

Position and Orientation Detection of a Magnetic Capsule Endoscope Utilizing the Signal-to-Noise Ratio of Magnetic Sensor Array under External Magnetic Field

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This study proposes an algorithm using magnetic sensors to robustly detect the position and orientation of a magnetic capsule endoscope (MCE) under the external magnetic field (EMF) generated by a magnetic navigation system (MNS). The magnetic flux density generated by the MCE was separated from the flux density data measured by the magnetic sensor array, and a magnetic field model was constructed using linear interpolation to overcome the limitations of the point-dipole model. Additionally, a weighting factor based on the signal-to-noise ratio (SNR) of each sensor was introduced to enable accurate detection of position and orientation even in noisy environments. Experiments were conducted to confirm that the proposed algorithm enhances the detection performance of the MCE.

Index Terms— Detection algorithm, external magnetic field (EMF), magnetic capsule endoscope (MCE), magnetic navigation system (MNS), magnetic sensor.

I. INTRODUCTION

Wired endoscopy, widely used for gastrointestinal examinations, has the disadvantage of causing discomfort to patients during the procedure [1]. To overcome this issue, the magnetic capsule endoscope (MCE), incorporating a permanent magnet (PM), has been developed. When a magnetic navigation system (MNS) generates an external magnetic field (EMF), the PM of the MCE produces magnetic torque and force, enabling active control of the MCE [2]. Since the EMF changes according to the relative position of the target point and the MNS, accurate determination of the MCE's position and orientation is essential for effective control. To achieve this, detection methods such as RF-based, X-ray-based [3], and magnetic sensor-based approaches [4] have been proposed. Among these, the magnetic sensor-based method estimates the MCE's position and orientation by measuring the magnetic flux density generated by the MCE. Since magnetic field is not attenuated by human tissue, it allows stable signal reception and enables system implementation at a much lower cost compared to other detection methods. Therefore, magnetic sensor-based detection is preferred as a promising and practical approach for MCE localization.

For magnetic sensor-based detection of the MCE, it is crucial to accurately separate the magnetic flux density generated by the MNS from the measured magnetic flux density. Previous studies calculated the EMF generated by the MNS using a point-dipole model. However, the approximation error may occur when the MNS includes large magnetic materials. Additionally, prior research did not consider the effect of magnetic noise from the surrounding environment, which could increase detection errors. In this study, position-specific magnetic flux density data generated by the magnetic material of the MNS were collected and used to construct a magnetic field model through linear interpolation. This model showed higher accuracy than the point-dipole model. In addition, a weighting factor based on the signal-to-noise ratio (SNR) of each sensor was applied to the objective function for estimating

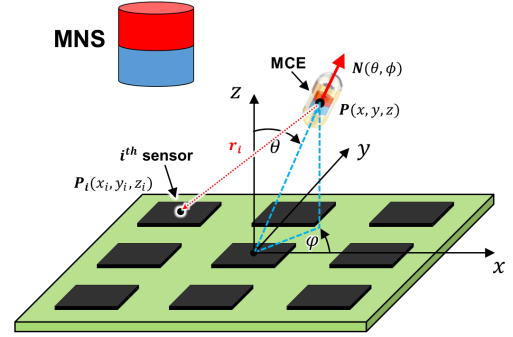


Fig. 1. The MCE and the coordinate system of the magnetic sensor array for the detection of the MCE.

the position and orientation of the MCE, enabling robust detection even in the presence of noise. Finally, experiments were conducted to detect the position and orientation of the MCE in the presence of the MNS. These experiments demonstrated the enhanced detection performance of the proposed algorithm.

II. DETECTION ALGORITHM OF MCE

To estimate the position and orientation of the MCE, it is necessary to separate the magnetic flux density $\mathbf{B}_{MCE.i}$, generated by the MCE, from the flux density $\mathbf{B}_{meas.i}$ measured by the i -th sensor in the magnetic sensor array:

$$\mathbf{B}_{MCE.i} = \mathbf{B}_{meas.i} - (\mathbf{B}_{earth} + \mathbf{B}_{offset.i}) - \mathbf{B}_{MNS.i} \quad (i = 1, \dots, n) \quad (1)$$

The magnetic flux density generated by the Earth's magnetic field and sensor offset ($\mathbf{B}_{earth} + \mathbf{B}_{offset.i}$) can be obtained by measuring the flux density after removing all magnetic materials around the magnetic sensor array. To calculate $\mathbf{B}_{MNS.i}$ generated by the MNS, the linear interpolation model was utilized by constructing a magnetic field model from position-specific magnetic flux density data of the MNS. Finally, $\mathbf{B}_{MCE.i}$ can be separated and it is compared with $\mathbf{B}_{MCE.i,model}$, calculated by the point-dipole model, for the localization of the MCE.

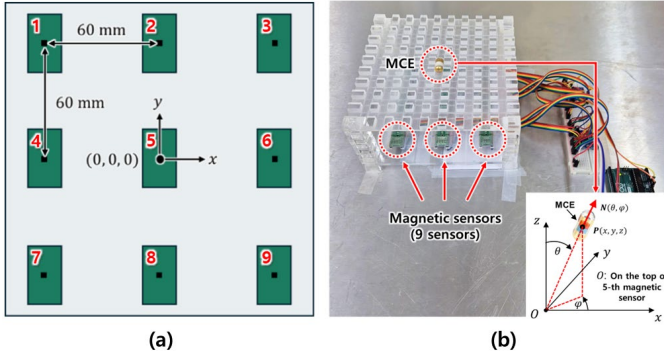


Fig. 2. (a) Schematic of the magnetic sensor array. (b) Experimental setup and coordinate system of the magnetic sensor array and the MCE.

