DEVELOPMENT OF 3-D POSITION SENSOR BY USING PERMANENT MAGNETS IN THE DIGESTIVE TRACT

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Abstract: Medical capsule devices such as video capsule endoscopes are finding increasing clinical application. At present, there are no technologies that can measure the capsule position in the digestive tract. We have developed a 3-D position sensor for the digestive tract based on a permanent magnet. The position of the magnet is measured using a fluxgate magnetometer and Newton's laws. A prototype sensor was developed and evaluated *in vitro* and *in vivo*. The sensor was capable of accurately measuring the position of the permanent magnet up to 300 mm from the magnetic sensor array with an accuracy of 6.5 mm.

Introduction

Many people throughout the world suffer from diseases of the digestive tract. Recently, such diseases are increasing in Japan due to changes in diet [1]. Endoscopic examination is particularly useful for the detection and diagnosis of these diseases. Since its development in 1868, the endoscope has become indispensable not only in the diagnosis of diseases of the digestive tract but also in numerous medical treatments. Endoscopic examinations must be performed by trained doctors, but even still the patient can experience a certain amount of pain during and after the examination. Moreover, although unlikely, there is the risk of puncturing the intestinal tract and related problems [2]. As such, development of a capsule endoscope has been desired for many years. Although such a sensor was developed as early as 1957 [3], medical application of this capsule-type sensor was not widespread due to high costs and the lack of related technology. The development of a video capsule endoscope was first announced in 2000 [4], and since then these endoscopes have been clinically applied [5]-[10]. This advance is significant because it means that endoscopic examinations can now be carried out in the small intestine where conventional endoscopes can not be used.

However, technologies for measuring the capsule position inside a living body have not yet been established. Although methods have been developed which can roughly measure capsule position, precise measurement over an extended period of time is difficult. Consequently, diagnosis using only the image transmitted from the capsule endoscope is difficult without positional information. To solve this problem, we have developed a small wireless sensor capable of continuously measuring capsule position in the digestive tract.

As a method of 3-D position measurement, various physical phenomena can be considered, for example, ultrasonic waves and electromagnetic waves, including light. However, these methods prove unsuitable for measurement inside a human body. More suitable for position measurement in the digestive tract is a method that uses a magnetic signal, because the signal is not suppressed by, or harmful to, living tissue. Many types of 3-D position sensors using alternating magnet fields have been commercialized and applied to various fields, including education, medicine, military affairs, and entertainment. However, it is difficult to apply these systems to the measurement of capsule position in the digestive tract because the sensor is connected to external control box by a thick cable and the sensor is too large to swallow. The present paper describes the fabrication of a sensor intended for medical application and the results of measurement accuracy *in vitro* and *in vivo*.

Materials and Methods

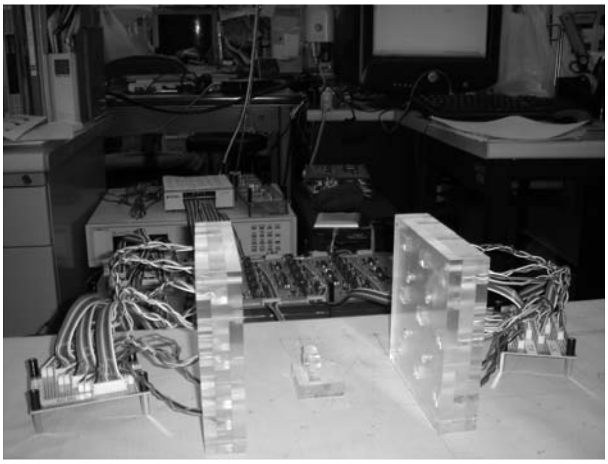

Figure 1: Photograph of the sensor system.

Figure. 1 shows our sensor system, which consists of two magnetic sensor (fluxgate magnetometer) arrays, a small permanent magnet and a display device with a signal processor. The magnetic field generated by the permanent magnet can be calculated by the Bio-Savart law, expressed for this application by (1), using the coordinate system of Figure 2.

