Magnetic Sensing Technology for *In Vivo* Tracking

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***Abstract*—This paper presents the viability of magnetic sensing technology for a low-cost, efficient and comfortable *in vivo* tracking system. The proposed tracking system is used for real-time localization of an endoscopic capsule intended for targeted drug delivery in the human gut. Magnetic sensing technology provides the optimum solution for *in vivo* tracking with much better performance than RF and ultrasounds. A modified mathematical model is used to find the distance between the magnet and the sensor. A linear tracking algorithm is developed to find the coordinates of the capsule in real-time. The paper also presents the system testing results for various sensor configurations. The minimum average error achieved is 1.82cm/9.1% with eight magnetic sensors in a 2-plane sensor configuration.**

***Index Terms*—Magnetic tracking system, *in vivo* tracking system, real-time magnetic tracking, gastrointestinal (GI) tract, magnetic technology.**

INTRODUCTION

Gastrointestinal diseases like Bowel Cancer, Obscure Gastrointestinal Bleeding (OGIB) etc. are very common in third world countries and growing even in Western and Australian societies due to various reasons. A health report by Australian Institute of Health and Welfare (AIHW) reveals that Bowel Cancer has been the biggest burden in 2010 out of all cancer cases and is included in the list of Australian national health priority area [1]. Such diseases may recur with worst symptoms due to changes in the functional properties of the GI tract. The traditional GI examination tools such as the fiber optic endoscope and colonoscope cause pain and discomfort for the patients during examination [2]. Moreover, these traditional instruments have a limited length of about 2.5 meters as compared to 9 meters length of the GI tract, so they cannot approach the mid to distal region of the GI tract.

Wireless endoscopic capsules have eliminated these difficulties and made the examination of the GI tract quite easier and comfortable [3]. These devices contain a miniature camera and/or pH and temperature sensors, RF transmitter, battery and associated electronics encapsulated in a swallowable material. A number of such devices exist today such as PillCam, SmartPill, Norika, Miro etc. However, none of these devices has the capability to deliver drugs in the gut to investigate the biological reasons of changes in GI functional properties [4].

Medical researchers need an engineering solution to reach the deeper regions of the GI tract to investigate the reasons of changes in the GI functional properties due to diseases, ageing or any other factor. One possible solution may be to deliver biomarkers at the affected spots of the GI tract and then analyze the response through breath tests [5]. This objective may be achieved by developing a new device called '*endofunctional*' capsule with an externally controllable drug delivery mechanism. The delivery of biomarkers at the designated spots can only be achieved if the real-time location of the capsule is known. The diagram in Fig. 1 shows a symbolic model of an envisaged *endofunctional* capsule.

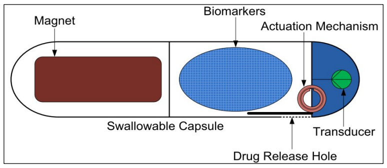

Fig. 1. The envisaged endofunctional capsule

Recent research literature has revealed that many *in vivo* tracking systems have been proposed to date. In [6], [7], [8], *in vivo* tracking systems have been proposed using radio frequency (RF) technology. Similarly, various tracking systems using magnetic sensing technology have also been proposed as in [9], [10], [11]. Almost all of them use large number of sensors (16 to 80) resulting in high system cost, complexity unreliability and discomfort for the patient due to large size of the systems. These systems use a mathematical model which is not optimized for real magnetic field distribution around a permanent magnet. The ultrasonic technology has also been used for this purpose [12]. Both RF and ultrasound signals face a variable attenuation due to absorption in various organs of human body [13]. Another major drawback with RF and ultrasound is the need of a constant, reliable and non-toxic source of power inside the capsule. In contrary, the magnetic signals are neither attenuated nor harmful for any human organ. This technology is also free from the need of any power source in the capsule. These features make the magnetic technology most suitable for *in vivo* tracking.

In this paper, we have proposed a real-time *in vivo* tracking system using magnetic sensing technology to determine the position of an endoscopic capsule in the GI tract. A linear tracking algorithm has been developed to locate the magnetic marker, in conjunction with a mathematical model which relates the magnetic field strength with the distance and orientation of the magnet with respect to the sensor. A customized data acquisition board has been developed to digitize the sensors' analog signals and transmit them to PC for real-time calculation of position.

