1. INTRODUCTION

Use of a highly accurate tracking system inside the human body is essential for medical applications such as catheters, endoscopes, etc. Conventional magnetic methods using a DC magnetic field, which utilizes a permanent magnet and magnetic field sensors1)-3), do not disturb the physiology because a magnet can operate without electric wires and batteries. However, these methods are hindered by the earth field. In conventional AC tracking systems 4), electrical wires or batteries are needed for transmitters and receivers.

The tracking system herein proposed is based on an AC magnetic position sensing system with a wireless resonated marker5). This system is available for highly accurate tracking without magnetic shielding because it is free from earth field noise. In a previous study6), we developed a tracking system utilizing a ribbon-type resonated marker, in which neither electric wires nor batteries inside the marker were necessary. We proposed a tracking system utilizing a nasogastric tube, the marker inside the tube being roughly tracked in the esophagus of a rabbit7). However, the proposed tracking system has a disadvantage in that the detectable area is smaller than the conventional AC magnetic tracking system4) in principle. The distance between the driving coil and the pickup coil array is only 300 mm because of a signal to noise problem6); therefore, expansion of the detectable area is one of the most prior factors for tracking markers inside a body or other applications. Thus, in the present study, a new tracking system with high-speed AD converters, a field programmable gate array (FPGA) and a high power amplifier was developed to enhance the signal to noise ratio of tracking markers. The distance between the driving coil and the pickup coil array was expanded so as to be about 2.7 times larger than that of the previously developed system6). The accuracy of the marker position was improved and the standard deviation of the marker position is high accuracy of about 10 times more accurate than that of the previously reported system6).

2. EXPERIMENTAL SETUP

2.1 Position sensing system

A new tracking system for a wireless magnetic ribbon type marker has been developed by using high-speed analog-to-digital [A/D] converters and a field programmable gate array (FPGA) module. The quality factor of the resonated marker (ribbon: 38 mm in length and 4 mm in width) was about 130. The standard deviation (position accuracy) was smaller than ~1/10 that of the previous system because the sampling frequency of the A/D converters was more than 100 times higher and because the FPGA operated at high speed. The distance between the driving coil and the pickup coil array was ~820 mm, which was ~2.7 times larger than that in the previously reported system. The profile of the marker we obtained was relatively smooth and reasonable up to a distance of 475 mm from the pickup coil array.

Key words: tracking system, resonated marker, position accuracy, FPGA
Marker position and direction are optimized by the Gauss-Newton method\(^8\) using equations (2)-(4).

\[ S(\bar{\mathbf{p}}) = \sum_{i=1}^{n} (B_m(i) - B_c(i)(\bar{\mathbf{p}}))^2 \]  

(2)

\[ B_c(\bar{\mathbf{p}}) = \frac{1}{4\pi m_e} \left( \frac{S}{r_1^3} + 3(M\cdot\bar{\mathbf{p}})\cdot\bar{\mathbf{p}} \right) \]  

(3)

\[ \bar{\mathbf{p}} = (x, y, z, \theta, \phi, M), \]  

(4)

where \( S \) is the least square value, \( n \) is the sensor number, \( B_m \) is the measured flux density and \( B_c \) is the theoretical flux density which is taken into account by the dipole field, \( p \) is the parameters of the resonated marker, \( M \) is the magnetic moment of the marker, \( (x, y, z) \) is the position of the marker, and \( \theta \) and \( \phi \) are the orientation angles of the marker. \( i \) is a pickup coil number. The algorithm is based on the equation of an ideal dipole field, which is expressed as a function of the position and orientation as shown in equations (2)-(4).

Fig. 2 shows the experimental setup of the driving coil, the pickup coil array and the marker. The distance between the driving coil and the pickup coil array is about 820 mm, which is about 2.7 times larger than in the previous system\(^6\). The marker was scanned for 100 mm by using a manual positioner (composed of a three-dimensional stage, each stroke being 100 mm). Fig. 3 shows the arrangement and the position of 40 pickup coils as a circle. The 40 pickup coils are arranged in the x-y plane (z=0 mm). The pickup coil array has a grid structure and the distance between the neighboring pickup coils is 75 mm. Fig. 4 shows a photograph of the PXI system. The AD converters convert the inputted sinusoidal signals into digital data at a sampling frequency (120 MS/sec), which is 100 times higher than that of the previously developed system\(^5\). The AD converters are connected to the FPGA modules (NI PXIe-7962R). Each FPGA module converts the sinusoidal digital data into the amplitude and the phase much faster than in the previous system in which the controller (CPU) converted the digital data directly.
3. EXPERIMENTAL RESULTS

3.1 Resonated marker
Photographs of the resonated marker are shown in Fig. 5. The marker is composed of magnetic ribbons (37 mm long and 4 mm wide) and a permanent magnet. The marker was originally developed by Sensormatic Electronics Corporation9). The magnetostrictive ribbons are vibrated by magnetic field at resonance frequency. Fig. 6 shows resonance characteristics of the marker. The quality factor was obtained by $f_r/\Delta f$, $f_r$ being resonance frequency and $\Delta f$ being half width of the resonance frequency. The resonance frequency of the marker is about 60 kHz and the quality factor of the resonance is about 130.