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$$\vec{B} = \frac{\mu_0}{4\pi}\left\{\frac{3\left(\vec{M}\cdot\vec{R}\right)\vec{R} - \vec{M}\left|\vec{R}\right|^2}{\left|\vec{R}\right|^5}\right\} \qquad (1)$$

$$\vec{R} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \quad \vec{M} = \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} = |M|\begin{pmatrix} \sin\varphi\cos\theta \\ \sin\varphi\sin\theta \\ \cos\varphi \end{pmatrix}$$

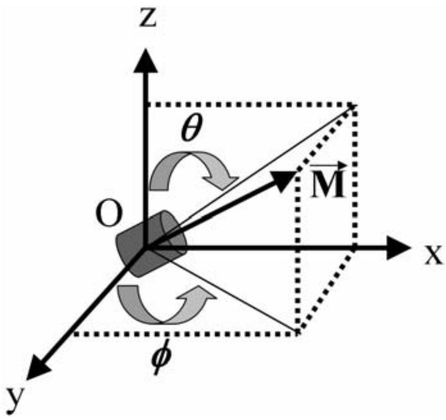

Figure 2: Coordinate system for Equation (1)

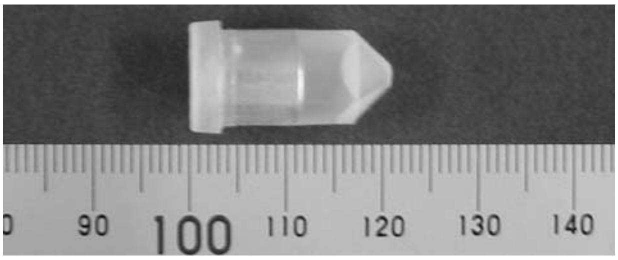

Figure 3: Permanent magnet in capsule

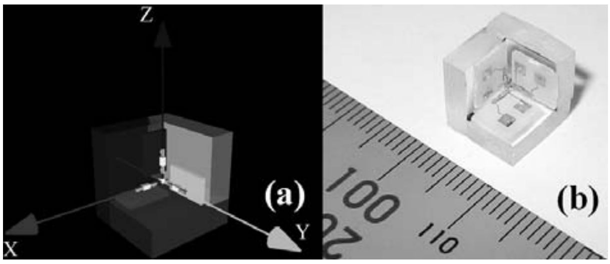

Figure 4: Magnet sensor
(a) CG Image of 3-axis sensor
(b) 3-axis sensor

Here, μ_0 is the permeability of a vacuum and M is the magnetic moment of the permanent magnet. Equation (1) is constructed with five unknown variables, *x, y, z, θ, ϕ*, that describe the position of the permanent magnet. Consequently, it is possible to measure the position of the permanent magnet by solving simultaneous equations with five variables using five measured data. The equations is solved by Newton's laws. Next, the measuring value is calibrated, as described in [11]. The calibration method used neglects the influence of magnetic metals but does take into account magnetizable metals. However, when using magnetic fields, the environment in the measurement space affects the accuracy of measurement. The calibration is necessary because magnetizable metals are likely to exist in measurement spaces such as operating rooms or hospital rooms.

Figure 3 shows the permanent magnet. A rare earth magnet of 0.5 T maximum flux density (NEOMAX) is used. The permanent magnet is set in a waterproofed cylindrical capsule about 20 mm in diameter and about 15 mm in length.

Figure 4 shows the 3-axis magnet field sensor used in the sensor array. As mentioned above, we use fluxgate magnetometers for the sensor. Because a fluxgate magnetometer can only measure the magnet field that crosses the sensor vertically, three sensors are arranged perpendicularly to measure the magnet field vector.

The signals generated by the magnetic sensors are taken into a computer (Precision 530, Dell Inc.) through an A/D converter; the computer then calculates the position. The A/D converter, signal processing and displays are controlled by a PC-based signal processing system (LabVIEW, National Instruments). The I/O of all signals is synchronized.

Results

Figure 5 shows the change in fluxgate output for measurement over a long time without the permanent magnet. The slight change in output was found to be due to an A/D quantization error; the output is shifted by 0.015V as a result of initial offset adjustment. To measure the magnet field with greater accuracy, a more efficient A/D device is considered necessary.

Figure. 6 and 7 show the results of an accuracy evaluation. The permanent magnet was placed on sectioned graph paper and the actual position of the capsule was compared with the measured position. In this evaluation, the maximum measurement error was 6.5 mm and 9.4 deg within a 300 mm range from the magnetic sensor array. The display device with the signal processor continued to function stably at 32 Hz.

