be such an arrangement of these objects in the operating room or surgery in which the area of deformation of the field distribution and the working space of the system do not superimpose. For this kind of objects the minimum necessary distance from the boundary of the working space depends on the required accuracy and can equal a few meters. Having in view an optimal arrangement of large objects one can use the reference sensor coil belonging to the system, located at the periphery of the working space. The object disturbing the field distribution should be moved towards the working space until the signal from the reference sensor coil changes.

4.3 The proposals of methods of decreasing the influence of large objects on the position measurement error's distribution

For small disturbing objects inserted in the working space two options have been considered: change of the shape of the exciting signal for rectangular waveform and lowering of frequency of the sinusoidal excited field. Because of the difficulty associated with measurements of weak DC fields in the background of strong noise it was decided to apply the second solution. However, it interrelates with lower sensitivity of the magnetic field sensors and complication of the design of the magnetic field generator. Solenoid coils of low dimensions, with steel core have been used as the magnetic field sensors. Their sensitivity is proportional to the frequency of the measured field.

Selection of the optimum frequency of the magnetic field alternations was performed applying FEM simulations. For the model of the metal object corresponding to a big surgical instrument the range of the acceptable position measurement error was determined for different values of the magnetic field's frequency. The selection of the optimum frequency should be a compromise between decreasing the harmful influence of the conductive objects and preserving the possibly good sensitivity of the system. The geometry of the model used in the simulations is shown in fig. 4 and the results obtained at different frequencies are shown in fig. 5. It was found that the compromise between the good sensitivity and the small range of disturbances is obtained at the frequency equal to 1 kHz.

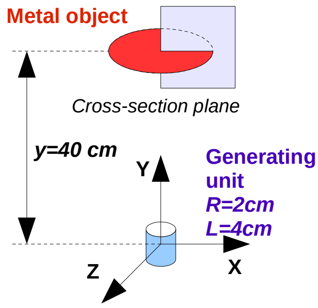

Fig. 4. Geometry of the model of a big surgical tool, dimensions of the disc: diameter 6 cm, height 3 mm, conductivity of material: $1.1 \cdot 10^6$ S/m

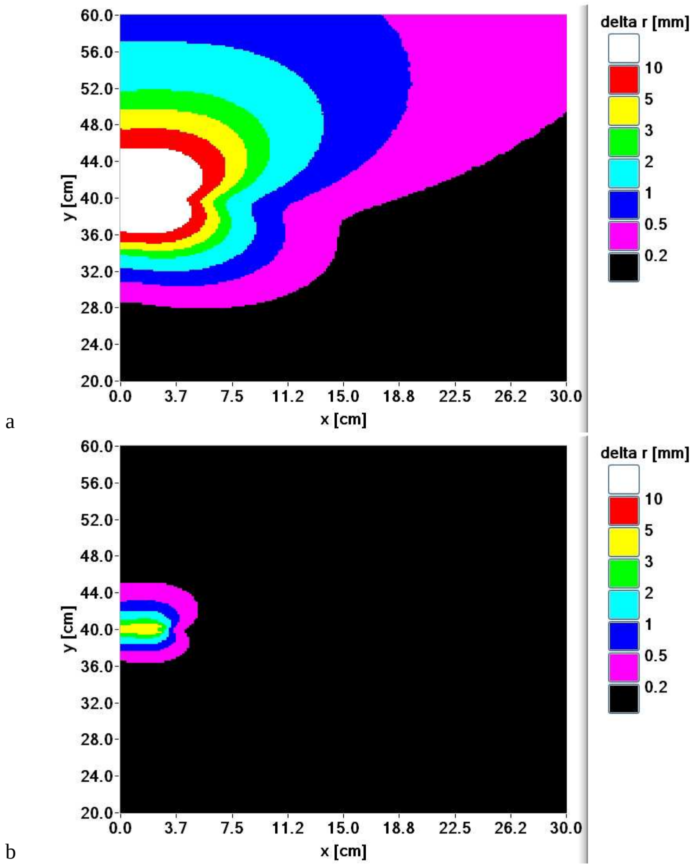

Fig. 5. Position measurement error for the model with geometry show in fig. 4 for the frequencies: 20 kHz (a) and 1 kHz (b)

The problem of lower sensitivity at lower frequencies can be solved by introducing an additional low-noise amplifier stage to the signal path, in the form of a controllable gain amplifier. Its gain should be set depending on the signal volume obtained from the sensor – this enables optimal use of the ADC dynamics. An improvement of the system's sensitivity decreased by lowering the frequency of the magnetic field can be obtained by increasing the intensity of the field. This is possible by replacing the set of mono-layer generating coils by a set of multi-layer ones.