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SYSTEM DESIGN

The proposed tracking system, as shown in Fig. 2, consists of a cylindrical permanent magnet, magnetic sensors, custom-designed data acquisition board and a PC for data processing and displaying the real-time location of the magnetic marker.

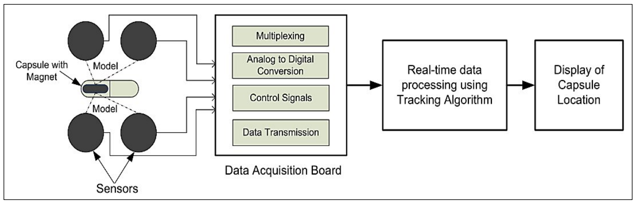

Fig. 2. Block diagram of the tracking system

The capsule houses a small yet strong permanent cylindrical Rare Earth Neodymium ($Nd_2Fe_{14}B$) magnet. To measure the incident magnetic field strength, we have used eight Honeywell 3-axis HMC2003 magnetic sensors. Each magnetic sensor measures three orthogonal components i.e. B_x, B_y and B_z of the incident magnetic field (B) and then provides three analog voltages depending on the orientation and distance of the magnet with respect to the sensor.

The analog voltage signals from eight sensors are applied as inputs to three 16×1 analog multiplexers, each selecting one signal at a time depending on the value of 'select lines' generated by the microcontroller. The selected signals are digitized sequentially in the microcontroller using a 10-bit ADC. These values are sent to the PC through standard serial port and processed using the developed tracking algorithm to measure and display the position of the capsule in real-time. The microcontroller (ATMega32A) is programmed to control the timings of all the processes in the data acquisition board. The developed tracking system with eight magnetic sensors and data acquisition board is shown in Fig. 3.

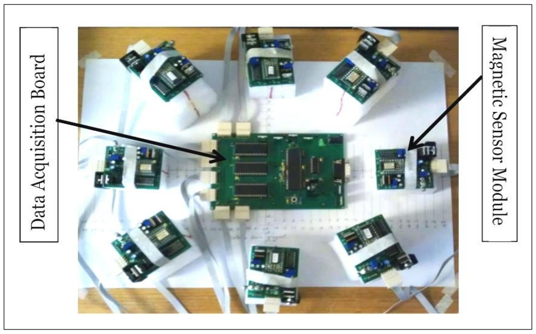

Fig. 3. Complete magnetic tracking system

MATHEMATICAL MODEL

Assume a cylindrical permanent magnet of radius r and length L is placed at the center of Cartesian coordinates system, as shown in Fig. 4. We want to find the magnetic field strength at a distant point P(a,b,c) located at a distance of R from the origin O. The projection of point P on xy-plane is P'. The azimuth angle of point P with respect to x-axis is θ, while the elevation angle is ⍰. The magnetic moment M_T of the cylindrical magnet can be found as [14]

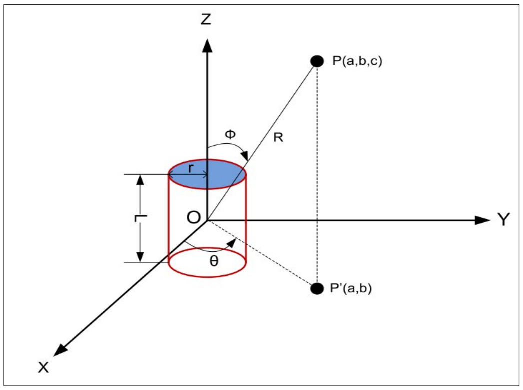

Fig. 4. Cylindrical magnet in Cartesian coordinates system

$$M_T = \pi r^2 M_0 \qquad (1)$$

$$M_0 = Flux \times \frac{L}{\sqrt{4(L^2+r^2)}} \qquad (2)$$

where, $Flux$ indicates the residual magnetic flux of the magnet. To determine the accurate relationship between the magnetic field density (B) and the distance R, we have modified the mathematical model already used in [9],[10] using MATLAB. The modified model is given as

