Position and Posture Estimation of Capsule Endoscopy with a Single Wearable Coil Toward Daily Life Diagnosis

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***Abstract*—This paper proposes a position and posture estimation method for capsule endoscopy. The proposed method aims to enable daily life diagnosis with a wearable device, which is a neck corset that includes a coil. The geomagnetic and acceleration sensors in the capsule endoscopy and the corset are used for localization. The accuracy of the estimated position and posture is evaluated with hardware measurements. Experimental results show that the proposed method estimates the posture within five-degree error and the position with the maximum error of 21.4 mm.**

I. Introduction

The advancement of the small mounting technology has enabled us to build a swallowable WCE (wireless capsule endoscopy) that can diagnose the gastrointestinal tract. WCE significantly mitigates the physical burden on patients compared to conventional wired endoscopes. Here, the position of WCE is one of the critical information in preoperative diagnosis. Therefore, many pieces of research have been actively conducted.

Magnetic field-based localization methods are reported as a promising technology for WCE localization since they potentially provide robust and precise localization. On the other hand, conventional magnetic field-based localization methods may require room-scale equipment, and patients cannot leave the hospital during diagnosis. This feature degrades the QOL(quality of life) of patients seriously, and hence the wearable system-based method is highly demanded. Although some researches proposed wearable device-based localization, they suffer from the environmental magnetic field, easiness of the device alignment, and the module size and complexity.

This paper proposes a magnetic field-based localization method for WCE with a single wearable coil. The proposed method only requires a single wearable coil, and hence the patients can live his/her daily life during the diagnose. The proposed method suppresses the effect of the environmental magnetism with a reference sensor and can achieve accurate localization. This paper evaluated the performance of the proposed method with a prototype sensor node. The experimental result showed that the proposed system could localize the sensor position with the maximum error of 21.4 mm in the range of 670 mm from the anchor coil.

II. Related Work

Computer vision (CV)-based localization utilizes the camera initially equipped in the WCE. Due to the limited energy in WCE, the number of photos is small, and hence the accuracy is not high [2]. Instead, CV is exploited to improve the accuracy and robustness by helping other approaches (e.g., [3]).

Electromagnetic (EM) wave is used for WCE localization. There are two approaches; EM wave is injected from the outside, and EM wave is radiated from the WCE. As the first approach, Refs. [4] and [5] radiate X-ray and γ-ray, respectively, for localization. However, these methods are harmful to our body [6]. The second approach often uses received signal strength indicator (RSSI) for localization (e.g. [7][8]). They use the transmitter equipped in the WCE, and hence the additional cost for the WCE is zero. However, they suffer from low accuracy since the EM propagation loss depends on internal organs and individual persons [9]. Another method of the second approach embeds a radio frequency identification (RFID) tag into the WCE and senses the signal from the RFID using an external antenna array [10]. This method uses ultra-high frequency (UHF) since signals with higher frequency than UHF severely attenuate in our bodies. Consequently, the external antenna becomes large, and hence the daily life diagnosis is difficult [6].

Magnetic field-based localization externally senses the magnetic force of a magnet inside the WCE. A magnetic field is not affected by the human body, which is an advantage of the magnetic field-based methods [11]. Magnetic resonance imaging (MRI)-based sensing achieves high estimation accuracy (e.g. [12]). However, using MRI for capsule endoscopy diagnosis is too expensive, and patients need to stay at a hospital for a long time. Toward daily life diagnosis, localization with wearable devices is proposed. Ref. [2] uses 18 external magnetic sensors to sense the magnet inside the WCE. A difficult issue is attaching the sensors on our body accurately and easily. Ref. [13] develops a wearable suit that has more than ten sensors. Due to triangulation-based localization, many sensors are necessary, and the device tends to be larger. Also, both methods suffer from the environmental variation of the magnetic field.

On the other hand, the proposed method senses the magnetic field that is generated externally. The necessary sensors are tiny and consume little power, and hence they can be embedded in the WCE. The magnetic field is generated by a single wearable coil implemented in a neck corset, which does not prevent our daily life. We turn on and off the wearable coil for localization, and hence the environmental variation of the magnetic field can be canceled in the localization process.

