30th Annual International IEEE EMBS Conference
Vancouver, British Columbia, Canada, August 20-24, 2008

Magnetic Endotracheal Tube Imaging Device

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Abstract— **This paper describes an accurate, economical, and portable device that helps to locate the position of an endotracheal tube (ETT) in situ. The device uses an array of magnetic field sensors to detect an anomaly in magnetic field caused by magnet embedded near the cuff of an ETT, and displays an intuitive map of relative magnetic field intensity under the sensor area. The device provides real-time feedback of the position to a clinician, so that corrective measures can be taken if the ETT is determined to be outside of normal positioning with respect to the patient's airway. Variations of the proposed design are suitable for continuous monitoring.**

I. INTRODUCTION

THE endotracheal tube (ETT) is a staple of hospital procedures, used to keep patient airways open during mechanical ventilation. The ETT is inserted a specific depth into the trachea through the mouth or nose, or through an incision in the neck. Properly placing this tube requires a high level of skill and training as ETTs can be accidentally placed into the patient's esophagus cutting off airflow to the lungs, or be placed into the bronchial tree for one lung, often leaving the other to collapse. Improper placement and unplanned displacement of these tubes are both catastrophic problems that can result in patient mortality or morbidity. Often times, these problems occur simply because the expertise required for immediate replacement of ETTs cannot be maintained at the bedside of every patient. Even though ETTs are currently secured in place with a variety of tape and/or tie systems, unplanned tube loss occurs about 10% of the time for a variety of reasons, including inadequate patient sedation, inadvertent traction on the ventilator tubing, or movement of the tongue, jaw, or head.

The position of the tube is currently monitored by inspection of the point of insertion and by periodic chest X-rays. Unfortunately, the former does not necessarily reflect the position in the trachea, as the tubes (especially in small children) are very pliable and enlarging curves of the tube may be obscured in the patient's throat. Chest X-rays, even if taken daily are too infrequent monitors of ETT position, and are undesirable because of unnecessary radiation exposure to patients. Given the difficulty and the importance of maintaining a properly positioned ETT, there is a need for a simple and reliable method to inspect the position of an ETT.

Manuscript received April 7, 2008. This work was supported by the Center for Integration of Medicine and Innovative Technology (CIMIT).

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II. THEORY OF OPERATION

A number of techniques for monitoring tube position have been investigated, each with inherent benefits and drawbacks. Acoustic reflectometry transmits audible sound waves into the respiration system and processes the reflected waves to determine the location of the tube inside the body [1]-[3]. This technique can be unreliable since proper placement is not registered to anatomical features of a patient. Additional methods using higher frequency ultrasonic waves have shown improved efficacy, at the cost of additional complexity [4], [5]. Another technique involves monitoring pulmonary compliance to infer proper ETT placement from volume and pressure measurements [6]. This method requires a specifically designed respirator, or complex supporting system to obtain the appropriate PV measurements. Carbon monoxide detectors [7] are used to assess placement of the ETT during initial intubation, but it does not provide sufficiently fast response time for continuous monitoring.

Magnetic field sensing is a highly attractive sensing modality for monitoring the position of ETTs as magnetic fields can penetrate the body tissue without impedance. By embedding a permanent magnet or a magnetically active object, the position of an ETT can be detected from the intensity of the magnetic interaction. This technique is also attractive for continuous monitoring since the hardware requirements are relatively simple and low-cost. One realization of this idea, developed by Cullen [8], uses magnetically coupled resonance between a metal band attached to the ETT and an external excitation source and detector. Another realization, developed by Pan [9], uses permanent magnet tags embedded in the ETT that are detected using a Hall-effect sensor.

The key engineering tradeoff in this measurement scheme is the size of the magnet versus the expected field strength at the detector. If the magnet is too large, it poses difficulties in being embedded into the ETT and can infringe on the patient's airway. This issue is especially important for ETTs used for children, which have smaller diameters and are

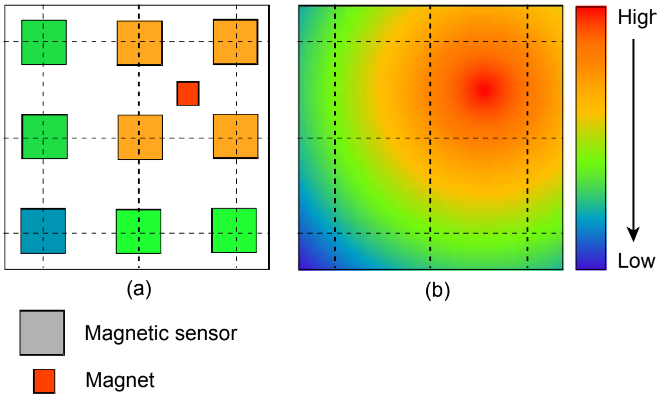


Fig. 1. Illustration of the METTID concept and color map output example.