Realization of experimental investigations performed with the use of real medical instruments is planned in the next stages of the research. It is aimed at: verification of the results of simulations, verification of the effectiveness of the methods of arrangement of large objects around the operating space, choice of optimal field frequency and estimation of the parameters of modified generating set.

5. MEASUREMENT SETUP, TOOLS FOR PROGRAMMING

Preparations for experimental works are drawing to a close. Investigations will be carried out with the use of a specially designed measurement setup enabling the location of the sensor coil in particular points of very precisely determined co-ordinates. The designed measurement setup is shown in fig. 6.

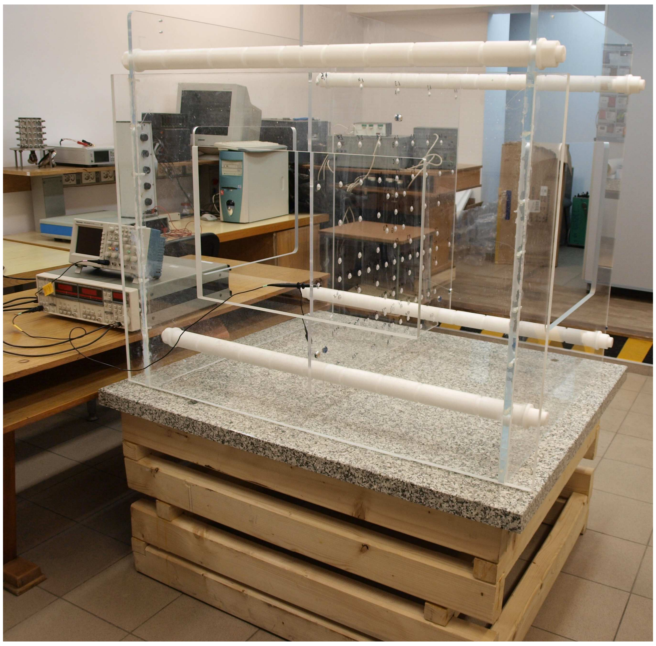

Fig. 6. The measurement setup for experimental studies of the navigation system

The sensors are long thin solenoid coils wound on ferromagnetic cores. Preliminary measurements are planned with the use of a vector voltmeter (lock-in amplifier). Further works involve using a measurement system designed especially for acquisition signals from many sensors. Finally, the full EM navigation system (fig. 7) will be completed and tested.

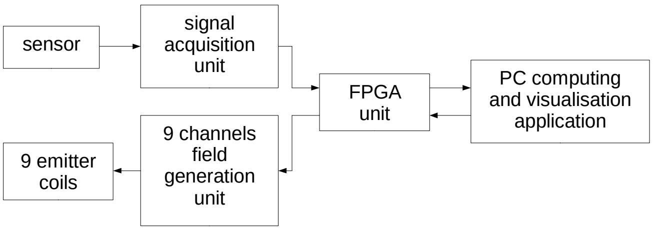

Fig. 7. System for electromagnetic (EM) navigation

FEM simulations were performed using the software package Comsol Multiphysics AC/DC [12]. Numeric calculations were carried out using Mathematica and Matlab packages and CVI National Instruments software.

6. SUMMARY

Some modifications of the electromagnetic navigation (EM) system, aimed at extension of the system working space without worsening the navigation accuracy, are described in this paper. Investigations of the disturbing influence of conducting and ferromagnetic objects worsening the accuracy of EM navigation are also presented there as well as the means enabling the improvement of the system immunity to the presence of such objects. Finite element method of modeling has been used for this purpose.

Efficiency of the proposed changes and improvements as well as results of the modeling and simulations will be verified in experimental tests of the system performed with the application of a specially designed precise measurement setup. Experiments with human body phantoms are also planned for the future.

6. ACKNOWLEDGEMENTS

This work has been financed by the Polish Ministry of Science and Higher Education, in the research project Nr N N518 382637.

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