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A Real-time Localization System for an Endoscopic Capsule

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***Abstract*— This paper presents a real-time magnetic tracking system for an endoscopic capsule intended to deliver biomarkers around specific locations of the gastrointestinal (GI) tract. Unlike radio frequency (RF) and ultrasonic signals, static magnetic signals suffer negligible attenuation within the human body. The magnetic tracking systems proposed to date use a large number of sensors, making them too complex to apply in practice. In this paper, a new magnetic tracking system is proposed with much reduced complexity. In this system, the capsule only needs a magnet for localization, and does not require any electronics or battery. Mathematical model and a tracking algorithm were developed to find the location of a magnetic marker in the gut. Laboratory test results and *in vivo* animal trials show that the system is capable of tracking a magnetic marker with expected accuracy.**

Keywords—In vivo tracking, magnetic localization system, real-time tracking, gastrointestinal tract, endoscopic capsule.

I. INTRODUCTION

Gastrointestinal diseases such as Colon Cancer, Crohn's disease, Obscure GI Bleeding etc. are growing in the world, even in Western and Australian societies [1]. A health survey report issued by the Australian Institute of Health and Welfare (AIHW) in 2011 indicated that Colon Cancer was the second largest cause of death during 2007 and 2010 with a burden of 15% and 19% respectively [2]. These diseases play a vital role in changing the functional properties of the gastrointestinal (GI) tract, commonly known as the gut. This phenomenon in turn results in recurrence of the same diseases with worst symptoms.

Medical researchers need an engineering solution to reach the mid to distal regions of the GI tract in order to investigate the biological reasons causing the functional changes. The average length of the human GI tract is about 9m. Traditional instruments such as fiber optic endoscopes and colonoscopes have an average length of about 2.5m, and therefore cannot examine deeper into the GI tract [3] and are unable to analyze the causes of functional changes in the gut.

Wireless capsule endoscopes such as SmartPill, PillCam, Norika etc. have made the GI analysis much easier by eliminating the pain associated with the insertion of conventional scopes [4]. However, these devices do not possess the capability to examine the functional changes in the GI tract [5]. A possible solution to this problem is to deliver biomarkers at or near the affected spots in the gut and then monitor the response through clinical procedures such as breadth test [6].

Delivery of biomarkers to a specific region within the gut requires information about the real-time location of the capsule carrying the payload. This requires a system to track the capsule location in real-time. Such an *in vivo* tracking system can be realized using a variety of technologies, for example, radio frequency (RF), magnetic and ultrasound technology. RF and ultrasound signals suffer very large attenuations through human body [7, 8] while magnetic signal is almost immune to *in vivo* attenuations [6]. This makes the magnetic technology more suitable for *in vivo* capsule tracking.

A typical magnetic tracking system has a magnet placed inside the capsule. As the magnet travels down the gut, a number of magnetic sensors placed outside the body continually measure the magnetic field strengths. These magnetic field readings are used to determine the location of the capsule. Quite a few magnetic tracking systems have been proposed to date [9], [10], [11], [12], [13], [14], [15]. The majority of them use a large number of magnetic sensors often placed in a two dimensional array. Although the accuracies obtained by some of them are in the range of millimeters, however the systems are impractical to use in a real scenario due to their large size, bulk of cables and huge complexity.

This paper presents a tracking system for a swallowable endoscopic capsule, which uses a magnetic marker placed within the capsule for tracking. Mathematical model and tracking algorithm have been developed to determine the location of the capsule from the magnetic field strengths. The proposed tracking system is much less complex than the tracking systems reported to date.

II. THE PROPOSED TRACKING SYSTEM

In the proposed tracking system, a small permanent magnet (Neodymium) is used as the source of static magnetic field. The system also consists of magnetic sensors with on-board microprocessor for data acquisition, data pre-processing and communication.

The magnetic sensors are attached to a flat panel, which is to be placed in front of the gut to measure the magnetic field strength. The signals produced by each sensor are sent to its dedicated (on-board) microprocessor, which collects and stores the data and forward to a PC. A tracking algorithm running on the PC uses the magnetic signals from all the sensors and displays the calculated location of the magnet (capsule) and its trajectory in real-time.

