Towards Real Time Imaging and Tracking of Human Organs for Surgical Navigation by Using Artifical Magnetic Fields and MEMS Magnetic Sensor Nodes

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***Abstract*— Towards real time imaging of human organs during medical surgeries for organ excision or tumor care, we have been engaged in developing a high-resolution tracking system by using artificial magnetic fields and 3D MEMS magnetic sensor nodes for years. This paper presents fundamentals of this approach, design and simulation of the electromagnetic system for the pursuit of unique magnetic fields with preferable spatial resolution, and configuration of the developed prototypes. The preliminary results reveal that spatial resolution of a few mm can be achieved after applying multi-pairs electromagnetics, which is powered by DC and AC signal respectively for noise cancellation as well as for rotation recognition. Moreover, temperature dependence, background noise of a surgical room, and many other specifications of the developed system were investigated, evaluated, and discussed herein.**

Keywords- surgical navigation; human organ; location tracking; magnetic field; MEMS sensor; MedTech innovation.

I. INTRODUCTION

Advances in electronic devices, robotics, and diagnostic techniques enable widely use of laparoscopic surgery for various diseases [1]-[3]. Laparoscopic surgery is less invasive to patients so quick recovery can be expected, but fatal bleeding may happen due to misunderstanding of vessels and its anatomical location by patient's posture change, etc., especially in the hepateetomy and pancreaticoduodenectomy [4]. Then, mental pressure will be introduced to surgeon during the operation since it is hard to find remedial measures in a very short time with limited capabilities of actions under endoscope. Developing a real time location tracking system for surgical navigation is thus essentially important, especially for liver excisions, which is believed one of the most complicated tasks, i.e., it was reported that third party mortality and 90-day in-hospital mortality rates were as high as 2.0% and 4.0% respectively even in Japan [5].

Trakstar® (Ascension Technology Corp.) [6] and AURORA® (Northern Digital Inc.) [7] are popular systems used for real time electromagnetic tracking of operative devices with imaged-guided simulation applications. Although there is no convincing evidence to suggest that exposure to high-frequency electromagnetic fields will cause any significant adverse health effect in humans [8], the system may introduce interferences to other medical instruments to a certain extend. In addition, due to big size and high cost of micro coils, which is used as the sensor to detect high frequency electromagnetic fields, practical application of above systems for human organs is somehow difficult. High sampling rate is required to achieve sub-mm spatial resolution, so wireless communication between sensors and the system is hard to be realized when number of the sensors increases intentionally.

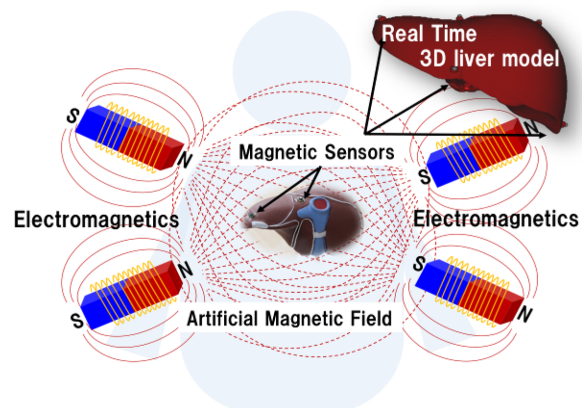

Figure 1. Principe of our proposed location tracking system by using multi-pairs electromagnetics and 3D MEMS magnetic sensors.

Figure 1 shows the principle of the proposed location tracking system. A 3D liver model is established prior to surgery by Computed Tomography (CT) and simulation tools. It is believed that human tissues, organs, etc., will have no effects to static magnetic field, therefore a few pairs electromagnetic are located around human body to create static and ultra-low frequency magnetic fields, in which intensity or direction is unique at individual locations. 3D MEMS magnetic sensors (AK09970, Asahi Kasei Corp.) are attached to specific points of the liver to track location by measuring corresponding intensity and direction of the fields. Tracking results from those sensors are used to update liver model image in real time during surgeries.

 ISBN: 978-1-61208-691-0

In this paper, besides fundamentals of this approach, design and simulation of the electromagnetic field, configuration and specifications of the developed wireless sensor nodes and the location tracking system, as well as preliminary evaluation results are presented in details, and then discussed.

In section 2 of this paper, system configurations will be presented. Experimental details and the results will be presented in section 3 together with discussions. And then, sections 4 will concludes this paper with future plans.