more pliable. If the magnet is too small, the magnet sensors will not receive sufficient signal to be measured above background signals such as the earth's magnetic field. The innovation presented in this paper overcomes this tradeoff by using an array of magnetic field sensors with spacing much greater than the size of the magnet tag. In this arrangement, the magnet can be reasonably approximated as a dipole point source. The position of the magnet in three-dimensional space can be estimated from the sensor signals using interpolation, while the effect of common-mode field can be subtracted as a constant offset value experienced by all sensors. We call the proposed device the Magnetic EndoTracheal Tube Imaging Device (METTID).

This measurement concept is illustrated in Fig. 1a as a three-by-three sensor array where the baseline level is shown in green, while stronger field intensities are represented with increasing shades of red. Operation of the METTID device is straightforward. To confirm initial intubation, or inspect a previously intubated patient, the handheld device is moved along the respiratory airway near the sternal notch. The LCD screen overlaid above the sensor array shows a color map of the local magnetic field, as shown in Fig. 1b. The color map allows the user to intuitively interpret and estimate the location of the magnet tag and to improve that estimate by moving the device.

The magnet tag in the ETT is embedded above the inflatable cuff, placing the tag at the patient's sternal notch, an easily locatable and highly invariable anatomical feature across individuals. At this location, accidental esophageal intubations are easy to detect, as the esophagus lies much deeper in the patient relative to the trachea.

The directional anisotrophy of magnetic sensors are an important consideration as all single element magnetic field sensors are directional, and thus sensitive only along one preferred axis. Off-axis magnetic fields produce a response proportional to the magnitude of the vector subcomponent along this direction. This property means that if the magnetic field is aligned perpendicular to the sensitive axis of the sensor, the net measurement will be zero. This scenario is generally not a problem as the curvature of the field will result in measurable fields even if the dipole-moment is perpendicular with the sensor array. Nonetheless, in order to maximize the signal detected by the METTID, the dipole direction from the magnet tag and the sensitive axis of the magnetic field sensors are both aligned axially along ETT to maximize the detected signal.

III. System Description

A. Magnetic Sensor Array

The METTID uses Giant Magneto-Resistive (GMR) sensors to measure the magnetic field. GMR sensors are more sensitive than Hall-effect sensors, but typically have a greater per-unit cost. As implemented in the prototype, and illustrated in Fig. 1, the sensor array is composed of a three-by-three array. The sensors are AAH-002 devices from NVE Corporation which have a supply-dependent sensitivity of 11mV/V/G, resulting in 36.3mV/G when operated from a 3.3V source.

A 16-input differential analog multiplexer (Analog Devices ADG726) is used to select the signal from the nine different sensors. This architecture enables a single signal conditioning circuit, amplification stage, and analog-to-digital converter to be used for all sensors.

B. Processing and Control

The central processor is responsible for digitizing the GMR sensor signal, interpolating the results, and computing the spatial position of the magnet. A single channel 10-bit analog-to-digital-converter (ADC) is used to serially sample each element on the sensor board, while updating the LCD.

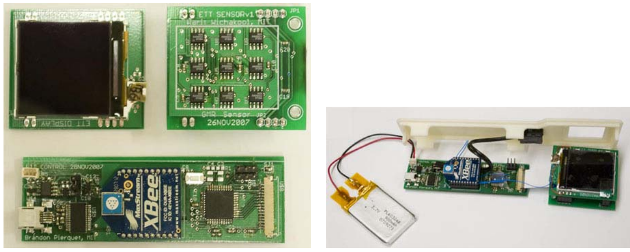
C. User interface

A 132x132 pixel color LCD is aligned with, and installed directly over the top of the sensor board. In one example interface, the display is divided into nine equal squares, where each square changes color progressively from green to red as the associated sensor magnitude increases from baseline to maximum. A more processor intensive version provides a full color gradient of the interpolated data, as shown in Figs. 6 and 7.

A second visual interface, employable alone or as an overlay, could calculate and display the location of the magnet. The location to be indicated by a circle with a radius that indicates confidence of the estimate, and a color based on the distance to the magnet.

D. Physical design

The METTID is designed to be portable, and sized to fit comfortably into the hand or a pocket. The sensor array is positioned in the head of the device for ease of use, and the LCD positioned directly over it to accurately convey the magnet position. The handle of the device houses the processing circuitry as well as the battery and communications hardware. Fig. 2 shows photographs of the circuit boards and how they assemble to fit into the case.