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A. Magnet

For a magnetic tracking system, the selection of material, shape and size of the magnet is very important. It is understood that the Rare Earth Neodymium magnets ($Nd_2Fe_{14}B$) possess the highest field to size ratio [6]. It is also known that the cylindrical or rod shaped magnets produce a higher magnetization in air compared to other shapes like disk, ring, sphere, tube etc. [16]. In order to select the proper size of the magnet, experiments have been conducted to determine the characteristic curves of several cylindrical Neodymium magnets of different sizes. Fig. 1 shows the graphs of the magnetic field strength versus distance for magnets having sizes (Length × Diameter in mm) 10×2.5, 12×6 and 10×10. It is pertinent to mention that the magnetoresistive sensor provides the peak reading when the magnet is moved very close to the sensor. The magnetic sensor is in saturation in such a situation. The graphs indicate the points of saturation *S1*, *S2* and *S3* and the detection ranges *D1*, *D2* and *D3* for the three magnets respectively. From this, it is obvious that the 10×10 magnet has the highest detection range of almost 20cm, however, its saturation point (*S3*) starts from a distance of 5cm from the sensor. The saturation point *S1* for the 10×2.5 magnet is quite reasonable as it starts from about 1.5cm from the sensor, but its detection range of 11cm is insufficient. The detection range for the 12×6 magnet is almost 15cm with the point of saturation (*S2*) starting from 4cm. The anatomy of human gut suggests that if the average diameter of the body around the gut is 30cm, the separation between the outer wall and the small intestine will always be greater than 4cm from any side. So, it can be concluded from the above experiments that the magnet with size 12×6, as shown in Fig. 2, is suitable for use with our tracking system.

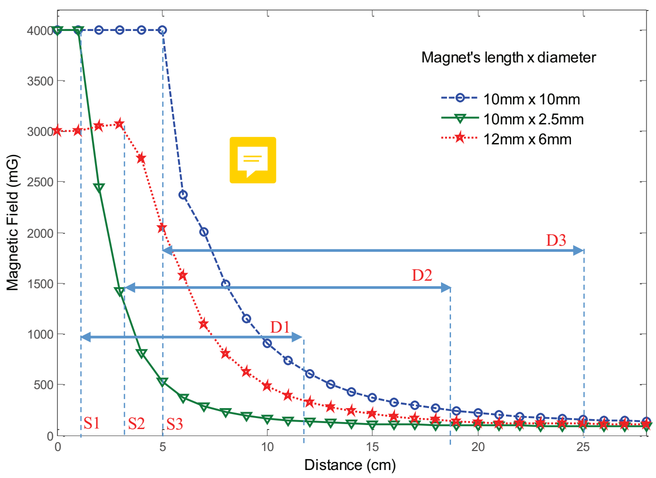

Fig. 1. Experimentally obtained characteristic curves for cylindrical magnets

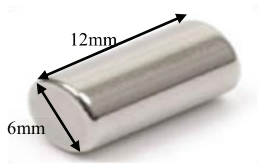

Fig. 2. A 12mmx6mm Neodymium magnet

B. Magnetic Sensors

The PNI RM3000 magnetic sensor suite has been used to measure the magnetic field strength. The RM3000 is an integrated magnetic field sensing module with highest accuracy in their class, a large magnetic field measurement range, high resolution, low power consumption, and large signal noise immunity under all conditions. It is also highly stable over temperature. Each RM3000 sensors suite has the ability to detect the magnetic field in three perpendicular axis (X, Y, Z) using three physical sensors. We identify them as SX, SY and SZ. The sensitivity of the sensors is inversely related to the sampling rate.

- At the highest sampling rate of 2.4 KHz/Axis, the sensor's resolution is ~140 nT
- At the lowest sampling rate of 300 Hz/Axis, the sensor's resolution is ~15 nT

In the proposed system, the sensor is set at the highest sensitive mode to achieve the highest Signal to Noise Ratio (SNR). The RM3000 sensor suite has a SPI interface for data communication. The SPI interface includes *CE (chip enable), MOSI (master output, slave input), MISO (master input, slave output), clock (SCLK)*, *data ready (DRDY)* and *CLEAR*. To read the data from the RM3000 sensor, the microprocessor must read each axis separately. The SPI interface shifts out a 24-bit field measurement value for each of the three axis which represent the three orthogonal components of magnetic field density i.e. B_x, B_y and B_z. The resultant magnetic field B, its azimuth angle θ and elevation angle φ are calculated from these values using (1), (2) and (3) respectively [17].

$$|B| = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{1}$$

$$\theta = \tan^{-1}\left(\frac{B_y}{B_x}\right) \tag{2}$$

$$\varphi = 90 - \cos^{-1}\left(\frac{B_z}{B}\right) \tag{3}$$

C. Processor board and communication module

The PNI RM3000 magnetic sensors suite is connected to a microcontroller board via a daughter board. The microcontroller board is based on the ATmega328 microcontroller. It communicates with the RM3000 sensors via SPI interface. The received magnetic field intensity data can be stored in the internal memory of the microcontroller and transmitted to a PC for further processing. Communication between the microcontroller and the PC is via USB interface or Zigbee wireless communication. Fig. 3 shows the microcontroller board with RM3000 sensor suite and XBee Zigbee wireless transceivers.

