A Study of Capsule Endoscopy Orientation Estimation Using Received Signal Strength

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***Abstract*— Comprehensive study of wireless communication for ingestible electronics is a very challenging task. To initiate the study on wireless capsule endoscopy, an innovative immersive platform containing an enhanced 3D human body model has been developed. This platform allows for flexible placement of a capsule inside the gastrointestinal (GI) tract and multiple receivers around the abdomen area. It is shown that any directionality (or equivalently null) in the antenna radiation pattern can be exploited to sense changes in the orientation of the capsule through observation of the S_{21} vector at a set of on-body receivers. Two methodologies i.e. complex cross-correlation and Minkowski distance were used to assess capsule orientation estimation with respect to a reference position. The study was performed within the Ultra-Wide Band frequency range as this technology is considered to be an attractive candidate for the next generation of wireless capsule endoscopy.**

Keywords—Wireless Capsule Endoscopy; Orientation Estimation; Ultra-Wide Band; Correlation Coefficient

I. INTRODUCTION

Endoscopy procedure plays a significant part in nearly all GI-related diseases as well as a crucial role in clinical research. It is estimated that more than 20 million GI endoscopies are performed each year in the United States [1]. A Wireless Capsule Endoscopy (WCE) is an ingestible capsule equipped with a miniaturized video camera. It provides a minimally-invasive alternative imaging technology for the entire Gastrointestinal (GI) tract of the human body. WCE is the only painless, and effective diagnostic technology for various diseases such as obscure gastrointestinal bleeding, tumors, cancer, Crohn's disease, and celiac disease. The breakthrough impact of WCE in medicine is that they allow observation of abnormalities in the entire 5 m to 7 m length of the small intestine from locations that are not accessible by today's conventional endoscopy or colonoscopy technology.

Eighteen years after the first invention of this technology, positioning and mapping metrology science in this area is still in its infancy. As a result, doctors receive clear pictures of abnormalities such as bleeding and tumors inside the GI-tract, but they have no way to determine their precise locations within the body or the relative distance of the abnormality from an anatomic landmark such as the pylorus or the ileocecal valve. This is due to lack of knowledge about location and orientation of a capsule at the time when an image is taken. Lack of such critical information necessitates follow-on use of expensive and invasive testing such as deep enteroscopy, CT enterography, or even surgery to determine the site of the tumor, lesion, or bleeding. The elasticity of the GI tract and looped and folded nature of some its components (e.g., small intestine) along with variable speed and irregular motion pattern of a WCE pose several unique metrology challenges for this problem.

Since, the next generation of endoscopy capsules are expected to deliver higher quality images or even videos as well as more diagnosis and therapeutic functionality, in this study, Ultra-Wideband (UWB) technology has been considered for the wireless communication links between the transmitter antenna inside the capsule and the receiver's nodes located on the body. Despite the high attenuation, higher bandwidth (i.e. data rate) and lower complexity of the transceiver makes UWB an attractive candidate for future WCE. To the best of the authors' knowledge, previous investigation of capsule position estimation or orientation in the literature has not considered unlicensed UWB frequency band.

Recent publications and research activities on WCE is mostly focused on developing accurate position estimation methodologies [2,3,4,5,6]; however, as the miniaturized camera in these capsules do not have a wide view angle, knowledge of the capsule orientation inside the Gastrointestinal tract could also be a valuable information for the physicians who review the transmitted images. This adds another layer of complexity to the already challenging localization problem for such capsules. Previous research on the detection (or control) of capsule orientation involved using magnetic field [4]. In this paper, a preliminary study of orientation estimation using the received signal strength by a set of receivers located on the patient's abdomen area is presented.

Another challenge in studying localization or orientation estimation of a WCE is the platform that is used to evaluate potential methodologies. Clearly, physical experimentation on patients are nearly impossible. Therefore, computational models or liquid phantoms are often used to carry out such studies. Liquid phantoms are aqueous solutions that mimic the electromagnetic properties of human tissues (e.g. muscle). Although, they enable simple physical experimentation, the results might not be so accurate as they fail to capture the inhomogeneous nature of the human body.

