A Novel and Compatible Sensing Coil for a Capsule in Wireless Capsule Endoscopy for Real Time Localization

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***Abstract*—Three orthogonal sensing-coils for six degrees of freedom (DOF) localization, translation (x, y, z) and rotation (α, β, γ), are designed and experimentally verified. The sensing method is intended for the use in Wireless Capsule Endoscopy (WCE). The coils are rectangular-shaped rather than conventional cylindrical and are compatible with existing commercial WCE capsules. The rectangular-shaped coils require less space but provide a larger area to induce higher voltages, which consequently increases the sensing range. They can also be used for locomotion and wireless power harvesting. Three orthogonal transmitting-coils ($9.5\,\mathrm{cm}$ in diameter and with 60 turns are used to generate electromagnetic fields. They are energized sequentially with a $0.6\,\mathrm{A}$ sinusoidal wave of $7.7\,\mathrm{kHz}$. Non-linear relationships are developed between the induced voltages in the sensing-coils and the six variables $(x, y, z, \alpha, \beta, \gamma)$ which are estimated with a non-linear solver.**

I. INTRODUCTION

Wireless Capsule Endoscopy (WCE) is a non-invasive medical process to examine the entire Gastrointestinal (GI) tract for a lesion. In the traditional tube based method, diagnosis is carried out in real time, and purposely carrying drugs to stop bleeding or tissue collection from a tumor can be possible. However, the examination in this method is not only unpleasant to the patient but also limited to the esophagus, stomach and large intestine only. WCE has overcome these limitations of the tube method and become very popular in these days. Since the innovation of the endoscope capsule in 2000, image processing capability has been improved significantly. Nevertheless, a technology is still to be developed for the capsule to view its accurate position and orientation of each image and to control its movement in real time. Embedding of such a technology is necessary to locate a lesion precisely and to enhance some robotic features of the capsule such as carrying drugs or collecting tissue from a tumor.

Some methods have already been investigated for developing a localization system. Among all methods, Radio Signal Strength Indicator (RSSI) method is usually used in WCE to locate a capsule in the GI tract. In this method, eight small receivers are placed in different positions on the stomach and the signal strength of the received image is used to guess only the position (x, y, z) of the capsule without adding any extra hardware. Yi Wang et. al [1] investigated this method using one 4×4 and two 4×4 sensor arrays and they found that the maxium position error is about 100 mm for the first case. To determine the presence of a capsule in the small intestine, occasionally X-Ray, Gamma-Ray, MRI, Ultrasound or visible waves are used. Nevertheless, they are expensive and there is a risk to health. Permanent magnet (PM) method has been investigated to determine the position and orientation of the capsule where a PM is placed inside the capsule and hall sensors are placed in four planes around the stomach [2]. This method is less expensive and the accuracy is very good [3]. However, due to the size constraint of the capsule, a small size of PM is not capable of providing a required sensing range. In addition, a small piece of ferromagnetic bar unintentionally placed in the detecting area could lead to a failure in precisely locating the capsule [4]. Again, the question of avoiding the interference which is occured in between magnetic localization and actuation is still unanswered. Therefore, Electromagnetic field (EMF) method [5], [6] is the preferred alternative solution for localization and actuation problem.

In EMF method, instead of a PM, a sensing coil is placed inside the capsule and an alternating magnetic field is generated from outside the body. The voltages that are induced in the sensing coil could be used for determining 6D localization. The obvious challenge in this method is to design a miniature sensing coil for the capsule, which will also provide a sufficient sensing range. Cylindrical shaped coil is being investigated for both magnetic field generation and as a sensing coil [7], [8], [9], [10]. Some experiments have already shown a good result to some extent. Six transmitting coils [11], several transmitting coils [12] and (8×8) numbers of transmitting coils [8] in one plane and a sensing coil inside the capsule have been tested to determine the position and orientation of a capsule. In [7], the 3D position is determined by one sensing coil, one transmitting coil and five different frequencies. Instead of a single induction coil, an LC circuit is suggested to utilize resonance for localization [9], [13]. Errors are minimized using particle swarm optimization (PSO) algorithm [12], however the standard deviation is still high. Sensing range could be extended by increasing the size of the coil or by inserting a ferrite core in the sensing coil [9] that may have an impact on size or may interfere if any static magentic field is used for movement control. Rather than distributing transmitting coils in a plane, they can be palced othgonally about the same center [14] which makes the system simpler.