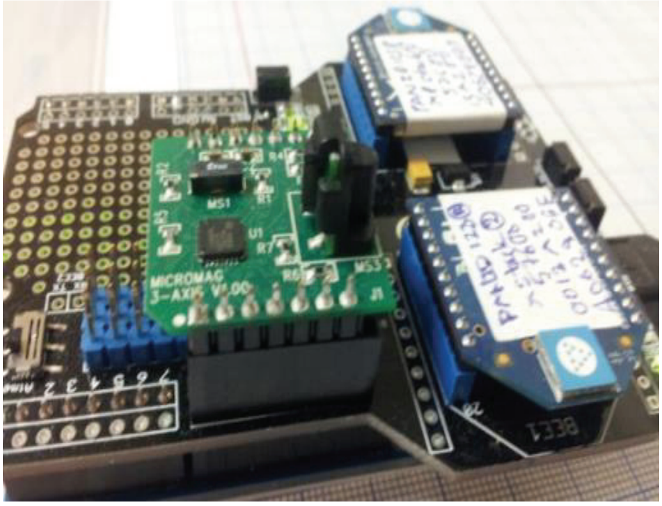

Fig. 3. Microprocessor board with magnetic sensors and wireless transceivers

D. Sensor location

In order to correctly locate the magnet, we must know the field strength as well as the location where the sensor measured the field. This means that the exact location of each of the sensors must be known and this location must be fixed for all measurements. For this reason, the sensors are mounted on a flat plastic base. This base ensures that the locations of the sensors do not change and that their relative positions to each other are fixed. The base also provides information about the location of each sensor in 3D.

The reference point (0, 0, 0) of the system is marked with a blue circle as shown in Fig. 4. Location of each sensor is marked with a red circle. From this arrangement, the locations of all 4 sensors were identified as shown in Table I.

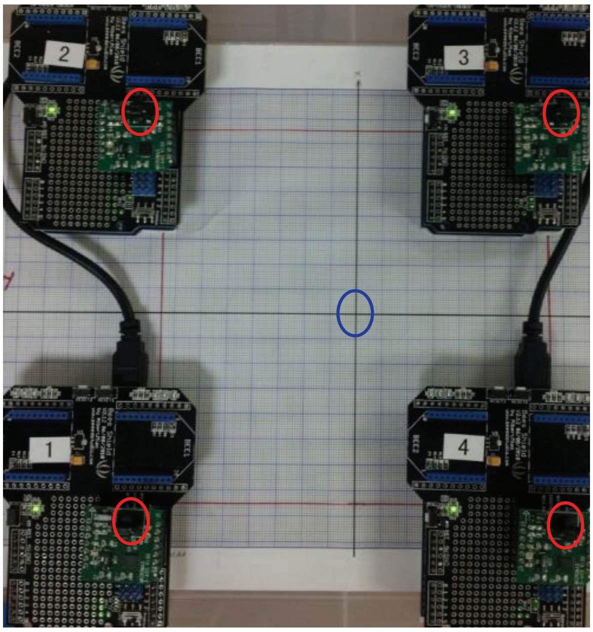

Fig. 4. System setup with four 3-axis magnetic sensors

TABLE I. SENSOR LOCATIONS

Sensor #	SX (x,y,z) mm	SY (x,y,z) mm	SZ (x,y,z) mm
1	(-75,-75,0)	(-75,-75,0)	(-75,-75,0)
2	(75,-75,0)	(75,-75,0)	(75,-75,0)
3	(75,75,0)	(75,75,0)	(75,75,0)
4	(-75,75,0)	(-75,75,0)	(-75,75,0)

As stated previously, each sensor board has three physical sensors: SX, SY and SZ. The sensor SX measures the magnetic field along the X-axis, SY measures the field along the Y-axis, and SZ measures the field along the Z-axis. Locations of SX, SY, SZ are shown in Table I.