II. System Design and Configurations

To design preferred artificial magnetic fields for the pursuit of a few mm spatial resolution, an magnetic simulator was used to calculate its intensity and direction within the volume of $60 \times 60 \times 40$ cm^3. Figure 2 shows calculated results and measured results for comparisons. Distance of the two electromagnetics in each pair was set at 60 cm, and a magnetic path was included in between them to increase intensity at the center of the field. A DC power source was used to supply voltage up to 80 V, which insures that minimum vector intensity is no less than 3 mT, 2 orders bigger than that of earth magnetics.

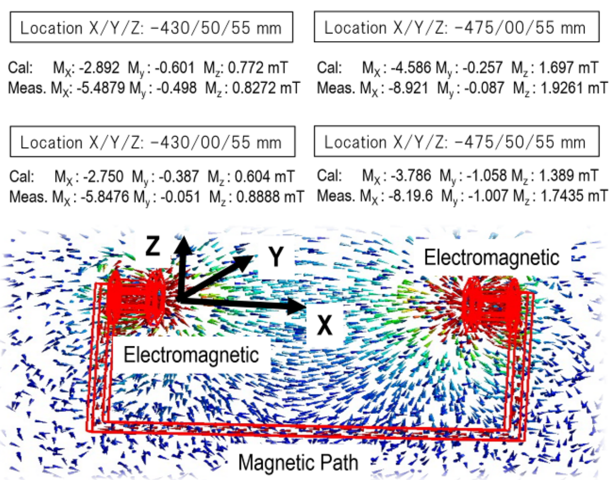

Figure 2. Simulated distribution of the magnetic field in one pair electromagnetics. The measured results are listed too for comparisons.

Figure 2 clearly reveals that the calculated distribution of the field fit well with the measured results, even though the individual data is slightly different due to the difference between model and actual profile of electromagnetics. It also indicates that experimental mapping of the field is essential to create database (also called 'map' in this work) for accurate location tracking. The measured resolution of the field was 76 uT/mm and 18 uT/mm in X and Y direction, respectively. It suggests that sensitivity (1.1uT/LSB) of selected 3D MEMS magnetic sensor is good enough to identify a few mm for surgical navigation as expected in this work.

Since intensity of the field dramatically decreases when its distance to electromagnetic increases, i.e., 3 mT at the center of the field while >30 mT at the surface of the electromagnetics, multi-pairs of electromagnetics were introduced in this system to compensate location variations, as well as to identify rotation of the sensor nodes. Figure 3 shows the photo of the developed 1st prototype system for further investigation and evaluation. To create the 'map' for navigation, a 3D robot with wooden arms were used to carry MEMS magnetic sensors for scanning, while a 3D camera system was used to record the actual location of the sensor simultaneously. Three pairs of electromagnetics were included in the system, among them, one pair was set up under the wooden desk for a more uniform distribution at the center of the field.

ON/OFF switching of all three pairs of electromagnetics in turn may help to separate the magnetic field created by each pair. However, as shown in Figure 4, it will lead to difficulties in real time tracking because 2-3 seconds is required to stabilize each magnetic field. Therefore, in this system, the three pairs of electromagnetics were powered simultaneously, among them DC signal was used in the first pair to create static magnetic field, AC signals with

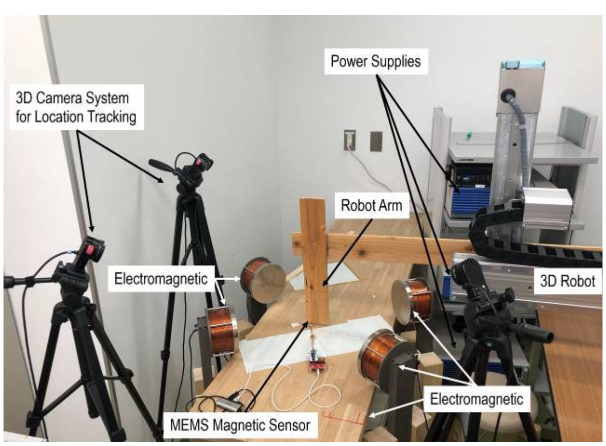

Figure 3. Photo of the develoepd location tracking system with 3D robot system and 3D camera system for further evaluation.