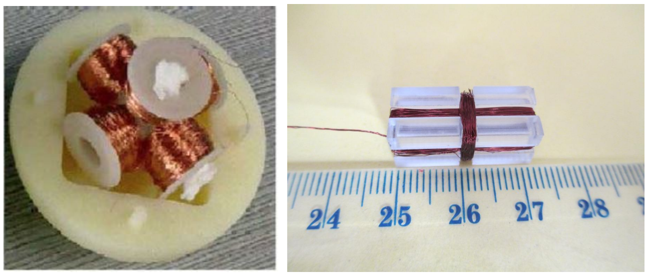
In this paper, we propose rectangular shaped three orthogonal sensing coils for 6D localization. This shape is chosen because the coils could be efficiently placed in the capsule without leaving any unused space and gives larger effective area normal to the magnetic flux. In addition, the coils could be used to develop a rotary motion by creating a force on the straight conductor using a static magnetic field. A localization system with three orthogonal transmitting coils of about 9.5 cm diameter is proposed to verify experimentally the performance of the sensing coils.

In the next section, we explain the construction of sensing coils and then the localization system is described in section III. Experimental results and a comparison are reported in section IV. We conclude the paper in section V.

II. SENSING COIL DESIGN

The voltages induced in the sensing coils are used for the capsule's 6D localization. The magnitude of the induced voltage depends on the coil's area normal to the flux and number of turns in the coil considering that the frequency and density of the magnetic field are constant. A minimum amount of voltage is needed for accurate localization. Therefore, the sensing range depends on the magnitude of the induced voltage. As the volume of a capsule is limited, it's challenging to design a sensing coil with minimum volume but maximum area. Our proposed rectangular shaped sensing coils are shown in Fig. 1b. Current sensing coils, which are in cylindrical shape and shown in Fig. 1a, occupy some unused space in the capsule whereas our proposed sensing coils do not hold any unused space and provide a larger area. Consequently, the same sensing range is achievable with a less number of turns that refers to volume minimization.

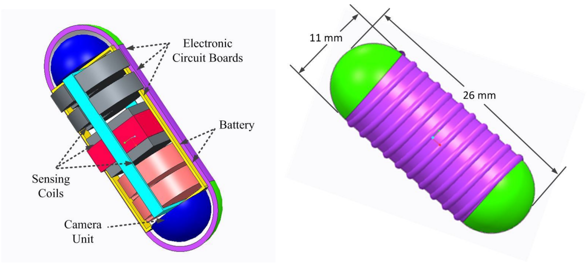
The dimension of the two similar large coils and a small coil are $20\,\mathrm{mm} \times 7\,\mathrm{mm}$ and $7\,\mathrm{mm} \times 7\,\mathrm{mm}$ respectively. The longer edge of the large coils could be placed through the surface of the capsule as shown in Fig. 2a. It can make the surface harder. The length and diameter of a commercialized capsule are $26\,\mathrm{mm}$ and $11\,\mathrm{mm}$ respectively. We used a $0.08\,\mathrm{mm}$ diameter copper wire for the sensing coil and the claculated total volume of the sensing coils is $48.88\,\mathrm{mm}^3$ which is only $1.92\,\%$ of the total volume of the capsule.



(a) Cylindrical coils [14] (b) Proposed rectangular coils

Fig. 1: Comparision of cylindrical and rectangular shaped coils

The sensing coils are compatible with the commercialized capsules and can be easily placed in. Fig. 2a shows the internal situation of the capsule after inserting the sensing coils. The red, light blue and yellow colours represent the three orthogonal sensing coils. We can create a force on the straight edges of the coils using an external static magnetic field. Therefore, reorientation and a rotary motion can be achieved. We propose a helix shaped outer surface of the capsule shown in Fig. 2b so that the rotary motion can be converted to linear motion.



(a) Interior of the Capsule (b) Exterior of the Capsule

Fig. 2: Fitting of sensing coils in the Capsule

III. LOCALIZATION SYSTEM

Our proposed localization system consists of three orthogonal transmitting coils and three orthogonal sensing coils. The system is shown in Fig. 3.

