

PAPER

Position Estimation for the Capsule Endoscope Using High-Definition Numerical Human Body Model and Measurement

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SUMMARY Currently, wireless power transmission technology is being developed for capsule endoscopes. By removing the battery, the capsule endoscope is miniaturized, the number of images that can be taken increases, and the risk of harmful substances leaking from the battery when it is damaged inside the body is avoided. Furthermore, diagnostic accuracy is improved by adjusting the directivity of radio waves according to the position of the capsule endoscope to improve efficiency and adjusting the number of images to be taken according to position by real-time position estimation. In this study, we report the result of position estimation in a high-definition numerical human body model and in an experiment on an electromagnetic phantom.

key words: capsule endoscope, position estimation, received signal strength, wireless power transmission

1. Introduction

Capsule endoscopy is a implant device that has been attracting increasing attention in the medical field in recent years. The capsule endoscope is a small, minimally invasive device with an outer diameter of 11 mm and a total length of approximately 26 mm that incorporates a small image sensor. Equipped with low power consumption imaging function and wireless transmission technology, the capsule endoscope swallowed from the mouth moves through the digestive organs by peristaltic movement, and images taken by the built-in camera are captured and sent outside the body for diagnostic imaging processing. The location of the confirmed lesion is calculated using the imaging time based on the time of the start and completion of the examination. Problems with capsule endoscopes include that the number of images that can be taken is limited because the built-in battery is the drive source, and the electrolyte that leaks from the battery when the capsule endoscope is damaged inside the body leaks into the human body. To address these issues, we are currently developing technology for wireless power transmission from outside the body. We are developing a method of supplying electric power by transmitting radio waves to the capsule endoscope using a sensor array that receives image data from the capsule endoscope. Since this method eliminates the need to incorporate a battery in the capsule endoscope, it is expected that the capsule endoscope will be smaller and easier to swallow, and that the number of

images taken will increase by eliminating the problem of battery depletion. In Wireless Power Transmission (WPT), it is expected that the efficiency of power supply will be improved by narrowing the directivity of radio waves to a position by specifying the position of the capsule endoscope. Immediate position identification is required to improve the efficiency of power supply. Various methods have been proposed to enable position estimation with high estimation accuracy [1]–[8]. However, the calculation time is long because a huge amount of calculation is performed in a complicated human body [9], [10].

The purpose of this study is to develop a real-time position estimation during capsule endoscopy. Real-time position estimation is also expected to adjust the number of images taken according to the digestive organs. In this study, we proposed a position estimation method using Received Signal Strength (RSS), similar to the previous studies [11], [12], and [15]. Various position estimation methods using RSS have been devised so far. Some of the position estimation systems that have been studied used a simple analysis model such as 2-dimension [7]. In addition, there is one that assumes that the transmitting or receiving antenna is an omnidirectional antenna [5]. However, there are few examples of proposing a position estimation system using the antenna proposed assuming WPT. The position estimation using the antenna proposed in the previous study [16] is strongly influenced by the directivity of the antenna. In the previous study [11], the influence of antenna directivity was investigated as one of the factors affecting the estimation accuracy.

In the previous study [11], an algorithm considering the angle character of the antenna due to the directivity of the receiving antenna was proposed, and simulation for a position estimation was performed using a simple rectangular parallelepiped human body model with a three-layer structure of muscle, fat, and skin. In the previous study [14], a rectangular parallelepiped human phantom with a two-layer structure of fat and muscle was used to determine whether the algorithm proposed in the previous study [11] could be applied to position estimation using a transmitting and receiving antenna developed for WPT. It was verified in the experiment used. In the previous study [15], we simulated the position estimation algorithm using the high-definition numerical human body model developed by National Institute of Information and Communications Technology (NICT). In this study, we improved the algorithm proposed in the previous study [11] and simulated the position estimation using a high-definition numerical human body model. Also,

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whether the proposed algorithm works effectively in the real environment. An experiment was conducted using a human phantom to evaluate. In the previous study [14], the simple two-layered human phantom was used, but the actual human body has a very complicated structure. Considering the shape of the small intestine region of the human abdomen and the effect of other organs on the estimation accuracy, in this study, we created a human body phantom containing multiple organ phantoms with reference to the abdominal structure of a high-definition numerical human body model.