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III. Proposed System

A. Overview

The proposed system is mainly based on a DC magnetic filed-based localization method that uses a single anchor coil and senses the magnitude and direction of the magnetic field for localization [1]. Fig. 1 illustrates the localization procedure, where the position of $y > 0$ is localizable. With the magnitude information, surface S_1 is derived, which roughly corresponds to the distance. Using the direction information, line l_1 is estimated, which suggests the direction of the sensor position. Finally, we identify the sensor position as the crossing point of S_1 and l_1. It should be noted that the variation of the environmental magnetic field is eliminated in the localization process [1], which is a significant advantage of the proposed system.

For adopting this localization method, finding an appropriate location of the anchor coil is crucial since it affects the localization accuracy. The important thing is that the coil defines the coordinate system for the sensor node, and then the relative position of the coil to the sensor node should be unchanged even in daily life activities. Taking into account this requirement and the proximity to the sensor node, we first considered a waist belt. The left figure of Fig. 2 shows the magnetic field direction, which suggests that the localization accuracy degrades in the region of the coil center since the magnetic field direction is constant. Next, we considered a neck corset since it fixes the neck direction and consequently keeps the relative location to the sensor node. The neck corset induces some unpleasantness, but still, we can continue our daily life. The right figure of Fig. 2 shows that the magnetic field direction spreads well inside the body of interest. Here, the slope of the neck corset helps diversify the magnetic field direction. Therefore, the anchor coil is embedded into the neck corset in the proposed method.

Fig. 3 illustrates the proposed system. In the capsule endoscopy application, in addition to the sensor location, the sensor posture is essential since both the position and posture are necessary to identify the areas of taken pictures. Furthermore, the localization method of [1] supposes that the sensor posture is known with other methods. We, therefore, need to incorporate a posture estimation method. For this purpose, the proposed system uses an acceleration sensor in addition to a geomagnetic sensor since the power dissipation

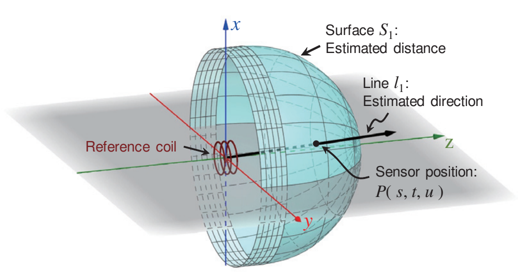


Fig. 1. Sensor node localization with a single reference coil using DC magnetic field [1].

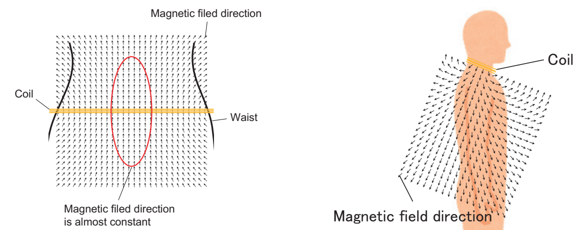


Fig. 2. Coil location and magnetic field direction.

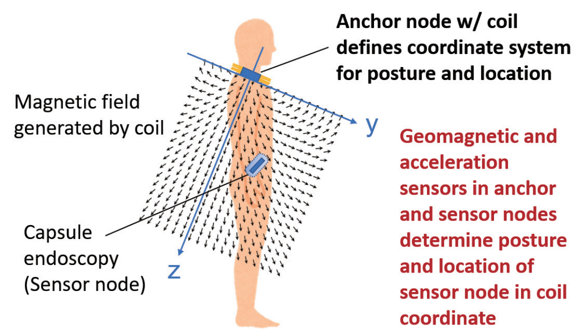


Fig. 3. Proposed system.