E. Communication of magnetic data to PC

The microcontroller is programmed to control the timing of all the signals. It also processes the data and transmits it to a PC via a USB hub. The present system is set up using wired communication between the sensors and the PC. In future, wireless communication can be used between the sensors and the PC using a reliable protocol similar to the one presented in [18].

F. Noise and sensor calibration

It is important to ensure that each of the *three-axis sensors* on each sensor board is calibrated properly. The criterion used for calibration of the individual axis sensors (X, Y, Z) is the fact that the overall magnitude of the field $|B|$ (as per Eq. 1) should not vary irrespective of the orientation of the sensor board. The Earth's magnetic field is used as a reference field for this calibration. The calibration process essentially removes the outliers by comparing with the reference field. Fig. 5 shows the Earth's magnetic field measured before calibration and Fig. 6 shows the same field after calibration. Clearly, the field magnitude is much more stable after calibration.

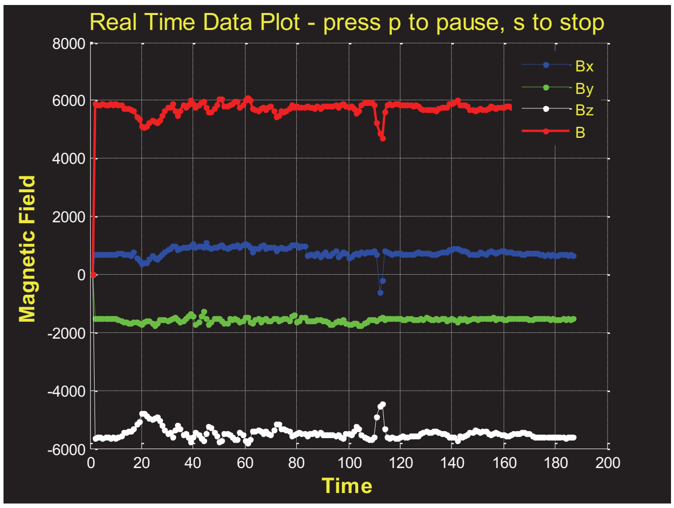

Fig. 5. Uncalibrated sensor data

The signal to noise ratio of the system was also determined. Fig. 7 shows the white background noise and Fig. 8 shows the signal level when using a 6x12mm magnet. Obviously, the noise range of +/- 20uG is very small compared with the signal level of 2G.