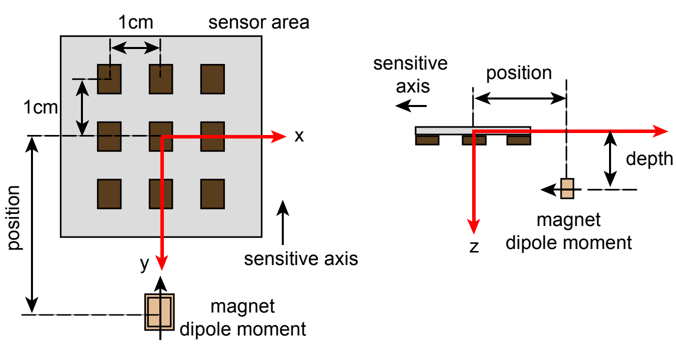


(a) Prototyped circuit (b) Device assembly

Fig. 2. Circuit boards and prototype assembly

IV. Results and Discussion

Experiments have been performed to quantify the sensitivity of the GMR sensors, as well as to demonstrate the efficacy of the proposed design. Using the setup shown in Fig. 3, the output signals from the sensor array are recorded at various positions of the test magnet. The magnet used in these experiments is a neodymium disc magnet with a 3 mm diameter and a 2 mm thickness, polarized in the axial direction, normal to the surface of the disc. The sensor array is placed in a test structure that enables the magnet to be placed repeatably at various coordinates along X, Y, Z directions with the origin being at the center of the sensor array. The sensor plane was aligned parallel to the magnet plane and its dipole moment direction to ensure optimal sensor response.



(a) (b)

Fig. 3. Sensor array dimension and test setup

Fig. 4 shows the response of the single center sensor as a function of magnet position in the Y-direction, the zero position represents when the magnet was below the center sensor. The result shows that the sensor is clearly responsive to the magnet within 1 cm along the sensitive axis. The secondary peaks seen outside of the 1 cm region for small Z values are a consequence of the single axis sensing in near-field measurement conditions.

Fig. 5 shows the sensor response in the Z-direction when placing the magnet directly underneath the center sensor at several depths. The results show the drop-off as the magnet separation increases, confirming the ability to measure sensor depth to approximately 2.2 cm.

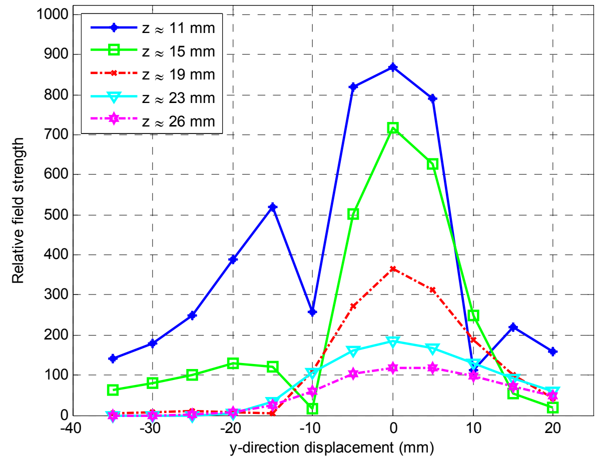


Fig. 4. Sensor responses at different distances and depths

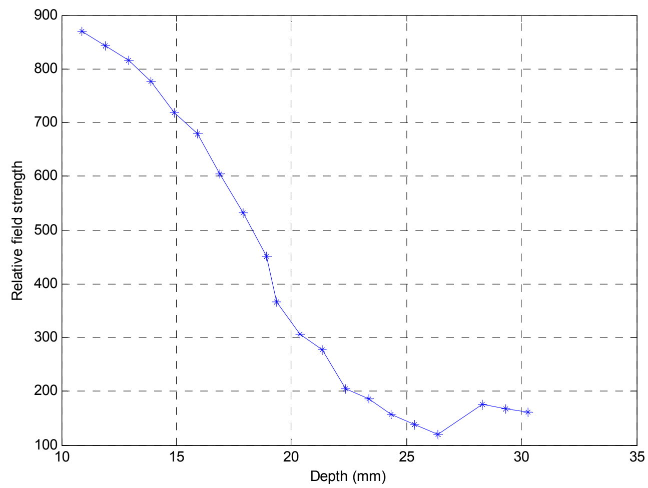


Fig. 5. Sensor responses as a function of depth when the magnet was placed directly under the sensor.

Two-dimensional visualizations of sensor data with the magnet located at various Z-coordinates are shown in Fig. 6. The (X,Y) position of the magnets are maintained at the (0,0) position for these plots. The sensor data are smoothed using cubic interpolation. These results demonstrate the improved robustness of the two-dimensional measurement array compared to a single sensor. If the magnet is not directly below the center sensor, the array reported the maximum field strength at the off-center location as shown in Fig. 7.