3.2 Position accuracy (comparison with previous system)
Positional accuracy of the tracking system was evaluated by the setup shown in Fig. 2. The distance between the driving coil and the pickup coil array was changed to 350 mm. Fig. 7 shows the x position and the y position as functions of the z position when the marker is slowly moved about 100 mm in the z direction. The marker direction is parallel to the z axis. The measured profile was compared with that of the previous system6) in Fig. 7. The same coils (the driving and the pickup coils) and the same marker were used for the comparison. The solid line and dotted line show the profile measured by the new system, symbols show that measured by the previous system6). The measurement and optimization cycle is about 10 Hz. The measured profile is smooth and the measured data roughly agree with those of the actual profile. A standard deviation of about 0.27 mm is obtained at z=200 mm, which was about 1/10 of that measured by the previous system (standard deviation was about 2.8 mm) because the sampling frequency of the AD converters is more than 100 times higher and because the FPGA operates at high speed.

3.3 Marker profiles
Fig. 8 is a schematic of movements of the marker in this section. The distance between the driving coil and the pickup coil array was 820 mm, as shown in Fig. 2. The marker was first moved by 300 mm in the z direction, the profile of the marker being shown in Fig. 9. The marker was then moved by 100 mm in the x and y directions, the profile being shown in Figs. 10, 11 and 12. The marker is set parallel to the z axis.

Fig. 9 shows the profile of the marker when the marker was scanned for 300 mm in the z direction (from z ≈ 175 mm to z ≈ 475 mm). The x-y position of the marker was around the center of the pickup coil array, as shown in Fig. 8. The measurement and optimization cycle is about 10 Hz. Fig. 9(a) shows the projective profile of the marker in the z-x plane (top view) and (b) shows that of the z-y plane (side view). The profile was combined with three strokes (each one z ≈ 175-275 mm, z ≈ 275-375 mm and z ≈ 375-475 mm; respectively), because the maximum stroke of the positioner is only 100 mm. The measured profile is smooth and reasonable up to position z of 475
mm from the pickup coil array. The position accuracy slightly decreases with an increase in the distance between the marker and pickup coil array. The detectable area is about 3.4 times larger than in the previous study\(^6\).

Fig. 10 shows the projective profile of the marker in the z-x plane (top view) when the marker was scanned for 100 mm in the x direction in \(z \approx 175\) mm, 275 mm, 375 mm and 475 mm. Fig. 11 shows the projective profile of the marker in the z-y plane (side view) when the marker was scanned for 100 mm in the y direction in \(z \approx 175\) mm, 275 mm, 375 mm and 475 mm. Fig. 12 shows the projective profiles of the marker in the x-y plane (parallel to the pickup coil array) when the marker was scanned for 100 mm in the x and y directions: \(z \approx 175\) mm, 275 mm, 375 mm and 475 mm. The straight stroke of 100 mm was accurate. However, the manual positioner was not fixed to the coordinate of the pickup coil array, and thus the measured profiles are not always parallel with each other in Figs. 10, 11 and 12. The measured profile is comparatively smooth and reasonable up to the z position of 475 mm from the pickup coil array. However, the profile accuracy slightly decreases especially for \(z\) of 375 mm and 475 mm.

Fig. 13 shows the relative position accuracy as a function of the \(z\) position. The accuracy, \(\delta\), was obtained from the measured position of Figs. 10, 11 and 12 by the equation (5).

\[
\delta = \sqrt{(d_x - d_x(\text{act}))^2 + (d_y - d_y(\text{act}))^2 + (d_z - d_z(\text{act}))^2},
\]

where \(d_x\) is the x part of the measured stroke, \(d_y\) and \(d_z\) are the y and z parts, respectively. \(d_x(\text{act})\) is the x part of the actual stroke of the marker, and \(d_y(\text{act})\) and \(d_z(\text{act})\) are the y and z parts, respectively. The accuracy was within 5 mm in the position of \(z=375\) mm or less, which is acceptable to distinguish marker inside an esophagus from that inside a trachea because the thickness of
The distance between the neighboring pickup coils should be expanded to enhance the position accuracy over 500 mm.

4. CONCLUSIONS

1. A new tracking system of a resonated marker (4 mm in width, 37 mm in length, Quality factor was 130) utilizing high-speed AD converters and a FPGA module was developed.

2. The standard deviation of the marker position is smaller than about 1/10 of that of the previous system because the sampling frequency of the AD converters is more than 100 times higher and because the FPGA module operates at high speed.

3. The distance between the driving coil and the pickup coil array is about 820 mm, which was about 2.7 times larger than that in the previous system. The obtained profile of the marker is relatively smooth and reasonable up to a distance from the pickup coil array of 475 mm. The detectable area is about 3.4 times larger than that in the previous study.

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