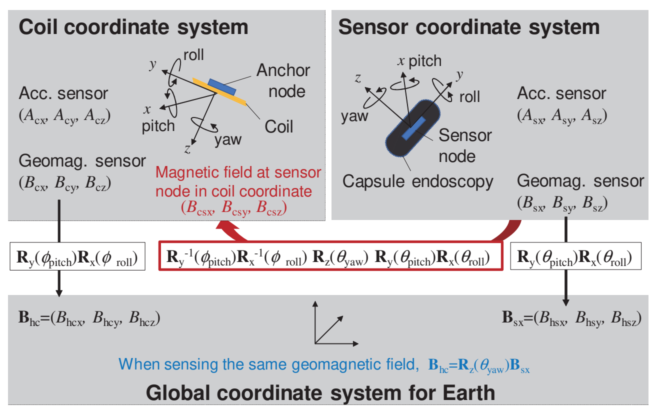


Fig. 4. Coordinate system definition and transformation.

of the acceleration sensor is small and comparable to that of the geomagnetic sensor, which helps to sustain the operation lifetime of the WCE. The detail of the posture estimation will be explained in the next subsection. Here, let us note that, with the geomagnetic and acceleration sensors, we can know the posture of the sensor node in the global coordinate system for Earth (Fig. 4). On the other hand, the goal of the proposed system is to know the location and posture in the coil coordinate system. For the coordinate transformation between the coil and global coordinate systems, the anchor node also includes the geomagnetic acceleration sensors.

B. Posture estimation

The posture of the sensor node, θ_{roll} and θ_{pitch}, are expressed as follows, where the coordinate systems are illustrated in Fig. 4.

$$\theta_{\text{roll}} = \text{atan2}\left(A_{\text{sy}}, A_{\text{sz}}\right), \quad (1)$$

$$\theta_{\text{pitch}} = \text{atan2}\left(-A_{\text{sx}}, \sqrt{A_{\text{sy}}^2 + A_{\text{sz}}^2}\right), \quad (2)$$

where $(A_{\rm sx}, A_{\rm sy}, A_{\rm sz})$ are the outputs of acceleration sensor in the sensor node. atan2(y, x) is an extended atan(y/x) defined in the range of $-\pi < \theta < \pi$. Using $\theta_{\rm roll}$ and $\theta_{\rm pitch}$, the geomagnetic sensor output of the sensor node, $(B_{\rm sx}, B_{\rm sy}, B_{\rm sz})$, can be transformed to the global coordinate system as follows.

$$\begin{bmatrix} B_{\rm hsx} \\ B_{\rm hsy} \\ B_{\rm hsz} \end{bmatrix} = \mathbf{R}_{\rm y}(\theta_{\rm pitch})\mathbf{R}_{\rm x}(\theta_{\rm roll}) \begin{bmatrix} B_{\rm sx} \\ B_{\rm sy} \\ B_{\rm sz} \end{bmatrix}, \quad (3)$$

where $\mathbf{R}_{\rm x}(\theta)$ and $\mathbf{R}_{\rm y}(\theta)$ are rotation matrices shown below.

$$\mathbf{R}_{\rm x}(\theta)=\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}, \mathbf{R}_{\rm y}(\theta)=\begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}. \quad (4)$$

On the other hand, the proposed system needs posture in the coil coordinate system. For this coordinate transformation, the anchor node also includes geomagnetic and acceleration sensors. Similarly to the sensor node, the posture of the anchor node, $\phi_{\rm roll}$ and $\phi_{\rm pitch}$, is derived from the acceleration sensor output of the anchor node $(A_{\rm cx}, A_{\rm cy}, A_{\rm cz})$.

$$\phi_{\rm roll} = \text{atan2}\left(A_{\rm cy}, A_{\rm cz}\right), \quad (5)$$

$$\phi_{\rm pitch} = \text{atan2}\left(-A_{\rm cx}, \sqrt{A_{\rm cy}^2 + A_{\rm cz}^2}\right). \quad (6)$$

Using $\phi_{\rm roll}$ and $\phi_{\rm pitch}$, the sensor outputs $(B_{\rm cx}, B_{\rm cy}, B_{\rm cz})$ can be transformed to the global coordinate system.

$$\begin{bmatrix} B_{\rm hcx} \\ B_{\rm hcy} \\ B_{\rm hcz} \end{bmatrix} = \mathbf{R}_{\rm y}(\phi_{\rm pitch})\mathbf{R}_{\rm x}(\phi_{\rm roll}) \begin{bmatrix} B_{\rm cx} \\ B_{\rm cy} \\ B_{\rm cz} \end{bmatrix}. \quad (7)$$