2. Proposed Algorithm

This section will explain the basic method of the position estimation algorithm and the error correction method of the algorithm proposed in this study. The same trilateration method as in the previous study [11] is used as the base method of the position estimation algorithm proposed in this study. In the position estimation of this study, two parameters, a mathematical model representing the distance characteristics of the antenna and the position of the receiving antenna, are required in advance.

The outline of the trilateration method will be described below. The image signal transmitted by the capsule endoscope is received by the receiving antenna attached to the outside of the body. Measured RSS is converted into a distance by the mathematical model of the distance characteristic between the transmitting and receiving antennas. Figure 1 shows the distance characteristics between the transmitting antenna for capsule endoscope in the small intestine model and receiving antenna used in this study. In Fig. 1, the horizontal axis shows the distance between the receiving antenna and the transmitting antenna, and the vertical axis shows the RSS measured by the receiving antenna. The red marker shows the simulation value (Finite Integration Technology (FIT) was used in the simulation), and the dotted line shows the approximate curve. As the distance between the transmitting and receiving antennas increases, RSS decreases at a constant rate, so a mathematical model was created using linear approximation. The formula in Fig. 1 is the function built at this time. By substituting the RSS value into this mathematical model, the estimated distance between the antennas can be obtained. As shown in Fig. 2, three spherical surfaces centered on each receiving antenna are drawn with that distance as the radius. The intersection of the three spheres is the estimated position of the capsule endoscope.

Since the position estimation system uses four receiving antennas in this study, there are four combinations of three spherical surfaces, that is, three receiving antennas, used in the trilateration method. Therefore, the average value of the four estimated coordinates was used as the temporary estimated position before correction.

Next, a method for correcting the estimation error will be described. For the correction of position estimation, we proposed two ways: correcting the temporary position by the trilateration method and correcting the error considering the angle character described later.

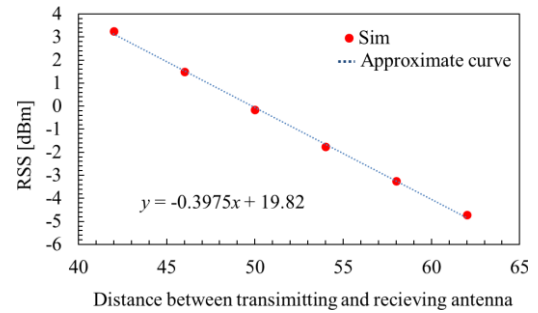


Fig. 1 Distance characteristics.

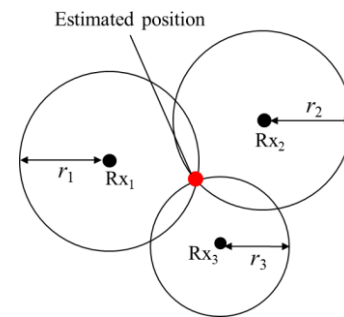


Fig. 2 Trilateration method.

First, a correction method for calculating a temporary position will be described. In the correction method considering the angle character described later, it is necessary to add correction based on the estimated position obtained by the trilateration method. However, in the method in the previous study [11], [12], [15], the intersection of spherical surfaces may not be possible depending on the RSS value measured by each receiving antenna, and the temporary estimated position may not be obtained. Considering the angle character, it can be considered that the receiving antenna that measured the RSS with the most significant value among the measured RSS values is located closer to the capsule endoscope. When the distance between the capsule endoscope and the receiving antenna is small, the influence of the angle character is relatively tiny. In that case, since the distance between the antennas can be obtained according to the distance characteristic model, the estimation error becomes small. Conversely, when the distance between one receiving antenna and the capsule endoscope is large, the RSS measured by that receiving antenna may be extremely smaller than the RSS measured by another receiving antenna. This is considered to be due to the influence of the angle character, and the distance between the antennas is estimated to be larger than the actual distance between the antennas. Considering the positional relationship between the capsule endoscope and the receiving antenna, at least one of the four receiving antennas is strongly affected by the angle character. Therefore, the radius of one or two of the three spheres in the trilateration method may be extremely large. In that case, the intersection cannot be calculated because one sphere is included in the other. If the intersection cannot be

calculated, position estimated result can not be obtained by the methods of proposed in previous studies [11], [12], and [15]. Therefore, we proposed an algorithm for calculating a temporary estimated position by converting the measured RSS value according to the magnitude relationship of the RSS value measured by a total of four receiving antennas used for estimation. Regarding the rate of change of RSS in the angle character, the measured RSS was normalized in the range of 0.1 to 1, and the reciprocal of the measured RSS was used as the correction value. The formula used to normalize the measured RSS is shown in Eq. (1).