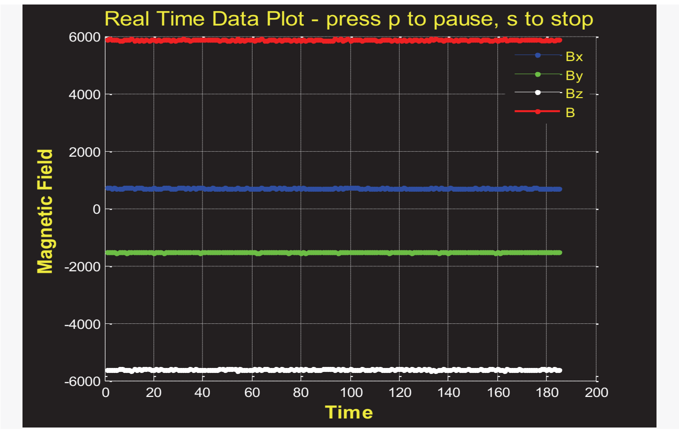

Fig. 6. Sensor data after calibration

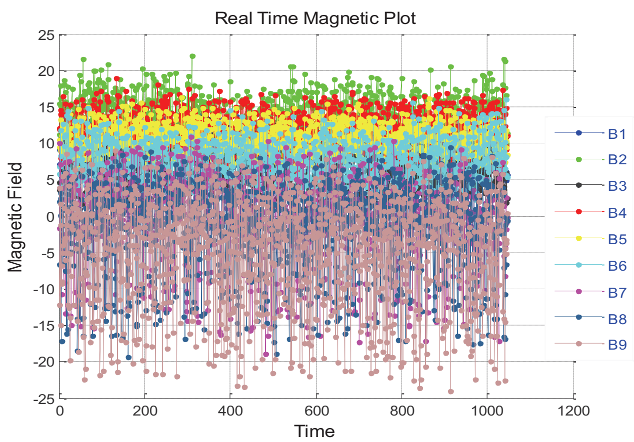

Fig. 7. Noise level of the sensor system in micro Gauss

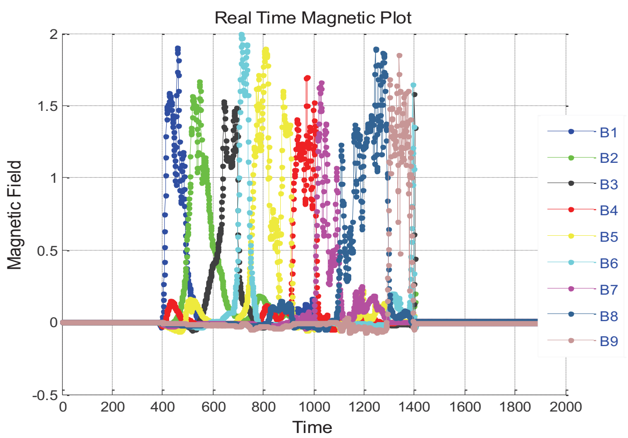

Fig. 8. Signal level the sensors system in Gauss

III. TRACKING ALGORITHM

A. *Magnet localization*

The magnet contained in the swallowable endoscopic capsule can be tracked inside the GI tract using multiple sensors placed outside the body around the gut region at pre-determined locations. Four 3-axis magnetic sensors are used and their fixed locations on the plastic base were shown in Table I. The problem can be considered as one of finding the location and orientation of a magnet whose calculated magnetic field most closely matches the field measured by the sensors at their respective locations. The calculation of the magnetic fields are done using mathematical models developed, however they are not presented here due to limitation of space. Instead, our focus in this paper is on the practical application and experimental results to determine the suitability of such a system for capsule localization. The problem as described above is a non-linear optimization problem to solve for the six parameters describing the position and orientation of the magnet.

Several nonlinear minimization algorithms have been reported, e.g., Powell's [19], Downhill Simplex [20], DIRECT [21], and Levenberg-Marquardt Algorithm [22]. These algorithms normally require an initial estimation of the parameters to begin the search for the minimum. If the initial estimation is too far away from the correct solution then these algorithms may fail because there may be many local minima. Besides that, the minimization algorithm should be fast enough to enable real-time implementation and should also be robust to noises in the sensor data. Comparing all the algorithms mentioned above, we come to the conclusions that the Levenberg-Marquardt Algorithm(LMA) is a suitable algorithm for our application as it provides satisfactory tolerance for initial estimated parameters, and fast search speed.

B. *Localization results*

Fig. 9 shows some tracking positions performed in the laboratory using the four sensors and the 6x12mm magnet. The magnet's positions is given in red and the sensor locations are given in blue. This example shows a test with the magnet move up and down above the sensors.

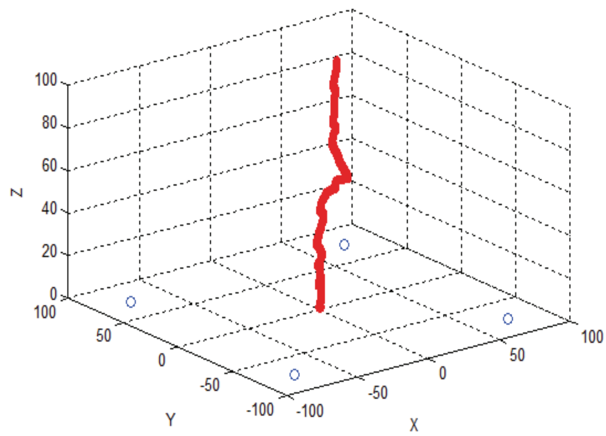

Fig. 9. An up-down trajectory test

C. Field test with animal model

The proposed tracking system has been used to track a magnet inside a capsule which was swallowed by pigs. Location of the magnet inside the pig's body is determined by the tracking system. Fig.10 shows the pig under test with the tracking system placed on its side. Four X-rays were taken during the tracking to cross check the magnet's location with those shown on X-rays. Fig.11 shows the location of the magnet as marked on the body of the pig. This location is verified by X-ray as shown in Fig.12. Test results show that the system is capable of tracking a magnetic marker inside the pig under test with expected accuracy.