Here, when sensing the geomagnetic, the output of the sensor node should be identical to the output of the anchor node after the coordinate transformation. In Eqs. (3) and (7), on the other hand, yaw rotation is not aligned. Therefore, the following relation should hold.

$$\begin{bmatrix} B_{\rm hcx} \\ B_{\rm hcy} \\ B_{\rm hcz} \end{bmatrix} = \mathbf{R}_{\rm z}(\theta_{\rm yaw}) \begin{bmatrix} B_{\rm hsx} \\ B_{\rm hsy} \\ B_{\rm hsz} \end{bmatrix}, \quad (8)$$

$$\mathbf{R}_{\rm z}(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (9)$$

From Eq. (8), $\theta_{\rm yaw}$ is derived as follows.

$$\theta_{\rm yaw} = \text{atan2}(B_{\rm hsx}B_{\rm hcy} - B_{\rm hsy}B_{\rm hcx}, B_{\rm hsx}B_{\rm hcx} + B_{\rm hsy}B_{\rm hcy}). \quad (10)$$

Finally, the magnetic field at the sensor node in the coil coordinate system $(B_{\rm csx}, B_{\rm csy}, B_{\rm csz})$ is expressed as follows. These rotation matrices are updated to overcome the variation of the environmental magnetic field and body movement while the wearable coil is off, i.e., no artificial magnetic field exists.

$$\begin{bmatrix} B_{\rm csx} \\ B_{\rm csy} \\ B_{\rm csz} \end{bmatrix} = \mathbf{R}_{\rm x}^{-1}(\phi_{\rm roll})\mathbf{R}_{\rm y}^{-1}(\phi_{\rm pitch})\mathbf{R}_{\rm z}(\theta_{\rm yaw}) \mathbf{R}_{\rm y}(\theta_{\rm pitch})\mathbf{R}_{\rm x}(\theta_{\rm roll}) \begin{bmatrix} B_{\rm sx} \\ B_{\rm sy} \\ B_{\rm sz} \end{bmatrix}. \quad (11)$$

IV. Experimental Results

This section experimentally validates the proposed system with a hardware prototype. For hardware prototyping, module LSM9DS1 [14], which includes a 3D acceleration sensor, 3D geomagnetic sensor, and 3D angular vector sensor, is used, where the angular vector sensor is disabled since it is not necessary and its power consumption is large.

A. Posture estimation

First, we evaluate the accuracy of the posture estimation using the hardware prototype. We fixed two of three rotation angles, i.e., roll, pitch and yaw, and swept the other with 30° step. For each configuration, the posture was estimated, where 1,000 raw sensor outputs were averaged since the geomagnetic sensor output includes random noise [15]. This estimation was performed ten times for calculating the average and standard deviation of the estimated rotation angle.

Fig. 5 shows the estimation results. We can see the rotation angles are well estimated, and especially the roll and pitch angles have a reasonable correlation. The maximum error of the yaw angle is five degrees. The standard deviations of three angles are within one degree. Thus, the posture is well estimated using the acceleration and geomagnetic sensors.

B. Localization experiment

Next, we evaluate the localization accuracy. Fig. 6 shows the experimental setup. In this experiment, we use a 140-turn coil whose internal diameter is 16 cm, where the diameter of 16 cm corresponds to typical neck corsets. The coil consists of 20-pin flat cables whose wire is AWG26. The current given to the coil was 1 A. In this case, the magnetic field of 2.6 μT is generated at the distance of 60 cm from the coil, where the WCE locates in our body in the range of 30 cm to 60 cm from the neck. Note that the proposed system intermittently operates due to the slow movement of the WCE, and hence the coil temperature does not elevate. The sensor module of LSM9DS1 [14] is located at the same height as the coil center. The sensor module is swept on the y-z plane using a 2-D plotter in the range of $(y, z) = (0, 300)$ to $(300, 600)$[mm]. We localized the sensor module with two postures of $(\theta_{\rm roll}, \theta_{\rm pitch}, \theta_{\rm yaw}) = (0°, 0°, 0°), (0°, 0°, 120°)$.