$$B = \frac{\mu_0 . \mu_r . K M_T}{4\pi}\left(\frac{3(H.\vec{R})\vec{R}}{R^2} - \frac{H}{R^5}\right) + F_0 \qquad (3)$$

where, K is an empirical constant, μ_0 is the permeability of free space, μ_r is the relative permeability of medium (human body), F_0 is the offset value of magnetic field strength, R is the distance OP and H is the vector representing the orientation of the magnetic field in space. The orientation vector H can be described by the azimuth and elevation angles θ and ⍰ respectively. The values of K and F_0 are used to adjust the curves, in order to minimize the error in distance measurement. Equation (3) is plotted in Fig. 5 for magnetic field density as a function of distance for various orientations of the magnet. This behaviour provides a close match to the actual behaviour obtained through vigorous experiments performed on a permanent cylindrical magnet [15]. The received magnetic field density consists of three orthogonal components B_x, B_y and B_z measured by 3-axis magnetic sensor and can be described as

$$B = B_x i + B_y j + B_z k \qquad (4)$$

The resultant magnetic field B and its orientation (⍰ and ⍰) in space with respect to origin can be determined by the following equations.

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{5}$$

$$\theta = \tan^{-1}\left(\frac{B_y}{B_x}\right) \tag{6}$$

$$\phi = 90 - \cos^{-1}\left(\frac{B_z}{|B|}\right) \tag{7}$$

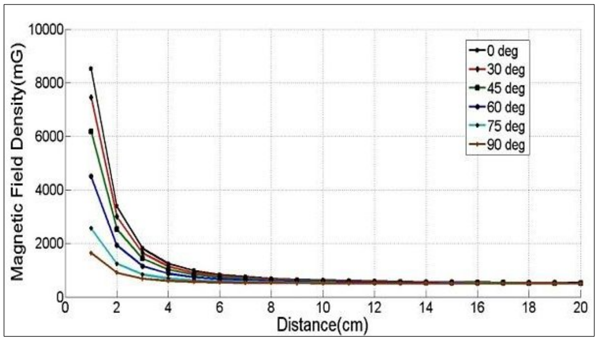

Fig. 5. Graphical plot of the model in (3)

LINEAR TRACKING ALGORITHM

The magnetic marker can be localized using multiple sensors arranged around the gut at known locations. Assume there are N magnetic sensors placed in a 2D plane at locations $S_i(X_i, Y_i, Z_i)$ with i = 1,2,3...N. As shown in Fig. 6, the distance R_i between the magnet at position $P(a,b,c)$ and i^{th} sensor can be determined as

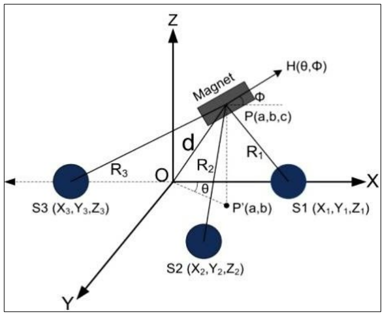

Fig. 6. Tracking magnetic marker using multiple sensors

$$|R_i| = \sqrt{(a - X_i)^2 + (b - Y_i)^2 + (c - Z_i)^2} \tag{8}$$

Since there are three unknown variables *(a,b,c)* in the above equation, so we need at least three equations to find them. We have developed a real-time tracking algorithm by writing the equations for relative distances of the magnet from three adjacent sensors [15]. Solving the intermediate equations, the position coordinates *(a,b,c)* can be determined using a matrix of nonhomogeneous equations as

$$\begin{bmatrix} K_{x12}^{-} & K_{y12}^{-} & K_{z12}^{-} \\ K_{x23}^{-} & K_{y23}^{-} & K_{z23}^{-} \\ K_{x31}^{-} & K_{y31}^{-} & K_{z31}^{-} \end{bmatrix} . \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} K_{12} \\ K_{23} \\ K_{31} \end{bmatrix} \tag{9}$$

where, the constants $\left[K_{xij}^{-}, K_{yij}^{-}, K_{zij}^{-}\right]$ and K_{ij} contain the information of 3D position and the measured distance of sensors with respect to the magnet. Equation (9) can be solved for *a*, *b* and *c* using Cramer's rule. Similar matrix equations are obtained for other adjacent troika of sensors like (2,3,4), (3,4,5) and so on. By this way we obtain eight different values of the same point P with respect to the origin O. The mean point is obtained by performing triangulation on these points. The error is calculated between the measured and the actual position of the magnetic marker. Finally, the overall error (E_{avg}) is calculated by the following formula.