$$w_i = \frac{RSS_i - RSS_{min}}{RSS_{max} - RSS_{min}}(M - m) + m \quad (1)$$

$$\delta_i = \frac{1}{w_i} \quad (2)$$

$$RSS'_i = RSS_i + \delta_i \quad (3)$$

RSS_i ($i = 1, 2, 3, 4$) in Eq. (1) is the RSS measured by each receiving antenna, RSS_{max} is the maximum value among the four RSS measured, and RSS_{min} is the minimum value. M is a parameter representing the maximum value of normalization, and m is a parameter representing the minimum value set to 1 and 0.1, respectively. δ_i is the reciprocal of w_i of the normalized value, and this is added to the RSS_i . δ_i is a value in the range of 1 to 10 dBm. Correct the measured RSS according to Eq. (3). By substituting the RSS'_i obtained in Eq. (3) into the mathematical model of the distance characteristics, the estimated distance between the antennas can be shortened. With reference to the sphere that is considered to have the smallest error, the calculation for correcting the radii of other spheres by Eq. (3) is repeated until an intersection is obtained. In the simulation, it was confirmed that an intersection could be obtained with an average of one correction.

Next, an error correction method in consideration of the angle character of the receiving antenna will be described. The angle character investigated in the previous study [11] is that the RSS value measured changes depending on the angle at which the electromagnetic wave is received, depending on the directivity of the receiving antenna. The angle character is defined by θ and φ as shown in Fig. 3. Previously, RSS changes and angle dependencies were defined as separate things for θ and φ . However, considering the three-dimensional directivity of the antenna, the change in RSS depends on both the values of θ and φ .

In this study, we created an approximation function for curved surfaces by three-dimensionally mapping these two angular variables and RSS changes due to angles. Figure 4 shows the designed curved surface. The objective variable ΔRSS was defined as follows.

$$\Delta RSS = RSS_{0,0} - RSS_{\theta,\varphi} \quad (4)$$

$RSS_{0,0}$ in Eq. (4) represents the RSS when the flat part of the receiving antenna faces perpendicular to the capsule endoscope and has the largest value among the RSS received at equidistant. $RSS_{\theta,\varphi}$ represent RSS when the angle of

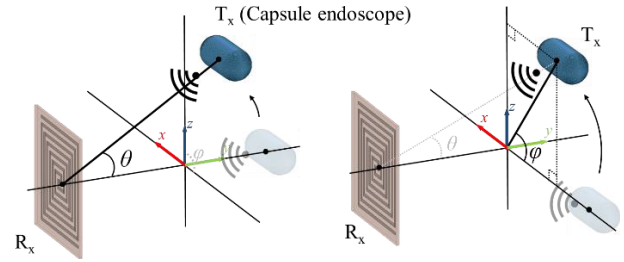


Fig. 3 Two types of angles considering angle characteristics.

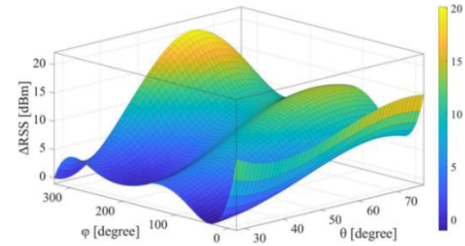


Fig. 4 Correction surface for angle correction.

the capsule endoscope concerning the plane of the receiving antenna is θ in the depth direction and φ in the surface direction. By mapping ΔRSS with θ and φ , we obtained the mathematical model shown in Eq. (5) below from the approximate function.

$$\Delta RSS(\theta, \varphi) = \sum_{n=0}^3 \sum_{m=0}^5 C_{nm} \theta^n \varphi^m \quad (5)$$

C_{nm} in Eq. (5) indicates the coefficient of the polynomial. From the temporary estimated position obtained by the trilateration method, the angles θ and φ with each receiving antenna are calculated, and $\Delta RSS(\theta, \varphi)$ representing the change in RSS is calculated from the approximate function of Eq. (5). By adding $\Delta RSS(\theta, \varphi)$ to the measured initially RSS, the decrease in RSS due to the angle is corrected.