Fig. 7 shows the estimated positions on the y-z plane. The black dots are actual positions, and the red dots are the

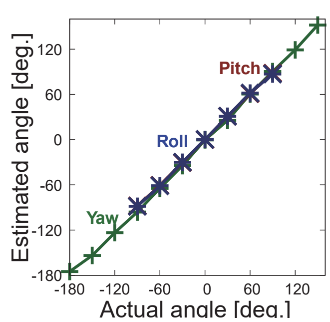


Fig. 5. Estimated rotation angles.

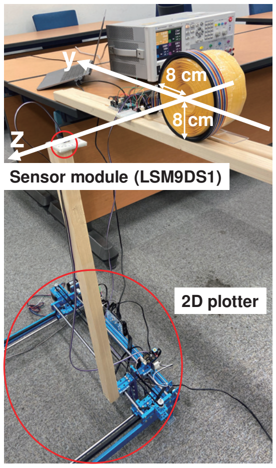
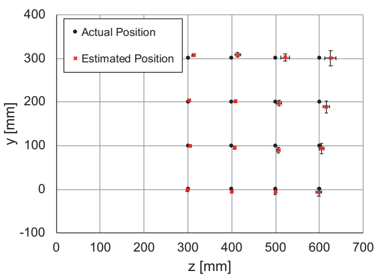
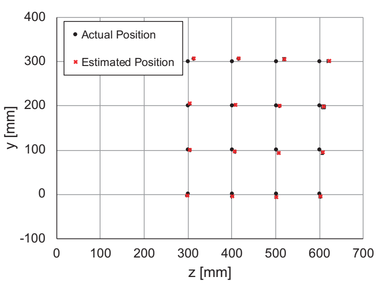


Fig. 6. Setup for localization experiment.



(a) Averaging count 100.



(b) Averaging count 1000.

Fig. 7. Localization results at $(\theta_{\mathrm{roll}}, \theta_{\mathrm{pitch}}, \theta_{\mathrm{yaw}}) = (0°, 0°, 0°)$.

estimated positions, where the error bars correspond to one standard deviation. The averaging count of the geomagnetic sensor is different in Figs. 7 (a) and (b), and it is 100 and 1,000, respectively. We can see that when the averaging count is 1,000, the localization uncertainty due to the geomagnetic sensor noise becomes negligibly small. The average and maximum errors are 9.56 mm and 21.4 mm, respectively, and the standard deviation is 2.07 mm. When the average count is 100, the estimation uncertainty is visible at distant positions.

We also evaluated the accuracy with the posture of $(\theta_{\mathrm{roll}}, \theta_{\mathrm{pitch}}, \theta_{\mathrm{yaw}}) = (0°, 0°, 120°)$. Fig. 8 shows the results. The proposed system achieved the accurate localization. The average and maximum errors are 8.85 mm and 20.6 mm, respectively, and the standard deviation is 3.57 mm.

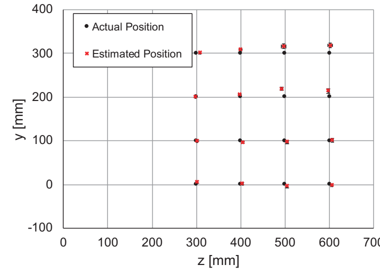


Fig. 8. Localization results at $(\theta_{\mathrm{roll}}, \theta_{\mathrm{pitch}}, \theta_{\mathrm{yaw}}) = (0°, 0°, 120°)$. Averaging count is 1000.

V. Conclusion

This paper proposed a position and posture estimation method for capsule endoscopy diagnosis in daily life. The proposed system attaches a neck corset that generates DC magnetic field and localizes the sensor node in the capsule endoscopy using geomagnetic and acceleration sensors. The hardware experiments show that the proposed system can estimate the position of the sensor node within the average error of 10 mm and the posture with the maximum error of 5 degrees in the distance range of our body of interest.

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