The values measured using the GMR sensors are vector components of the total magnetic dipole field along their axis of sensitivity. The expected magnitude variation as measured by the sensor is govern by the equation,

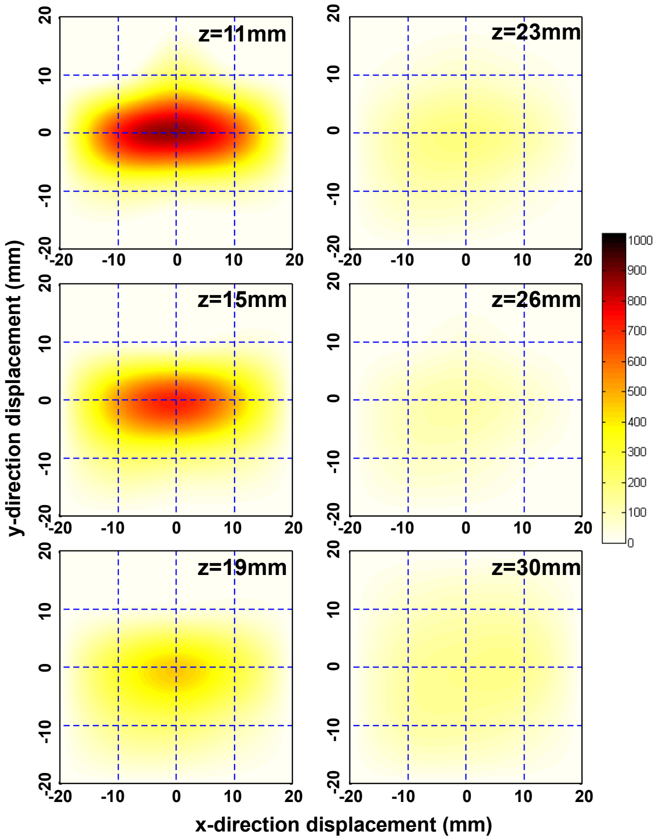


Fig. 6 Visualization of the depth perception of the center sensor reading as the sensor was moved away from the magnet vertically

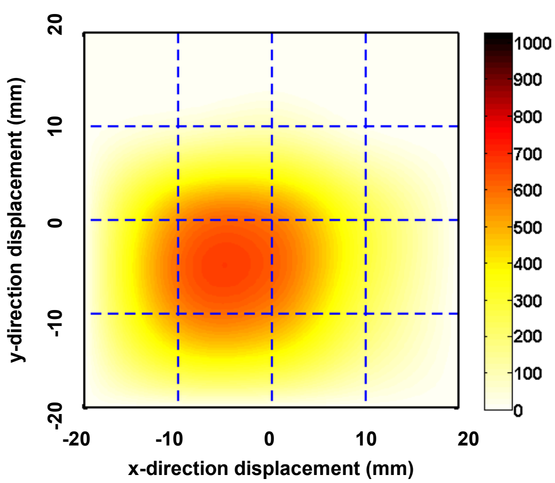


Fig. 7 The color map of the magnetic field strength when the magnet location was off-center, z=15mm

$$B(\vec{r}) \propto \frac{3{r_y}^2}{|\vec{r}|^5} - \frac{1}{|\vec{r}|^3}, \quad (1)$$

where $\vec{r}$ is the vector to the dipole, and r_y is the Y-component. This equation yields an increasingly ellipsoidal shape for near-field measurements as seen in Fig. 6. The rapid decay of the magnetic field in both X and Y constrains the density of the sensor array to prevent blind spots within the area. Higher sensor density may further improve the measurement resolution, and reduce reliance on the computationally intensive interpolation algorithm.

A key limitation of this measurement technique is the directional anisotropy of the magnetic field. This means that the user must manually maintain alignment of the sensor in order to obtain a valid estimation of the Z-distance. Alternatively multi-dimensional magnetic field sensors can be used at the expense of additional cost and complexity.

V. Conclusion

We have developed a hand-held, battery operated device to determine the position of a small magnet affixed to an endotracheal tube. The device has a high sensitivity and the two-dimensional sensor array configuration allows the unit to display an intuitive, user-friendly color map on the LCD. The color scheme enables the depth perception of the magnetic tag, allowing differentiation between intubation in the trachea and esophagus. This device will allow doctors and hospital staffs to perform intubations with increased confidence, and monitor intubated patients for tube movements to prevent unplanned extubations.

Acknowledgment

The authors would like to acknowledge Shane Colton and Chris Salthouse for their help with debugging the prototype circuits.

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