Figure 5 shows the flow of the proposed algorithm. The Position estimation is roughly divided into three steps. First, a temporary estimated position is calculated by the trilateration method. Next, if an intersection cannot be obtained, correction is made using Eq. (3), and the calculation is repeated until an intersection is obtained. Finally, based on the angle calculated from the temporary estimated position, correction is performed using Eq. (4), and the final estimation result is calculated. In this study, the error between the estimated position coordinates and the position coordinates of the placed capsule endoscope is evaluated as the performance of the proposed algorithm.

3. Simulation

3.1 Simulation Model

This section describes the numerical human body model and the antenna model used in the analysis. FIT was

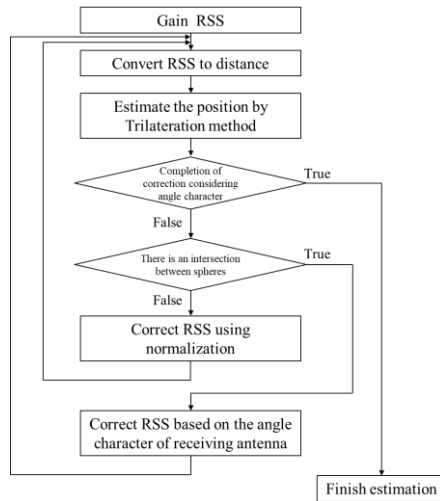


Fig. 5 Flow of proposal algorithm.

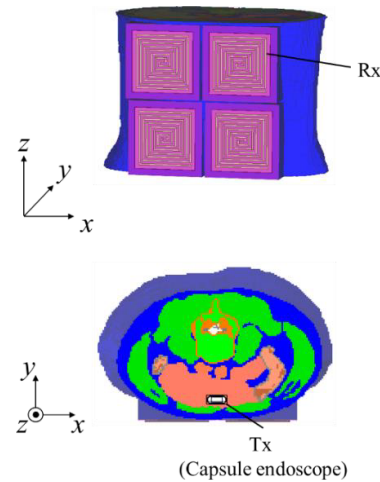


Fig. 6 Simulation model.

used for electromagnetic field analysis. In consideration of power transmission, we used the 433.92 MHz band (433.05 to 434.79 MHz, Europe and Africa), which has less radio wave attenuation and can obtain a high RSS value. A high-definition numerical human body model developed by NICT was used as the analysis model. For the simulation of this study, the same analysis model as in the previous study [15] was used to examine whether the position estimation by the proposed algorithm is possible in the complex human body structure. In the position estimation in the previous study [15], the correction was not performed in consideration of the angle character.

Therefore, in the same analysis model, we compared how much accuracy can be obtained by the algorithm incorporating the correction method proposed in this study compared to the case without incorporating it. The small intestine region to be analyzed has a size of $200 \times 90 \times 200$ mm. Also, when attaching the receiving antenna, the curvature of the abdomen creates an air layer between the numerical human body model and the receiving antenna. To bring the receiving antenna into close contact with the numerical human body model, the air layer was supplemented with fat. On top of the fat, the gel used to attach the receiving antenna is attached with a thickness of 1 mm. Figure 6 shows the simulation model with the above modifications. The numerical human body model contains approximately 25 tissues and organs. Table 1 shows the electrical constants of the primary tissues. The measurement points for the position estimation of the capsule endoscope were 78 points that fit within the small intestine region of the numerical human body model shown in Fig. 8. The estimated intervals were 26 mm in the x -axis direction and 11 mm in the z -axis direction for one capsule endoscope. We also moved it in the y -axis direction at 11 mm intervals. In the actual environment, the tip of the capsule endoscope may be vertical or diagonal, but in this study, the position was estimated only in the horizontal direction (the direction in which the x -axis direction is the long-axis direction of the capsule).

Table 1 Electrical constants of tissues and organs@433.92 MHz.