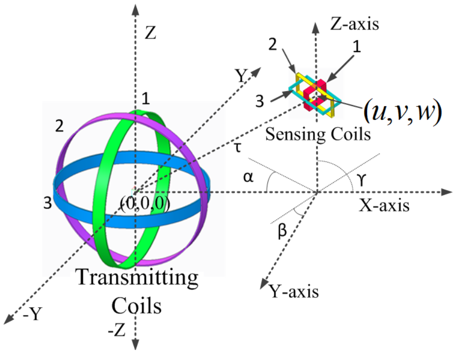


Fig. 3: Proposed localization system

The transmitting coils are placed outside the body and the centre of the coils is considered as a reference point or

TABLE I: Summary of Experimental Results

Parameters	Close Distance ($\tau = 117\,\text{mm}$)				Far Distance ($\tau = 257\,\text{mm}$)			
	Actual Position	Experimental Outcome		Error	Actual Position	Experimental Outcome		Error
		Mean	Std			Mean	Std	
u(mm)	114	118.8	0.7	4.8	200	196.8	0.25	3.2
v(mm)	-100	59	0.93	2.4	150	152.7	0.28	2.7
w(mm)	59	50.2	0.073	8.8	59	46.4	0.32	12
$\alpha(^o)$	25	24.30	0.017	0.7	-40	-32.75	0.2	7
$\beta(^o)$	50	48.95	.066	1.04	50	50.33	.088	0.33
$\gamma(^o)$	35	36.59	0.038	1.6	29	30.19	0.25	1.2

TABLE II: Comparison with Other Works

Different Proposals	Dimension	Total Volume (mm^3)	Effective Area (mm^2)	Sensing Range (mm)	Error			
					Position (mm)		Orientation (^{o})	
					Mean	Std	Mean	Std
X. Guo et. al. [12]	10 mm(ϕ) × 9 mm(L)	706	78.54	≤ 100	11.6	22.3	7	6.22
T. Nagaoka et. al [7]	6.5 mm(ϕ) × 2.3 mm(L)	76.32	33.18	≤ 100	11.6	22.3	7	6.22
S. Hashi et. al [9], [13]	4 mm(ϕ) × 10 mm(L)	125.664	12.56	200	-	-	-	-
X. Guo et. al. [11]	unexposed	-	-	150	14	39.3	7.6	7.5
Our Proposed method	20 mm(L) × 7 mm(W), 7 mm(L) × 7 mm(W)	48.88	140	≥ 257	6	0.28	1.11	0.04

ϕ = Diameter, L= Length, W= Width

$(0, 0, 0)$. The sensing coils are placed in the capsule. Consider the position of the capsule is (u, v, w) and the orientation of the capsule is (α, β, γ). The three orthogonal transmitting coils are so placed that they generate magnetic fluxes to X, Y and Z axis. Each transmitting coil works as a magnetic dipole. Therefore, the magnetic field, B that is generated by each coil, has three components, such as B_X, B_Y and B_Z, at any point around the coil. On the other hand, area of a sensing coil normal to X, Y and Z axis varies due to the different orientation of the capsule. At any moment, each sensing coil may have three area components normal to X, Y and Z axis. Therefore, the total induced voltage in each coil is the algebraic sum of voltages induced for B_X, B_Y and B_Z. Based on the induced voltages information in those three sensing coils equations can be developed to determine 6D localization $(u, v, w, \alpha, \beta, \gamma)$ of the capsule.

IV. EXPERIMENTAL RESULTS

A block diagram of the experimental setup is shown in Fig. 4. A signal (sine wave) is generated from a Signal Generator (MSO-X 2012A). The signal is then amplified using a wideband amplifier (WPA 116). The amplified signal is then sent to the three transmitting coils through three relays. The relays are operated one by one to energize the transmitting coils sequentially. Relays are operated using a data acquisition card (NI USB-6008). Sensing coils are connected to the three channels of the oscilloscope (MSO-X 2012A). We used MATLAB program to operate transmitting coils through data acquisition card and to collect data from the oscilloscope. The sensing data is then used to determine the position and orientation of the capsule in the MATLAB environment.