On the other hand, computational human body model can capture details of the inhomogeneous environment between the capsule and the on-body receivers. However, extensive computational time and high memory requirements often create an obstacle in performing sophisticated simulation involving a WCE. In this study, using a dedicated computing facility and an innovative and immersive computational platform, a preliminary study of capsule orientation estimation using received signal strength (RSS) is conducted. The results indicate the possibility of extracting some orientation information from the RSS. This study is meant to highlight an innovative platform and establish the framework for further research on WCE position and orientation estimation inside the human small intestine.

The rest of this paper is organized as follows. Section II describes the computational human body model that has been used in our study. Section III provides a brief overview of the analysis used to process the information as well as the estimation methodology. Simulation results are presented in section IV. Finally, Conclusions and future work are discussed in section V.

II. COMPUTATIONAL PLATFORM

A novel 3D immersive platform to emulate the communication link between a WCE and several on-body sensors has been developed at the Information Technology Laboratory of the National Institute of Standards & Technology (NIST) [7,8]. A high-resolution 3D GI tract model without self-intersections or other "non-manifold" features has also been developed and integrated with a 3D computational human body model of an adult male (Fig. 1). The 3D body model has a resolution of 2 mm and includes frequency-dependent dielectric properties of 300+ parts of a male human body. These dielectric properties are user-definable in case custom modifications or changes are desired.

Validated models of practical antennas have also been incorporated in the computational system to accurately characterize the wireless link between the capsule and the on-body receivers' antennas. The receiving antenna is an L-shape lower band UWB planar antenna with linearly polarized radiation. The antenna has overall size of (24 x 25 x 1) mm and made on a FR4 substrate with dielectric constant of $\varepsilon_r = 4.4$, loss tangent of $\tan \delta = 0.02$, and thickness of 1 mm. The antenna is fed by coupled tapered transmission line. The geometry of the taper is chosen to minimize the reflection and optimize impedance matching and bandwidth [9]. The transmitter antenna inside the capsule is a total band UWB antenna and it is single side metallic layer planar antenna, made on a Rogers[1] RT Duroid 6100 (tm) substrate with dielectric constant of $\varepsilon r = 10.2$ and thickness of 0.8 mm. The optimum structure of the antenna is 8.4 mm x 6 mm x 1.036 mm, which appropriately fits to the size of WCE pills. The antenna is designed with respect to the surrounding tissues of the endoscopic pill; these are esophagus, stomach, small intestine, and large intestine [10]. The 3D in-body radiation pattern of this antenna at 3.6 GHz frequency is shown in Figure 2.

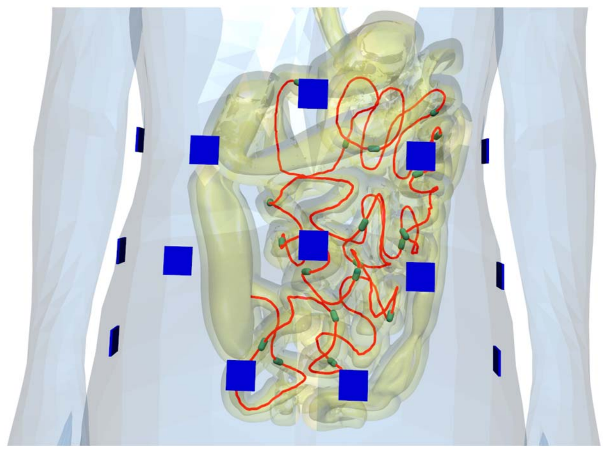

Figure 1. Computational human body model with enhanced GI tract

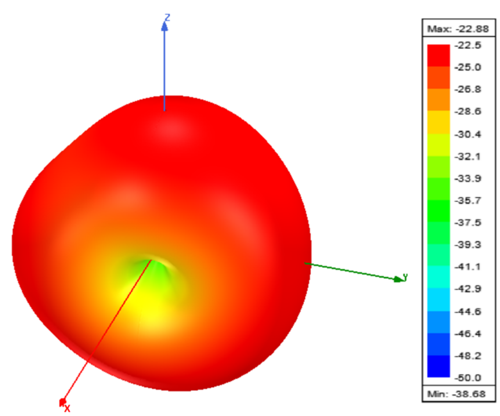

Figure 2. Transmit antenna in-body radiation pattern at 3.6 GHz

[1] This product has been mentioned in this paper to foster research and understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that this product is necessarily the best available for the purpose.