Tissues and organs	Relative permittivity ϵ_r	Conductivity σ [S/m]
Muscle	57.7	0.83
Fat	11.8	0.08
Skin	47.7	0.69
Small intestine	65.3	1.92
Large intestine	62.0	0.84
Stomach	67.2	1.01

Next, the transmitting and receiving antenna models are explained. In the capsule endoscopy position estimation, the position is estimated based on RSS of the image data transmitted from the capsule endoscope. Therefore, in this study, the capsule endoscopy antenna is called the transmitting antenna. The sensor array mounted outside the body is called the receiving antenna. A helical antenna having a folded structure was used as the transmitting antenna. Since the receiving antenna is also required to function as a power transmission antenna that stably sends power regardless of the direction of the capsule endoscope, a 2-wire spiral antenna that radiates circularly polarized waves similar to the previous study [11], [14] and [15] was used. The antenna model is shown in Fig. 7. Receiving antennas were attached to the body surface at 104 mm intervals so as to cover the area of the small intestine.

3.2 Result of Simulation

First, the calculation time for position estimation is described. The calculation time was measured from the input of the RSS measured by the receiving antenna to the program to the output of the position coordinates of the capsule endoscope. The PC used Panasonic Let's note, CF-SZ5 core i7. As a result, it was confirmed that it takes an average of 0.016 s to estimate one capsule endoscope point with the proposed algorithm. As shown in Fig. 8.

We moved the capsule endoscope antenna from top to

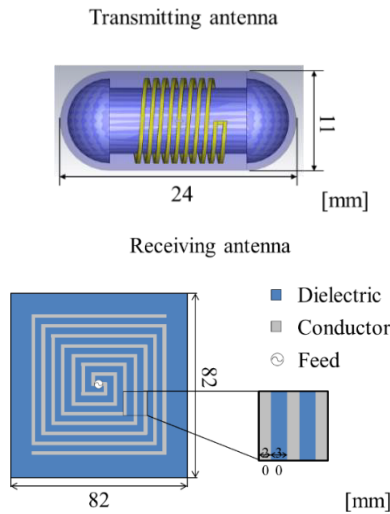


Fig. 7 Antenna model.

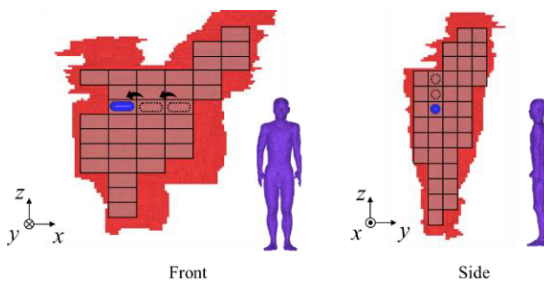


Fig. 8 Setting the capsule endoscope in small intestine.

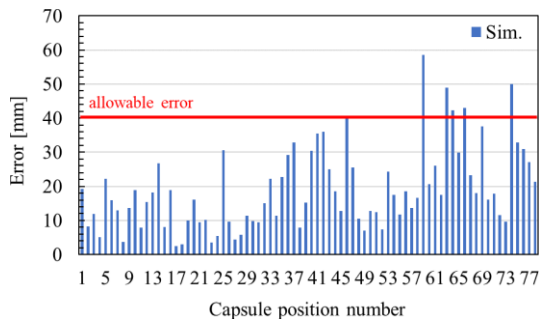


Fig. 9 Result of position estimation.

bottom and from front to back. Numbers are assigned to the places where they are placed, and the smaller number indicates the front side of the abdomen, and the more significant number indicates the backside. The evaluation criteria for estimation accuracy are the same as in previous studies [11], [14], [15], and the allowable error was 40 mm, which is equivalent to about the size of two capsule endoscopes. The allowable error of 40 mm is sufficient for the accuracy required by the WPT system.

Figure 9 shows the result of position estimation in the simulation. The horizontal axis indicates the number when the capsule endoscope is placed, and the vertical axis shows the estimation error. In addition, a line is drawn on that