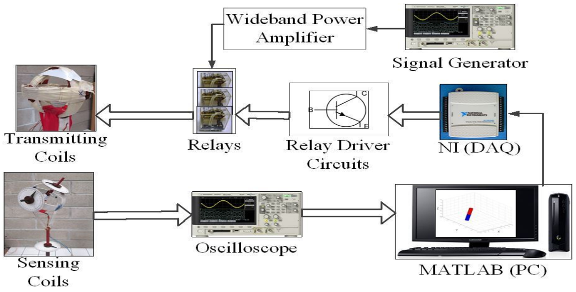


Fig. 4: Block diagram for experimental setup for localization system

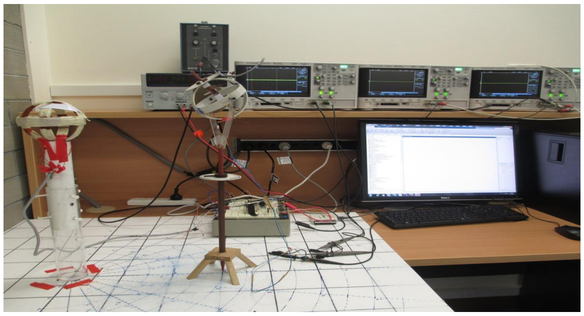
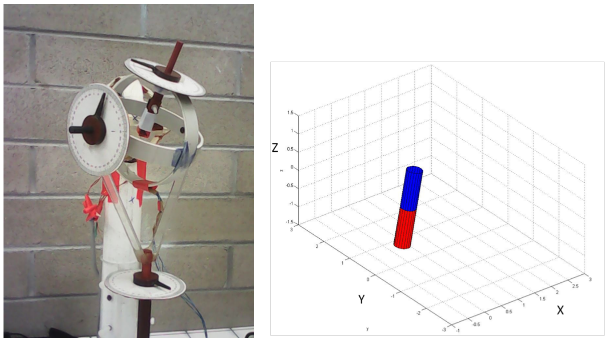


Fig. 5: Experiment for localization

The real experimental environment is shown in Fig. 5. All the structures are made of plastic to avoid any sort of interference or disturbance from metallic material. A white plastic board is taken as a base and marked off in cm. The transmitting coils are fixed at a position. The prototype of the capsule can be moved in X, Y and Z directions as well as it can be rotated about X-axis, Y-axis or Z-axis.

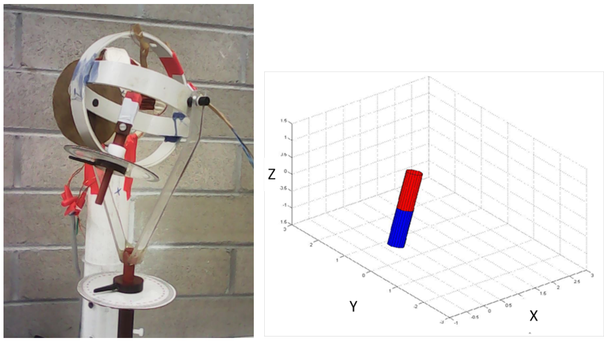
Experiemnt is carried out for two different positions and orientaitons of the capsule. The prototype of the capsule is kept at 117 mm and 257 mm distance from the reference point. Each voltage data is taken by averaging 128 samples using oscilloscope. The experimental results are summarized in the Table I. For a closer (τ =117 mm) and far (τ= 257 mm) distances the orientation errors are 1.6^o and 7^o respectively and the position errors are found 8.8 mm and 12 mm respectively

The results of this work is compared with other recent works in Table II. It is explicit from the table that our proposed sensing coil takes less space and gives more effective area to the magnetic flux. Therefore, it induces more voltage for the same distance and consequently provides longer sensing range. In other experiments, the error they found for 100 mm is more than the error we got for 257 mm. The standard deviation is comparatively very low that assures the system is stable.



(a) Capsule's Orientation (b) MATLAB view

Fig. 6: Real time display of orientaion of the capsule in MATLAB for position 1



(a) Capsule's Orientation (b) MATLAB view

Fig. 7: Real time display of orientaion of the capsule in MATLAB for position 2

The real time orientation display is done using MATLAB. Fig. 6 and Fig. 7 presents two different setups of the capsule. The red and white colored tapes on the prototype of the capsule are represented by red and blue colours in MATLAB respectively. The orientation shown in MATLAB is very close to the original setup. This experimental outcome clearly express that the method is working well.

V. CONCLUSION

In this paper, three orthogonal and rectangular shaped sensing coils are proposed for the tracking of an endoscope capsule in the GI tract. The sensing coils are compatible with the commercialized capsules. Compared to the other cylindrical shaped coils they take less space, 1.92% of total volume of a capsule. As they provide larger area, for the same sensing range S/N ratio is improved which assures less localization error. The localization performance is experimentally verified. The coils are so designed that the same coils could also be used to control the movement of the capsule.

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