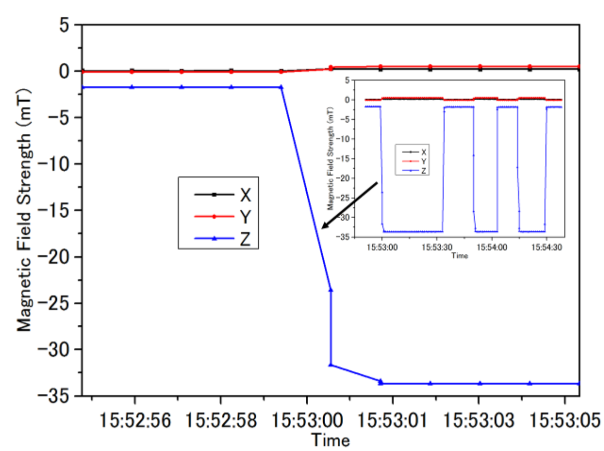

Figure 4. Maesured respponse of the magnetic field when ON/OFF the field by switching power supply.

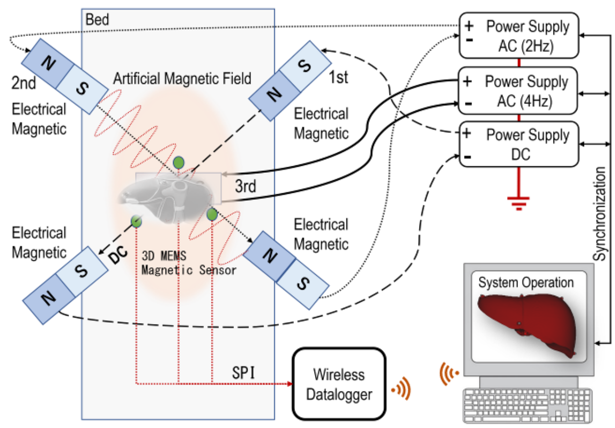

Figure 5. Configurations of the proposed system, which include multi-pairs electromagnetics and its power supply, 3D MEMS magnetic sensors and its signal processing unit, and PC.

frequencies of 1 Hz and 2 Hz were used in the second and the third pair to create ultra-low frequency magnetic field, respectively. Kalman filter [9] and self-developed algorithm were carried out to separate AC and DC signal from the mixed raw data recorded by MEMS magnetic sensors.

Another advantageous of above method is to identify artificial magnetic field from earth magnetic field and background noise by their frequency spectrum. Based on the above considerations and design, layout and configurations of the location tracking system is hen shown in Figure 5.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Backgound noise

Various types of medical devices and instruments are used in a surgery room to monitor physical signs and bio-logical information of a patient. Figure 6 shows measured electromagnetic noise, especially when turn on electrical knife for organ excision. The measured background noise, 20-30 uT (peak-to-peak value) as shown in Figure 6 (a), is similar or even lower than typical value of earth magnetics, indicating neglectable effects to the positioning system. Although the noise from electrical knife is 2-3 times bigger than background noise, it can be easily removed by using digital filter since its frequency (~0.25Hz) is much lower than that of the developed positioning system. The interferences of the developed positioning system to other medical instruments was not found yet in experiments.

B. Temperature dependence and stabilities

It was found in Figure 7 that temperature was stabilized in 15 min when AC signal was applied. Whereas, temperature of the DC signal powered electromagnetics was keep raising even 55 min after switch the power ON. However, the upper inset of Figure 7 clearly indicated that intensity of the magnetic field was stable without any noticeable dependence on temperatures, thanks to constant current mode of the power supply. Moreover, variation of the DC magnetic field was 300-500 ppm, which is reasonably good for a preferred system resolution.

Above results also suggested that minimum vector intensity of the field can be as small as 1 mT, while keeping system spatial resolution with no remarkable change. It enables us to use much lower power, much smaller electromagnetics, and remove magnetic path to further improve stability of the field. These works are ongoing in the 2nd prototype system.

C. Location tracking accuracy

To achieve a few mm spatial resolution, 1 mm pitch size is required when creating the navigation 'map' as described above. However, it may takes weeks or even months since there are millions of points within the volume of 60×60×

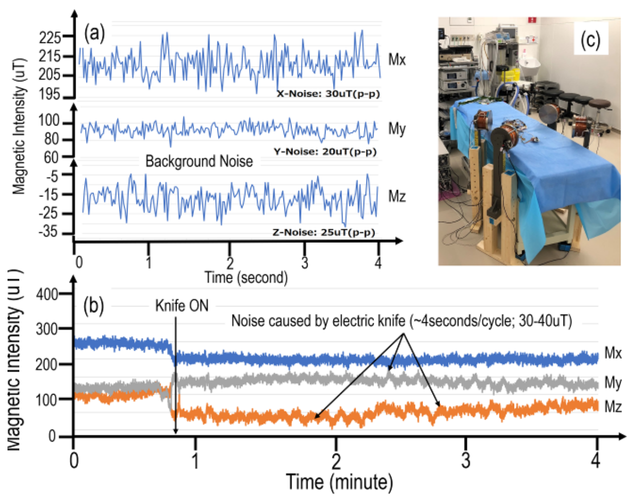

Figure 6. Measured electromagnetic noise in a surgery room (a); electromagnetic noise when using electrical knife a few cm far from the sensor (b); photos of the measurement system (c).