value in the graph. Of the total 78 points, 72 points, or 92%, achieved a target estimation error of less than 40 mm. The mean value of the estimation error is 19 mm, and the standard deviation is 11.8 mm. In a previous study [15], it was less than 40 mm at all points of -52 mm in the x-axis direction, but the proposed algorithm achieved the target value at all of the above points. The estimation accuracy improved by 12% compared to the previous study [15]. At positions 46, 59, 63, 64, 66, and 74 of placement numbers in Fig. 9, the estimation error was 40 mm or more, exceeding the allowable error. These are mainly located on the backside of the numerical human body model and are the interface with other organs or tissues. As the angle between the capsule endoscope and the receiving antenna increases, it is strongly affected by the angle character, and the RSS to be measured tends to decrease. However, when the measurement RSS at the position where the error is large is examined, the tendency is contrary to that tendency. For example, when comparing the distance characteristics of capsule installation numbers 63 and 71 with almost the same angle, the magnitude relationship of RSS is inverted. If the proposed correction method is provided under the tendency contrary to the distance characteristics of the antennas, the RSS'_i in (3) becomes large, so that the estimated distance between the antennas obtained from the mathematical model of the distance characteristics becomes small. Therefore, the capsule is estimated to be closer to the center of the small intestine than the actual position, and the error becomes larger. In the electric field distribution when the capsule endoscope is placed at the edge of the small intestine region, it can be confirmed that electromagnetic waves are reflected from the neighboring tissues, and this reflected electromagnetic wave at the receiving antenna will increase the RSS and result in a larger position estimation error. However, it was possible to record higher estimation accuracy than previous studies, and we have confirmed the effectiveness of the proposed algorithm.

4. Experiment of Position Estimation

4.1 Transmitting and Receiving Antenna

In the experiment, an experimental environment similar to that conducted in the previous study [14] was constructed. The only difference between the experimental environment of this study and the previous one is that a high-frequency switch was used in this study. A high-frequency switch was connected between the receiving port of the network analyzer and the coaxial cable of the receiving antenna in order to easily switch between the four receiving antennas to be measured. Since the phantom contains water, it deteriorates slightly during the experiment. The switch shortened the experiment time and suppressed the significant deterioration of the characteristics of the phantom during the experiment. First, the reflection coefficient of the transmitting and receiving antenna was measured, and the operation of the antenna was confirmed. The manufactured transmitting and receiving antennas and their reflection coefficients are shown in

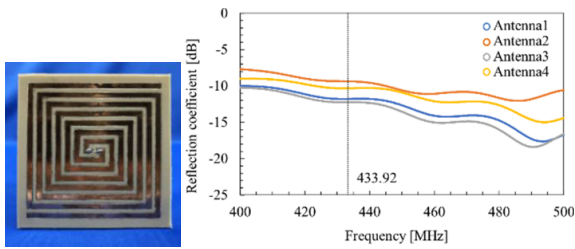


Fig. 10 Receiving antenna.

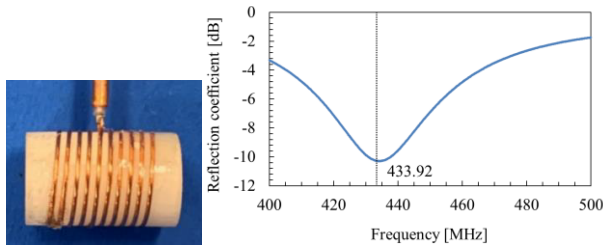


Fig. 11 Transmitting antenna (antenna for the capsule endoscope).

Fig. 10 and Fig. 11. The horizontal axis of the figure shows the frequency, and the vertical axis shows the reflection coefficient. The transmitting antenna for the capsule endoscope showed -10.3 dB at the desired frequency, confirming that it operates with adequate performance. In Fig. 10, the performance of the receiving antenna 2 is worse than that of the other antennas. Since the measured value before connecting to the high frequency switch was less than -10 dB, the problem was probably caused by the bending of the coaxial cable connecting to the antenna 2. Although it has deteriorated by about 1 dB, since the other three antennas are operating well, it was judged that the position estimation is sufficiently possible with the algorithm proposed in this study.

4.2 Abdomen Phantom

This section explains an abdomen phantom for measurements. The abdomen of the human body model contains about 25 types of tissues and organs, but it isn't easy to reproduce all of them. Therefore, only the anterior surface of the abdomen and major organs, which are thought to affect the accuracy of position estimation, were reproduced. The prepared abdominal electromagnetic phantom consists of the stomach, large intestine, small intestine, muscle, and fat phantom. Among them, the small intestinal phantom was made of a liquid phantom in consideration of moving the capsule endoscope inside. Table 2 shows the target electrical constants and measured values of each organ/tissue phantom. Since the error between the target value and the measured value for both the relative permittivity and the conductivity is generally within the permissible range, it was judged that it could be used for measurement. These electromagnetic phantoms are arranged in order inside the Styrofoam container processed refer to the shape of the abdomen of the numerical human body model. The internal dimensions of the Styrofoam container are 204×304 mm, which is the

Table 2 The electric constant of the manufactured electromagnetic phantom.