The center-line that passes through the GI tract (e.g. small intestine) in 3D space has been calculated and used as the reference line for the capsule placement within the GI tract (i.e. shown as a red line in Fig. 1). Multiple on-body receivers (indicated with blue squares in Fig. 1) have been considered around the abdomen area. The collection of the signal strength at these receivers are typically used to estimate the location of the capsule within the GI tract. The RSS values can also be processed to infer further information about the orientation of the transmit antenna (or equivalently the orientation of the capsule) at a given location. To see this possibility, consider the coordinate system illustrated in Fig. 3. The angles α and β specify the orientation of the capsule located at the origin of a coordinate system that is completely parallel to the global body coordinate.

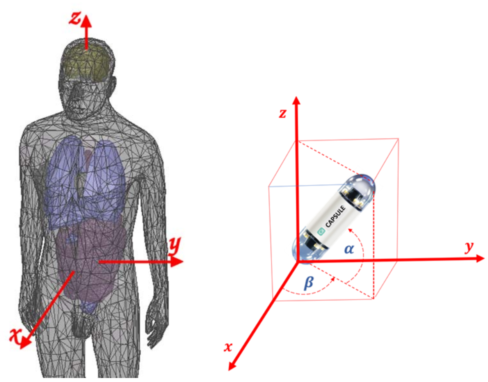

Figure 3. Specification of the capsule orientation (α and β)

Figure 4 demonstrates the magnitude of the forward transmission coefficient (i.e. S_{21}) between the transmit antenna (inside the capsule located at a sample position inside the small intestine) and one of the receivers on the body surface (e.g. RX1). As observed, variations in α and β directly impact the magnitude of S_{21} and therefore the received signal strength at RX1. In the next section, we study if this observation can be exploited to estimate the values of α and β.

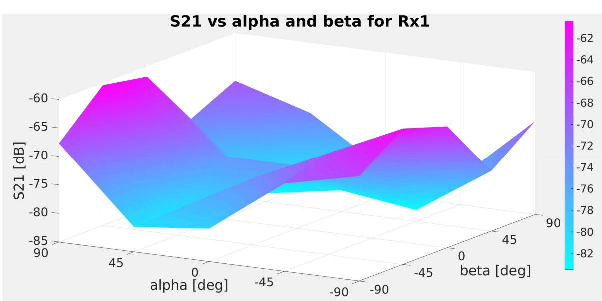

Figure 4. Magnitude of S_{21} at receiver 1 versus orientation angles α and β

III. Orientation Analysis & Estimation

Consider L receivers that are located on several rows covering the abdomen area of the body model as shown in Fig. 1. Define the vector $\vec{S}_{21}^{\alpha,\beta,\overline{P}_k}$ as:

$$\vec{S}_{21}^{\alpha,\beta,\overline{P}_k} = \left[S_{21}^{\alpha,\beta,\overline{P}_k}(i)\right] \qquad i = 1,2,\ldots,L$$

Where $S_{21}^{\alpha,\beta,\overline{P}_k}(i)$ is the complex forward transmission coefficient (i.e. S_{21}) between the transmitter antenna (inside the capsule) and receiver 'i' when the capsule is located at position $\overline{P}_k = (x_k, y_k, z_k)$ inside the small intestine and facing the direction specified by α and β.