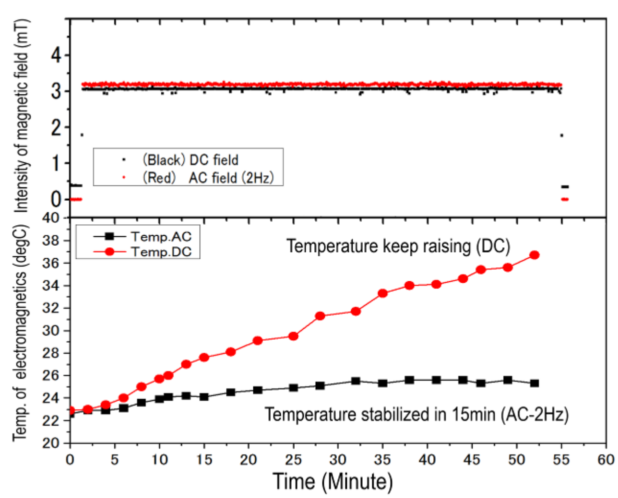

Figure 7. Measured temperature dependance of the electromagnetics and the magnetic field when powered by DC and AC signal, respectively.

 ISBN: 978-1-61208-691-0

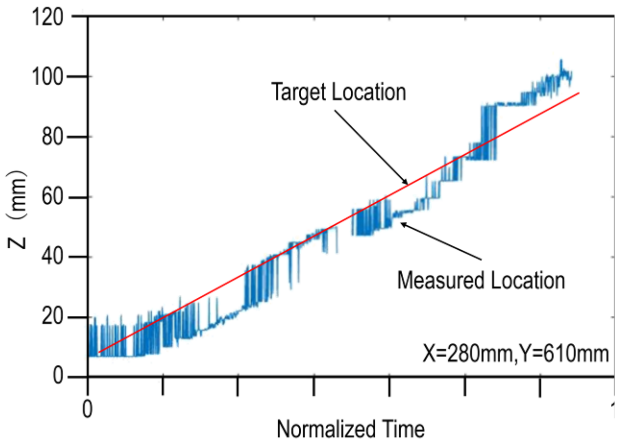

Figure 8. Measured and actual location in Z direction when X and Y was 280mm and 610mm, respectively.

40 cm^3. To demonstrate and evaluate resolution of the system, the pitch was set to 4 mm and created the 'map' within the volume of $8 \times 12 \times 12$ cm^3. As shown in Figure 8, about 11 mm spatial resolution was obtained. This preliminary result is not good enough for a practical application, but sufficient to prove this approach both theoretically and experimentally.

As demonstrated in 2D movement, 2-3 mm spatial resolution was obtained when the pitch size was set at 1 mm during 'map' creation. However, a simulation-based approach for quick database creation is believed necessary to improve efficiency, in which experimental mapping will be required only for system calibration. The lasted results indicated that 1 mm spatial resolution can be obtained, if the pitch size of the database is 1 mm. This work is on progress and the preliminary results are attractive. The details will be presented in future publications.

IV. Conclusions and Future Works

This paper presents the development and evaluation of a real time imaging and tracking system for surgical navigation by using artificial magnetic fields and MEMS magnetic sensor nodes. Spatial resolution of a few mm was achieved as the preliminary result. It is encouraging and promising at the current stage, while further development and improvement are necessary for practical applications.

As the next step of this work, we will focus on developing the simulation-based approach for creating navigation 'map', as well as system optimization for a better spatial resolution. Animal test is also on the schedule to investigate effectiveness of the system. Moreover, the state-of-the-art research results are not sufficient to draw any conclusions about potential health effects of static magnetic field exposure, while it needs further study to make it clear.

This paper strongly suggested that MedTech innovations, which is extremely important for modern society, can be accelerated by the advances in MEMS and sensing technologies.

Acknowledgment

This work is supported by Japan Agency for Medical Research and Development through "Technological development of a real-time navigation system for laparoscopic hepatectomy with wireless microsensor for tactile sensing and with position monitoring of instrument" project.

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