Tissues and organs	Relative permittivity ϵ_r		Conductivity σ [S/m]	
	Target	Meas.	Target	Meas.
Muscle	57.7	55.4	0.83	0.89
Fat	11.6	12.8	0.08	0.12
Small intestine	65.3	65.3	1.92	2.16
Large intestine	62.0	62.0	0.84	0.84
Stomach	67.2	66.4	1.01	1.32

same size as the abdomen of the numerical human body model used in the simulation. The size of the organ phantom was also created regarding the size of the numerical human body model. In the simulation, it was confirmed that the boundary surface between the organs most affects the position estimation accuracy, so it is important to accurately reproduce the shape of the small intestine region in the actual measurement. Therefore, in the small intestine region of the electromagnetic phantom, a mold was formed to pour the liquid small intestine phantom using the small intestine model of the numerical human body model reproduced by a 3D printer.

The procedure for manufacturing the electromagnetic phantom will be described below. First, As shown in Fig. 12(a), the receiving antenna is placed on the bottom of the Styrofoam container. Then put the gel on it and spread the fat phantom. Next, stomach and large intestine phantoms are processed and positioned so that they fit in the Styrofoam container. Furthermore, a small intestine model is placed from above, and a liquid muscle phantom is poured. After a sufficient amount of time, from the solidified muscle phantom, dig out a small intestine model so as not to lose its general shape. Finally, by pouring a liquid small intestine phantom into the excavated cavity, an electromagnetic phantom in the abdomen that has no air layer and accurately reproduces the shape around the small intestine is completed. The above situation is shown in Fig. 12(b)–(d).

4.3 Result of Position Estimation

During the measurement, the capsule endoscope antenna was fixed using an acrylic plate with a hole the same size as the diameter of the balun attached to the antenna. The total number of places where the capsule endoscope was placed was 78, and the placement intervals and the dimensions of the electromagnetic phantom were made to match exactly those in the simulation. In position estimation, the distance characteristic between antennas, that is, the attenuation tendency of RSS is an important parameter. Therefore, we first investigated the attenuation tendency of RSS. The coefficient of the mathematical model of the distance characteristic shows the attenuation tendency. The attenuation tendency of the created abdominal phantom was -0.384 . Since the attenuation tendency shown in Fig. 1 is -0.397 , it is a generally