Fig. 10. Pig under test with the tracking system

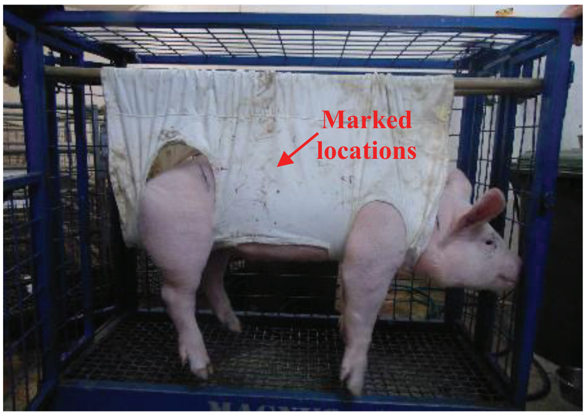

Fig. 11. Location of the magnet is determined and marked on the pig

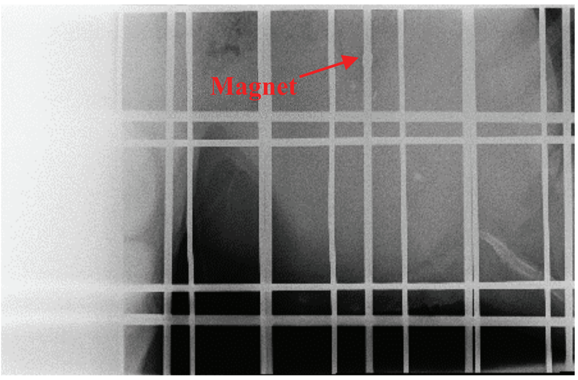

Fig. 12. Location of the magnet is verified by X-Ray

IV. PERFORMANCE COMPARISON

In vivo tracking systems can be compared on the basis of accuracy, cost, complexity, portability and patient's comfort etc. Table II shows a comparison of the proposed system with existing *in vivo* magnetic tracking systems reported to date.

TABLE II. COMPARISON WITH OTHER SYSTEMS

Work	Number of Sensors	Sensing Volume (cm3)	Algorithm	Error
Proposed	4	20x20x20	LMA	5mm
[6]	3	10x10x10	?	10mm
[11]	25	30x30x30	Linear	4.2mm
[12]	16	12x12x10	LMA	4.0mm
[13]	16	24x24x?	LMA	2.0mm
[14]	80	?x?x?	LMA	2.1mm
[15]	16	50x50x50	LMA	4.5mm
[17]	64	40x25x40	LMA	3.9mm
[23]	16	24x24x?	LMA	4.6mm
[24]	49	?x?x?	LMA	3.3mm
[25]	64	50x50x50	LMA	5.0mm
[26]	64	?x?x?	LMA	3.0mm
[27]	16	10x10x10	LMA	3.3mm

? These dimensions were not found in these papers.

For some existing systems, information on the measurement volume is missing or given partially [13],[14],[23],[24],[26]. In [6], the magnet used has a volume that is 1.4 times that of the one used in the proposed system and also testing is conducted in a measurement volume that is 8 times smaller. Yet the average error in [6] is 2 times that of the proposed system. In [11], the error is slightly lower, however it uses 25 sensors as opposed to only 4 used in the proposed system. In [12], the error is 20% lower than that of the proposed system, however the measurement volume is 8 times smaller and uses four times the number of sensors as compared to the proposed system. In [13], although the error is much smaller, the information on measurement volume is incomplete. [14],[17],[24],[25] and [26] use a significantly large number of sensors to inhibit their practical use. The error reported in [15] and [23] are comparable to that of the proposed system but they both use four times the number of sensors compared to the proposed system. Also, [15] uses a complex arrangement of two permanent magnets placed 10cm apart, and therefore is impractical to use in a swallowable endoscopic capsule. In [27], although the error is lower than that of the proposed system it uses 4 times the number of sensors and the measurement volume is 8 times smaller than that of the proposed system. From the above it is clear that the proposed tracking system provides a significant reduction in complexity (number of sensors) of the *in vivo* tracking system. Its tracking accuracy is better than the majority of tracking systems reported to date.

V. Conclusions

A new *in vivo* magnetic tracking system has been presented in this paper to determine the real-time location of an endoscopic capsule. Using only four 3-axis magnetic sensors, the proposed tracking system achieves high localization accuracy. This is quite acceptable for the intended application of biomarker delivery in the gut. Although there are quite a few tracking systems reported in literature, the majority of them uses many more sensors than the proposed one and do not provide much advantage in terms of accuracy. Unlike other tracking systems, the proposed system has been used in animal trials involving pigs, and its operation has been satisfactorily verified. Test results obtained from the animal trials have demonstrated the potential of the system to be used in human. The low complexity and high tracking accuracy of the proposed system make it suitable for *in vivo* tracking of a magnetically marked endoscopic capsule.

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