As mentioned above, calibration is necessary to correct for the effect of magnetizable metals. Figure 8 shows the relationship between the position of magnetizable metals in the immediate environment and error without calibration. A steel can with a volume 500 times that of the capsule was used as the magnetizable metal object. Figure 8 shows that a large magnetizable metal object within 100 mm of the sensor caused the error to increase 2-3 times. This experiment provided a means to confirm the efficacy of our calibration method. A magnetizable metal object (iron) was placed in the measurement space, and the true value, measured value and calibrated value were compared (Figure 9). Using the calibration method, the error was decreased by 34 %.

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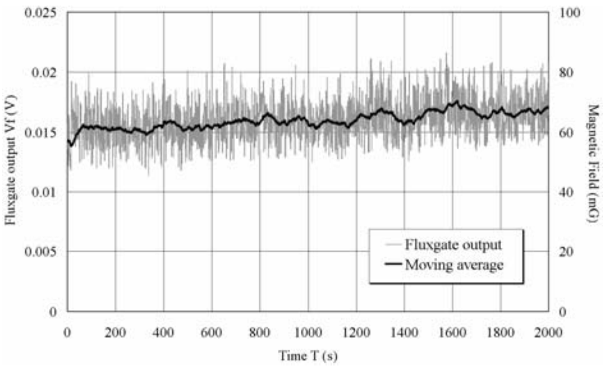

Figure 5: Change of fluxgate output over time

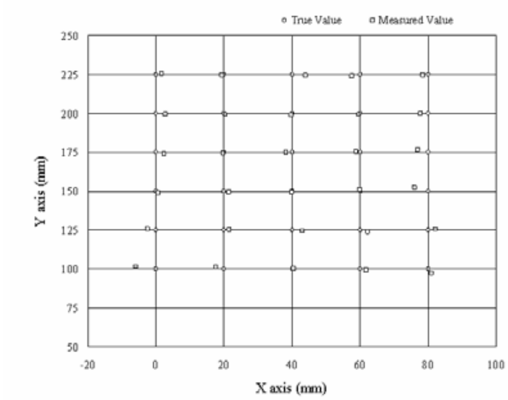

Figure 6: Accuracy verification in a field parallel to the magnetic field generator