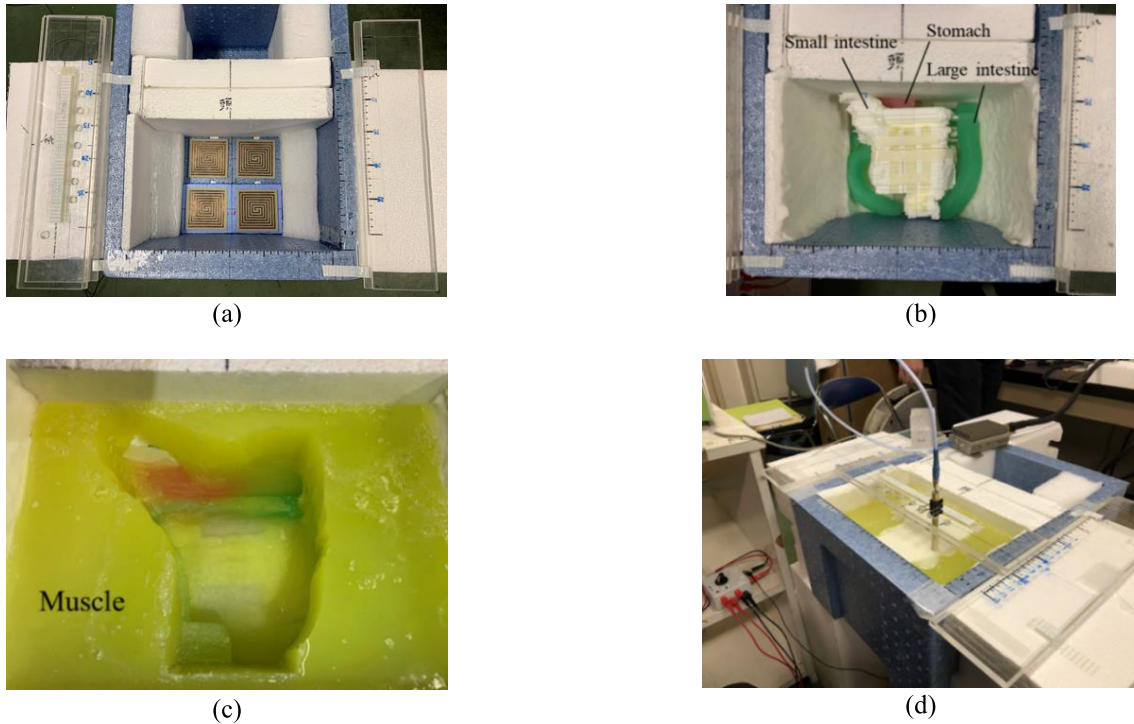


Fig. 12 (a) Installation of antenna. (b) Arrangement of organ phantoms. (c) After pouring a muscle phantom and digging out a small intestine model. (d) Measurement environment.

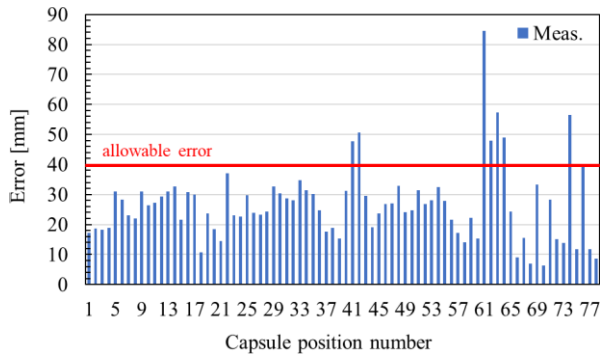


Fig. 13 Result of position estimation.

acceptable error. From this, it can be judged that the prepared abdominal phantom reflects the characteristics of the human body model we referred to.

Next, the result of position estimation is shown in Fig. 13. The target tolerance of less than 40 mm was achieved at 70 points, 89.7% of all 78 points. The mean value of the estimation error is 22.2 mm, and the standard deviation is 13.7 mm. Where the estimation error was significant, the same tendency as the result of position estimation in the simulation was observed. Fig. 14 shows a part of the small intestine model where the estimation error is large. the position where the error is 40 mm or more. The factors that increase the estimation error are the same as the factors of the error in the simulation.

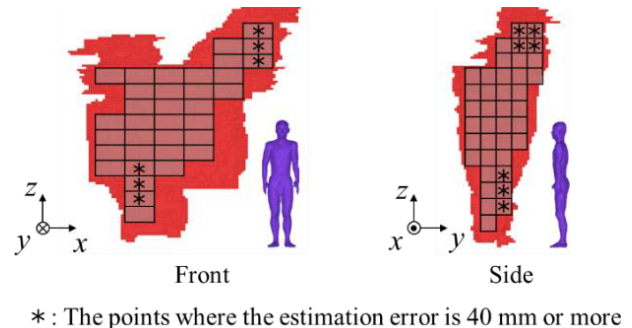


Fig. 14 Where the estimation error is large.

5. Conclusion

In this paper, we proposed the algorithm for real-time position estimation of capsule endoscopes in wireless power transmission. The base of the algorithm uses the trilateration method using RSS. In this study, we proposed the correction method using the measured RSS magnitude pattern and made it possible to calculate a tentative estimated position. In addition, the correction method that takes into account the angle character of the receiving antenna proposed in the previous study [11] has been improved. With proposed algorithm, we achieved 92% estimation accuracy in simulation. Furthermore, we created the electromagnetic phantom that simulates the abdomen of the human body, including the organ phantom, and verified the effectiveness of the proposed algorithm. As a result, the target estimation

accuracy was achieved in 89.7% of all measurement. The place where the error is large is almost the same in the simulation and the actual measurement. It was confirmed that the algorithm proposed in this study is also effective in the actual environment. As a future task, it is essential that the desired estimation accuracy is achieved at all estimation points. Therefore, it is necessary to develop a method for incorporating an algorithm that processes RSS separately for reflected waves and direct waves. In addition, since the estimation accuracy is generally high, if the estimated coordinates are extremely different from the coordinates estimated immediately before that, developing a method such as correcting the new estimated coordinates is necessary.

Acknowledgments

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