However, due to experimental errors, $\mathbf{B}_{MCE,i}$ and $\mathbf{B}_{MCE,i,model}$ cannot perfectly match, and it may cause the estimation errors of the position and orientation of the MCE deviating significantly from the actual values. To address this issue, $\mathbf{res}_i$ was defined as shown in (2), and an optimization problem was formulated to minimize the sum of the squared residuals $\mathbf{res}_i$.

$$\mathbf{res}_i = \mathbf{B}_{MCE,i} - \mathbf{B}_{MCE,i,model} \quad (i = 1, \dots, n) \quad (2)$$

Fig. 1 illustrates the magnetic sensor array and the coordinate system of the MCE for its detection. The measured $\mathbf{B}_{MCE,i}$ may include noise components ($\mathbf{B}_{noise}$) from the surrounding environment. Therefore, sensors with low $\mathbf{B}_{MCE,i}$ values are significantly affected by $\mathbf{B}_{noise}$, resulting in a low SNR value. The low SNR values indicate that the measured data are less reliable and may degrade the detection performance of the MCE's position and orientation. To resolve this problem, a weighting factor w_i proportional to the $\mathbf{B}_{MCE,i}$ was introduced. However, since $\mathbf{B}_{MCE,i}$ of sensors located far from the MCE is very small, w_i becomes close to zero, which may cause numerical instability when directly applied to the objective function. To mitigate this issue, we introduced a filtering function based on the tanh (hyperbolic tangent) function to prevent the numerical instability. In (3), the coefficient k regulates the sensitivity of the tanh function, and we selected $k = 5$ to alleviate extreme imbalance among sensor data. Finally, w_i was incorporated into the objective function of an optimization problem minimizing the sum of squared residuals $\mathbf{res}_i$ defined as the cost function (f) in (4).

$$w_i = \tanh\left(k \cdot \frac{\|\mathbf{B}_{MCE,i}\|}{\max(\|\mathbf{B}_{MCE,1}\|, \dots, \|\mathbf{B}_{MCE,n}\|)}\right) \quad (i = 1, \dots, n) \quad (3)$$

$$\text{Minimize } f(x, y, z, \theta, \varphi) = \sum_{i=1}^n \|\mathbf{res}_i\|^2 \cdot w_i \quad (4)$$

We used the Levenberg-Marquardt algorithm of *lsqnonlin* solver in MATLAB to solve the optimization problem in (4).

III. EXPERIMENTAL RESULTS

We conducted experiments comparing the proposed algorithm with the conventional algorithm, which applies the same weighting factor to all sensors. Fig. 2(a) illustrates the 3×3 array with nine three-axis magnetic sensors (IIS2MDC, STMicroelectronics, Switzerland), uniformly spaced with a total size of 120 mm×120 mm. Fig. 2(b) shows the experimental setup used to evaluate the detection performance of each algorithm. The commercial MCE (MiroCam, Intromedic, South

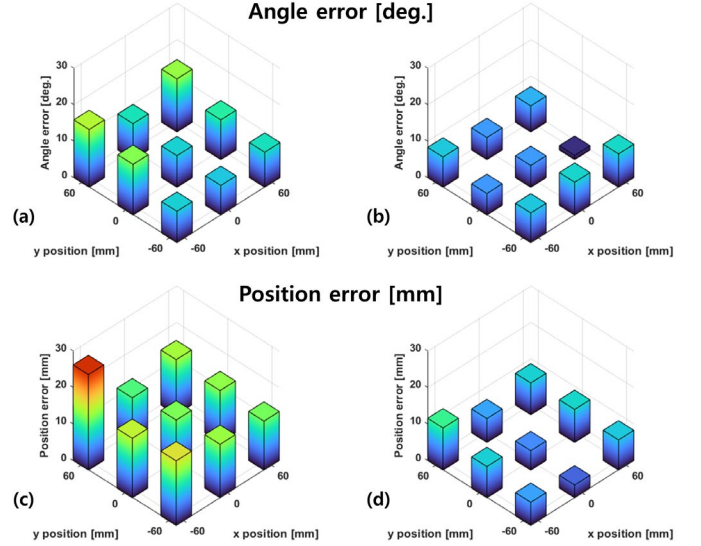


Fig. 3. Angle and position estimation errors for each location of MCE on the plane $z=70$ mm with an EMF. (a, c) Using the algorithm without weighting factor. (b, d) Using the proposed algorithm when the MCE's orientation was along the y -axis, respectively.

Korea) contains an axially magnetized PM with a diameter of 9 mm, thickness of 2 mm, and a residual magnetic flux density of 1.45 T. The upper permanent magnet (axially magnetized) of the MNS [2] was positioned at (0, 0, 500) mm. The MCE was placed at nine locations on the $z=70$ mm plane. We compared the position and orientation detection errors of the proposed algorithm with the conventional ones. The detection error was defined as the difference between the estimated position and orientation obtained by each method and the actual values. Fig. 3 shows the experimental results when the MCE's orientation was along the y -axis. The average orientation error was 11.1° for the conventional algorithm and 6.76° for the proposed algorithm, representing a 39.1% reduction in error with the proposed algorithm. Similarly, the average position error was 15.93 mm for the conventional algorithm and 7.54 mm for the proposed algorithm, indicating a 52.7% reduction in error. The proposed algorithm also showed lower detection errors when the MCE was oriented along other axes. Consequently, we verified that the proposed algorithm shows more stable and higher detection performance.

In conclusion, the proposed algorithm demonstrated more stable and higher detection performance. These results suggest that the proposed algorithm can contribute to enhancing the automation of MCE control and improving the efficiency and reliability of gastrointestinal examinations using the MNS.

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