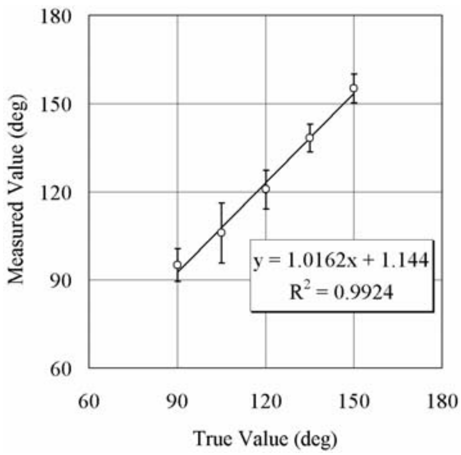

Figure 7: Accuracy verification for angle

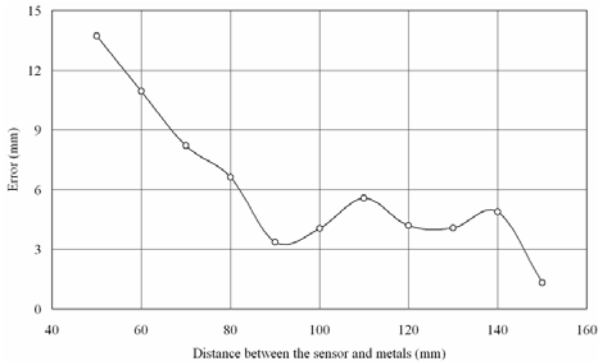

Figure 8: Relationship between position of magnetizable metal and error

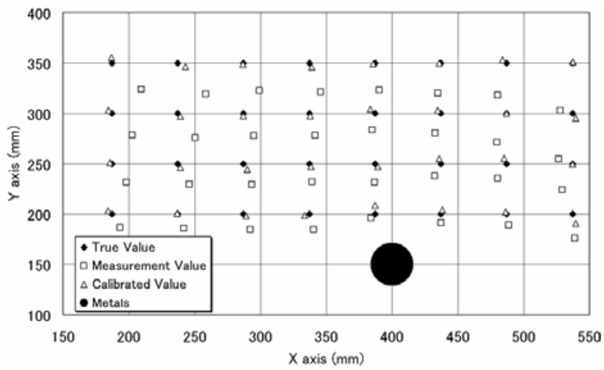

Figure 9: Calibration of measured values at locations near a magnetizable metal

The sensor system was tested on a goat with the treatment conducted with the approval of the Tohoku University. The organs used for measurement were the esophagus and a lung; for measurement in the esophagus, a permanent magnet was inserted and moved using a transparent pipe (shown in Figure 10) because the movement of the gullet decreases under anesthetizing, and for measurement in the lung, the chest was opened and the permanent magnet sewn directly onto the lung surface to observe the movement of the lung during breathing.

The position of the magnet in the esophagus was monitored simultaneously by ultrasound CT. Figure 11 shows the magnet position in the esophagus. The measured 3-D position of the magnet attached to the lung surface is shown in Figure 12. The goat breathed 10 times per minutes with an artificial respiration device under anesthesia. Figure 12 shows the lung moving back and forth every 5 or 6 seconds.

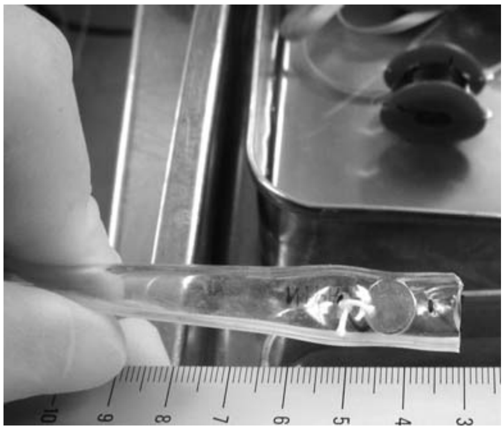

Figure 10: Magnet enclosed with tube

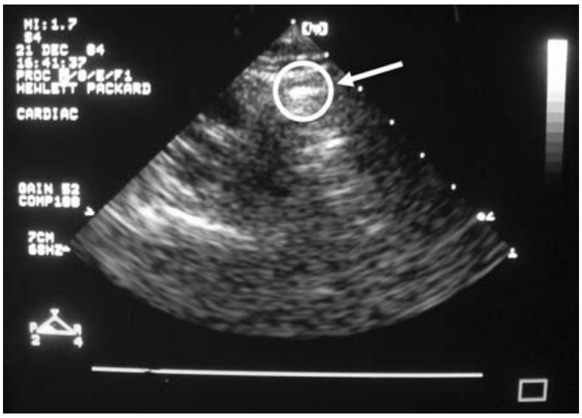

Figure 11: Observation of the permanent magnet by ultrasound CT. The marker shows the permanent magnet.

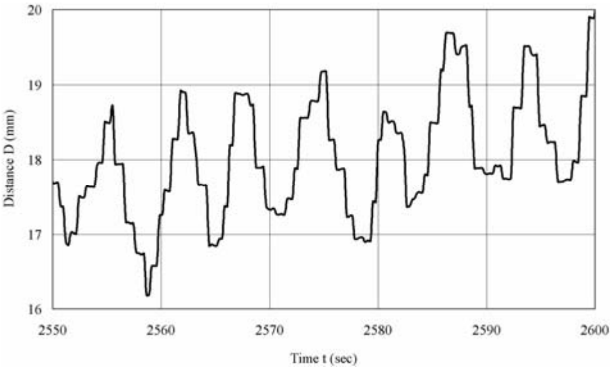

Figure 12: Movement of the permanent magnet attached to the lung surface

Discussion & Conclusions

The newly developed 3-D position sensor performed adequately *in vitro* and *in vivo*. Although the new sensor is approximately half the size of conventional 3-D position sensors that use a magnetic field, the proposed sensor exhibited almost the same performance with respect to accuracy and response. However, the proposed sensor could not measure several position especially far from the array because the sensor was not able to measure the magnetic field precisely. This problem may be solved by improving the accuracy of the sensor using a new design. For future work, we plan to develop a new sensor array, as depicted in Figure 13. The new device will have more sensors than the present device, enabling the magnetic field to be measured more accurately. Currently, we are searching for the best array arrangement of the sensors by computer simulation.