Define the correlation coefficient ρ as the following:

$$\rho^{\alpha,\beta,\overline{P}_k}(m,n,j) = \sum_{i=1}^{14} \frac{S_{21}^{\alpha,\beta,\overline{P}_k}(i).\, S_{21}^{(\alpha+m\Delta),(\beta+n\Delta),\overline{P}_{k+j}}(i)}{\left\|\vec{S}_{21}^{\alpha,\beta,\overline{P}_k}\right\| . \left\|\vec{S}_{21}^{(\alpha+m\Delta),(\beta+n\Delta),\overline{P}_{k+j}}\right\|}$$

Where Δ is the unit angular step that is used to change α and β; and

$$m,n = 0, \pm 1, \pm 2, \ldots \quad \text{and} \quad j = 0,1,2, \ldots.$$

This correlation coefficient defines the cross-correlation between the S_{21} vector at position $\overline{P}_k$ with orientation α and β and the S_{21} vector at position $\overline{P}_{k+j}$ with orientation α+mΔ and β+nΔ. High values of this coefficient could be translated to similarities between two capsules positions or orientations. Therefore, if prior knowledge of S_{21} vector at a reference location is available, then some information regarding orientation α, β and $\overline{P}_k$ can be obtained by looking at the values of this coefficient. For example, define the correlation matrix $R_{\overline{P}_k}$ at position $\overline{P}_k$ and orientation α and β as follows:

$$R_{\overline{P}_k}(\alpha,\beta) = \left[\rho^{\alpha,\beta,\overline{P}_k}(m,n,0)\right] \quad m,n = 0, \pm 1, \pm 2, \ldots$$

Then, the orientation of the capsule can be estimated by:

$$(\hat{\alpha},\hat{\beta}) = Argmax_{(\alpha,\beta)}\left[R_{\overline{P}_k}(\alpha,\beta)\right] \qquad (1)$$

Where $(\hat{\alpha},\hat{\beta})$ is the estimate value of the angles α,β.

To study, how far from the reference position a capsule can move before similarities among S_{21} vectors disappear, the correlation vector R_{α_0,β_0} at position $\overline{P}_k$ and orientation α_0, β_0 is defined as follows:

$$R_{\alpha_0,\beta_0}(\overline{P}_k) = \left[\rho^{\alpha_0,\beta_0,\overline{P}_k}(0,0,j)\right] \quad j = 0,1,2, \ldots.$$

$\overline{P}_{k+j}$ indicates a sequence of capsule displacement along the centerline of the small intestine. Although these displacements can be defined in equal increments, the 3D distance from the reference position might not always be linearly increasing due to the shape of centerline in 3D space. In some cases, the 3D distance could be increasing even with increasing linear displacements along the centerline. The maximum value of the above correlation vector signifies the maximum displacement under which equation (1) (or alternative approaches) can be used to determine the estimates of capsule orientation.

Another approach that is commonly taken in other applications to determine the similarity between two vectors is using the Minkowski distance. This methodology can also be used to estimate α, β as follows.

Define Minkowski distance of order 'r' among two S_{21} vectors as:

$$d_{L_r}\left(\vec{S}_{21}^{\alpha_1,\beta_1,\overline{P}_k}, \vec{S}_{21}^{\alpha_2,\beta_2,\overline{P}_k}\right) = \left(\sum_i \left|S_{21}^{\alpha_1,\beta_1,\overline{P}_k}(i) - S_{21}^{\alpha_2,\beta_2,\overline{P}_k}(i)\right|^r\right)^{1/r}$$

Then, $\hat{\alpha}, \hat{\beta}$ is obtained through the following equation:

$$\left(\hat{\alpha}, \hat{\beta}\right) = Argmin_{(\alpha,\beta)} d_{L_r}\left(\vec{S}_{21}^{\alpha,\beta,\overline{P}_k}, \vec{S}_{21}^{(\alpha_0+m\Delta),(\beta_0+n\Delta),\overline{P}_k}\right) \quad (2)$$

$$m, n = 0, \pm 1, \pm 2, \ldots$$

This methodology was also implemented and compared with the correlation coefficient approach. The results are summarized in the next section.