$$E_{avg} = \frac{\sum E_{rms,i}}{N} \tag{10}$$

EXPERIMENTS AND RESULTS

For the testing of the tracking system, we have used a 12mm (L)x6mm(Dia) Neodymium permanent magnet with eight magnetic sensors and a customized data acquisition board. The magnet is placed at various arbitrary locations inside a cube having a volume of 20x20x20cm^3. The eight sensors are arranged in three different configurations as shown in Fig. 7.

(a) Config 1 (b) Config 2 (c) Config 3

Fig. 7. Sensor configurations for testing

These configurations are chosen to obtain the optimum tracking performance. The graph indicating the values of error at various locations of the magnetic marker is shown in Fig. 8. The average errors obtained for these configurations are 2.83cm/14.15%, 1.82cm/9.1% and 3.33cm/16.65% respectively. The minimum average error is achieved for second configuration in which the error generally stays between 2-3cm. The average error for first and third configuration rises to almost 8cm for those locations of the magnet where it lies out of detection range of most of the sensors.

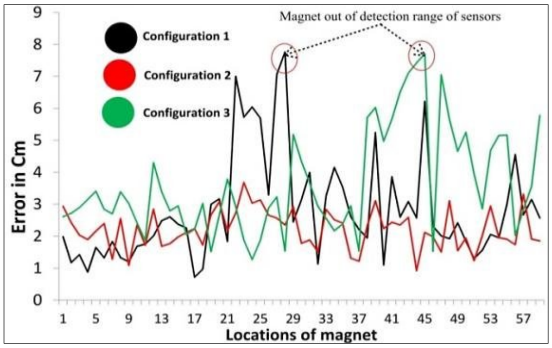

Fig. 8. Tracking results for three sensor configurations

PERFORMANCE DISCUSSION AND COMPARISON

The *in vivo* tracking systems can be compared on the basis of accuracy, system cost, patient's comfort, complexity etc. The parametric comparison of the proposed system with existing magnetic tracking systems is shown in TABLE I. The parameter 'Complexity' includes hardware, model and algorithm. The estimation of cost is derived from the number of sensors used in the system.

TABLE I: Parametric comparison table

Article	Sensors	Error	Comfort	Complexity	Cost
This paper	8	9.10%	High	Less	Less
[10]	16	2.75%	Mod	More	More
[11]	25	12.5%	Mod	More	More
[16]	64	Un	No	Much	High
[17]	16	8.33%	Mod	More	More
[18]	80	Un	No	Much	High
[19]	64	10%	No	Much	High

Un: Unknown, Mod: Moderate

For some tracking systems[16],[18], the value average error is not provided, so a fair comparison cannot be made with those. It is obvious from TABLE I that the proposed system has some features better than the existing tracking systems. The proposed system is less complex than others in terms of number of sensors, hardware, model and tracking algorithm. The average accuracy of about 91% is reasonable to detect and track a magnetic marker in the gut. Our system uses only eight sensors, so the patient will be more comfortable during the examination as compared to using others with 16-80 sensors shown in TABLE I.

CONCLUSIONS

The viability of magnetic sensing technology for a low-complexity *in vivo* tracking has been proposed in this paper. A modified mathematical model has been used along with a new linear tracking algorithm in order to calculate the coordinates of the magnetic marker in real-time. The complete system is tested using a cylindrical permanent magnet in a volume of 20x20x20cm^3 and with three different sensor arrangements. A minimum average error of 1.82cm/9.1% is achieved for a 2-plane sensor configuration. The achieved accuracy is reasonable to sense the magnet in the GI tract. The potential applications of the proposed tracking system may be to obtain the biological profile of the gut by testing the drugs having various concentrations. It may also be used to predict the problems in the gut by obtaining the velocity profile of the capsule and then comparing it with the biological profile.

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