Using the sensor in the present work, it was possible to measure the position of the permanent magnet without any significant increase in error, even in a measurement space in which a magnetizable metal was present. The sensor is targeted towards the digestive tract, for example, in tracking of the movement of the digestive tract. Although this aspect has been studied since the 19th century [12], many of the functions of the large and small intestine have not been completely clarified because of the difficulty of quantitative measurement. In addition to investigation of the digestive tract, the sensor could also be used in other applications. The wireless sensor developed in the present study is a step towards the future development of medical capsule devices.

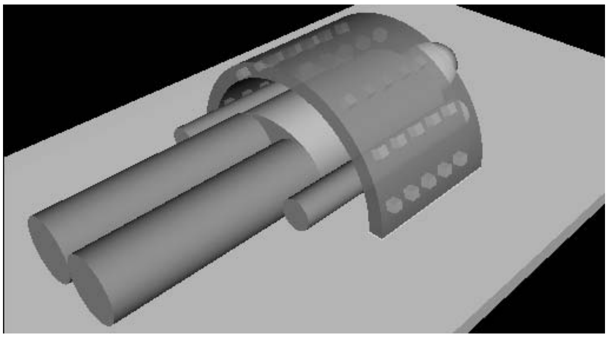

Figure 13: Optimization of sensor arrangement by computer simulation

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References

[1] Statistics and Information Department Minister's Secretariat Ministry of Health and Welfare, Summary of Vital Statistics (1999)

[2] YOSHIHARU U. (2002): 'Complications and their Managements During Diagnostic Colonoscopy', *Clinical Gastroenterology*, **17-8**, pp.1165-1173

[3] MACKAY R. S. and JACOBSON B. (1957): 'Endoradiosonde', *Nature*, **179**, pp.1239-1240

[4] IDDAN G., MERRON G., GLUKHOVSKY A. and SWAIN P. (2000): 'Wireless capsule Endoscopy', *Nature*, **405**, pp. 417

[5] COSTAMAGNA G., SHAH S.K., RICCIONI M.E., FOSCHIA F., MUTIGNANI M., PERRI V., VECCHIOLI A., BRIZI M.G., PICCIOCCHI A. and MARANO P. (2002): 'A prospective trial comparing small bowel radiographs and video capsule endoscopy for suspected small bowel disease', *Gastroenterology*, **123-4**, pp.999-1005

[6] LEWIS B.S. and SWAIN P. (2002): 'Capsule endoscopy in the evaluation of patients with

suspected small intestinal bleeding: Result of a pilot study', *Gastrointestinal Endoscopy*, **56-3**, pp.349-353

[7] ROSSINI F.P. and PENNAZIO M. (2002): 'Small-bowel endoscopy', *Endoscopy*, **34-1**, pp.13-20, 2002

[8] HAHNE M., ADMAEK H.E., SCHILLING D. and RIEMANN J.F.(2002): 'Wireless capsule endoscopy in a patient with obscure occult bleeding', *Endoscopy*, **34-7**, pp.588-590

[9] APPELEYARD M., FIREMAN Z., GLUKHOVSKY A., JACOB H., SHREIVER R., KADIRKAMANATHAN S., LAVY A., LEWKOWICZ S., SCAPA E., SHOFTI R., SWAIN P. and ZARETSKY A. (2000): 'A randomized trial comparing wireless capsule endoscopy with push enteroscopy for the detection of small-bowel lesions.', *Gastroenterology*, **119-6**, pp.1431-1438

[10] ELL C., REMKE S., MAY A., HELOU L., HENRICH R. and MAYER G. (2002): 'The first prospective controlled trial comparing wireless capsule endoscopy with push enteroscopy in chronic gastrointestinal bleeding', *Endoscopy*, **34-9**, pp.685-689

[11] DAY J. S., MURDOCH D. J. and DUMAS G. A. (2000): 'Calibration of position and angular data from a magnetic tracking device', *Journal of Biomechanics*, **33-8**, pp.1039-1045

[12] JACOBJ C (1890): 'Oharmakologische Untersuchung über das Colchicumgift', *Arch. Exp. Path. Pharmakol*, **27**, pp.119-157

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