IV. Results

Consider $\Delta = 45^\circ$, $L = 14$, $\alpha_0 = 0$ and β_0=0. Given a sample capsule position inside the small intestine i.e. $\overline{P}_k$, the sample correlation coefficient vectors $\left[\rho^{\alpha_0,\beta_0,\overline{P}_k}(m,0,0)\right]$ $m = -2,-1,0,1,2$ and $\left[\rho^{\alpha_0,\beta_0,\overline{P}_k}(0,n,0)\right]$ $n = -2,-1,0,1,2$ highlight the sensitivity of the S_{21} vector with respect to α, β angular rotations.

$$\left[\rho^{0,45^\circ,\overline{P}_k}(m,0,0)\right] = [1.00 \quad 0.84 \quad 0.81 \quad 0.52 \quad 0.82]$$

$$\left[\rho^{45^\circ,0,\overline{P}_k}(0,n,0)\right] = [1.00 \quad 0.77 \quad 0.70 \quad 0.19 \quad 0.74]$$

As observed, the correlation coefficient is sensitive to rotations in α and β. This can be expected by looking at the antenna pattern in Fig. 2. Changes in the values of α or β will effectively change the direction where the null of the antenna is pointing. For example, for fixed α=45°, the correlation coefficient is monotonically decreasing as β changes from -90° to 45° in steps of 45°. Similarly, for fixed β=45°, the correlation coefficient decreases as α changes from -90° to 45° in steps of 45°. The coefficient again increases at $\alpha = 90^\circ$ due to the symmetry in the antenna pattern. In fact, if the origin of the coordinate system shown in Fig. 3 is instead considered to be the center of the capsule, changing α from -90° to $+90^\circ$ for a fixed β would effectively flip the antenna in the same position. Therefore, a correlation coefficient of nearly 1 can be expected for such 180° rotations.

For this specific WCE antenna, the orientation of the null in its pattern is indeed equivalent to orientation of the camera which is typically mounted in one end of the capsule. Estimation of α and β can effectively identify the direction of this null, and in turn the capsule. So, following the methodology outlined in equation (1), and using 10 different sample points, Figures 5 and 6 show the real and estimated values of α and β.

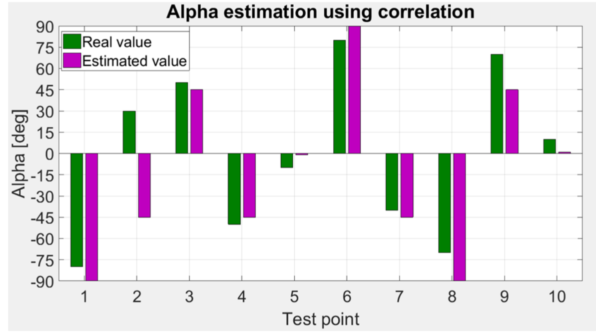

Figure 5. α versus $\hat{\boldsymbol{\alpha}}$ using correlation coefficient

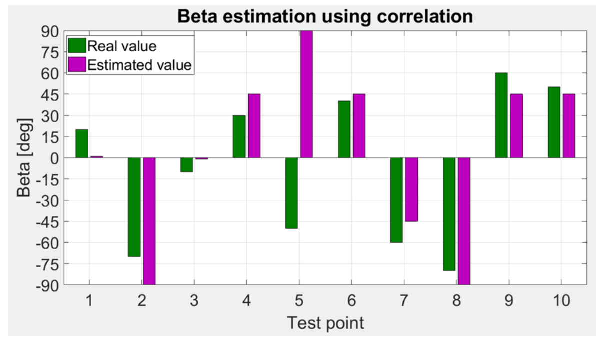

Figure 6. β versus $\hat{\beta}$ using correlation coefficient

As observed, in 9 out of the 10 test scenarios, the estimated α and β are close to their actual values. The average error in both cases are 13.5°. Similarly, following the strategy in equation (2), and trying different orders for calculating Minkowski distance, it was determined that the 2nd order results into better performance in estimating α and β. Figure 7 shows the comparison between the real and estimated β. The results showing estimated α have been omitted for brevity. With the current number of samples, and on average, the correlation coefficient methodology resulted in a lower average error compared to the Minkowski distance. Although the current results seem to be promising, more detailed studies along with higher number of test scenarios are required to better evaluate the performance of each methodology.

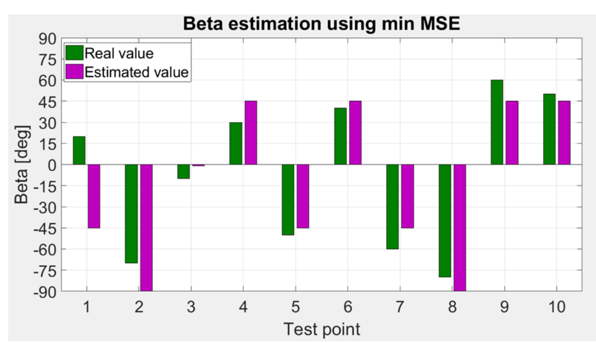

Figure 7. β versus $\hat{\boldsymbol{\beta}}$ using Minkowski distance of order 2

Finally, assuming a displacement step of 0.25 cm, the correlation coefficient of the S_{21} vector (i.e. $R_{\alpha_0,\beta_0}(\overline{P}_k) = 1,2,\dots,12$) was also studied. The results for 3 different sample positions $\overline{P}_k$ are displayed in Fig. 8.

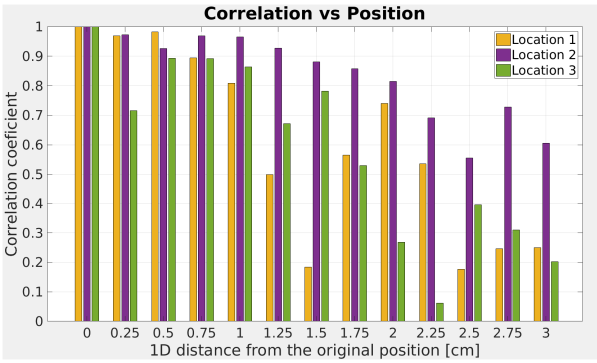

Figure 8. Correlation coefficient variation versus capsule displacement along the centerline

The behavior of coefficients typically depends on the initial location of the capsule, and the geometrical shape of the GI tract (or equivalently the centerline) around that location. As mentioned before, the displacement of the capsule is done in linear steps of 0.25 cm along the centerline and without any change to angles α and β. However, since the 3D direct distance between the new and the initial locations does not necessarily follow an increasing trend, there will be instances where the coefficient value increases with increasing displacement. Although more scenarios need to be studied, based on the chart in Fig. 8, one can conclude that a correlation coefficient of 70% is maintained for distances of at least one centimeter around the original location of the capsule.

V. CONCLUSIONS

Ingestible Wireless Capsule Endoscopy can basically be considered as the first generation of passive microbots (i.e. micro-robots) for use inside the human body. The ability to track the location and orientation of these miniature-sized medical devices (i.e. microbots) will significantly increase the diagnostic and/or therapeutic capabilities of these devices. The platform discussed in this article has been developed to focus on methodologies that can assist in estimating the position or orientation of a WCE. Although for data communication purposes, it is clearly preferred to have a completely omni-directional antenna for the capsule, the initial results presented here indicate that any directionality (or equivalently any nulls) in the capsule antenna pattern could be exploited to estimate its orientation through observation of the signal strength by a set of on-body receivers. It is conjectured that more number of sensors on the abdomen area or lower value for Δ could lead to higher accuracy in the estimated orientation. Further studies are needed to determine the optimal locations for these sensors around the abdomen.

Although, only the cross-correlation and Minkowski distances results were presented here, other methodologies that are based on similarity metrics such as Earth Mover and Hausdorff Distances are also being implemented and evaluated. Their results will be available in future publications. The simulation results provided in this paper are helpful to identify appropriate scenarios and methodologies to study capsule orientation. Authors are also investigating the possibility of using a model-based approach to generate the reference point data, and its impact on the average error.

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