

Detection of Weak Magnetic Signal for Magnetic Localization and Orientation in Capsule Endoscope*

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Abstract - A permanent magnet is embedded in the capsule endoscope to perform as an excitation source for tracking capsule's position and orientation, and a magnetic sensor array is built around the capsule to capture the signals from magnet. However, the magnet-field signal is weak and attenuates dramatically when the spatial distance between the magnet and the sensor increases. How to detect this weak magnetic signal will be the key factor to influence the tracking accuracy, so a high stable, sensitive, anti-interference magnetic measurement system must be developed. In this paper, we present a weak magnetic signal detection system which is composed of Honeywell 3-axis magnetic sensors, high performance analog multiplexers, low noisy amplifiers, 16 bits A/D converter, and ARM controller. Especially, some processing measures are employed to reduce the sensors' tolerance and enhance the sensitivity and dynamic range of localization system. The experimental results show that this detection system can be effectively applied for the cubic magnetic sensor array with the measurement space of $0.5\text{m} \times 0.5\text{m} \times 0.5\text{m}$.

Index Terms - *Wireless Capsule Endoscope, Magnetic Localization and Orientation, Magnetic Sensor, Weak Signal Detection*

I. INTRODUCTION

Diseases in the Gastrointestinal (GI) tract are among the most widespread threatening diseases all around the world. According to a publication of the Hong Kong Cancer Registry in March 2003, the cancer caseload in Hong Kong has been increasing [1]. Currently, for the gastrointestinal (GI) tract examination, the endoscopes provide an effective treatment tools. Typically, GI endoscopes can be categorized into two major groups: cable endoscopes and wireless capsule endoscopes. The former one was used in the traditional treatment over the past decades, while the latter one has been used as a multidisciplinary production just in the recent years. Comparing with the traditional cable endoscope, the wireless endoscope has its advantages. The patients will no longer suffer much uncomfortable during the GI tract examination, and it makes possible to examine entire intestine [2]. On the other hand, the doctor can analyze the interesting tissues by

viewing the captured images after the examination. However, the current capsule endoscope can only capture the images, which might miss some information for diagnosing. Sometimes, the doctors need to know the accurate positions of the pathological tissues to make more accurate diagnosis. Also, for the further treatment or operation, the surgeon needs to know position of the target tissue.

However, the capsule endoscope goes through the GI tract inside the human body, we can not see it directly during the whole examination process. To address the problem, we should develop a novel technique to accurately track the position and movement of target capsule endoscope. Although there are some localization techniques, the magnetic localization is a practical and available choice. This is because magnetic technique has some advantages in such applications. The human body has the magnetic permeability very close to that of the air, and exerts very little influence on the static (or low frequency) magnetic signal such that it is possible to achieve high tracking accuracy [3-4].

For the magnetic localization, there exist some difficulties, corresponding to the accuracy and measurement range. Although the accuracy can be improved by developing some new robust algorithms [5-6], it is difficult to enlarge the measurement range, due to the dramatic magnet's signal attenuation in space [7]. Therefore, a high stable, sensitive, anti-interference magnetic measurement system must be developed. In this paper, we present a novel efficient magnetic sensor array system with the measurement space of $0.5\text{m} \times 0.5\text{m} \times 0.5\text{m}$.

An entire magnetic localization and orientation system includes two parts: the hardware system and the software system. In this paper, we mainly consider about the design of hardware. Especially, the weak signal detection system, it is a main component in hardware system.

The rest of this paper is organized as follows: In section II, we introduce the hardware system briefly. In section III, we analyze the offset voltage of sensor and provide a compensation technique. In additional, the reset/set circuit is

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discussed. In section IV, we introduce the amplifier gain combination for weak signal. In section V, we present the experimental results and give some analysis. At last, the conclusion is given in section VI.

II. HARDWARE SYSTEM OVERVIEW

Fig. 1 shows the block diagram of hardware system of magnetic localization and orientation system. Hardware system is constructed by a Honeywell 3-axis magnetic sensors array, high performance analog multiplexers, analog signal procession circuits, low noisy instrumentation amplifiers, a Compensation circuit, a 16 bits A/D converter, a power apply module, and an ARM controller.

The controller LPC2387 is the brain of hardware system, which is NXP product, 32bits ARM-based microcontroller. It manages all components and executes software system. The magnetic sensor array is made of sixty-four 3-axis magnetic sensors. Each of the 3-axis sensors has 3 channels analog outputs X, Y, and Z. It sends out an analog voltage signal relative to magnetic intensity in the sensor position. To amplify the weak magnetic signal, a high performance amplifier is necessary. We use AD8251 that is an instrumentation amplifier with digitally programmable gains with several $G\Omega$ input impedance, low output noise, and low distortion. It is suitable for the interfacing with the sensors and high sample-rate analog-to-digital converter. The amplifier gains are selected by ARM controller's GPIO pins. Because there are 192 (sixty-four 3-axis sensors * 3 channels/sensor) signal channels, analog multiplexers are used to switch the different analog signals corresponding to different magnetic sensors. Also, the analog channels are selected by controller's digital output pins. The 16 bits analog-to-digital converter ADS8509 provides high ADC resolution to ensure the precision of sampled signal for localization. Moreover, because of the requirements for weak signal detection, we focus on the compensation of sensor and amplifier gain combination to reduce the sensor's error and enhance the sensitivity and input range of amplifier.

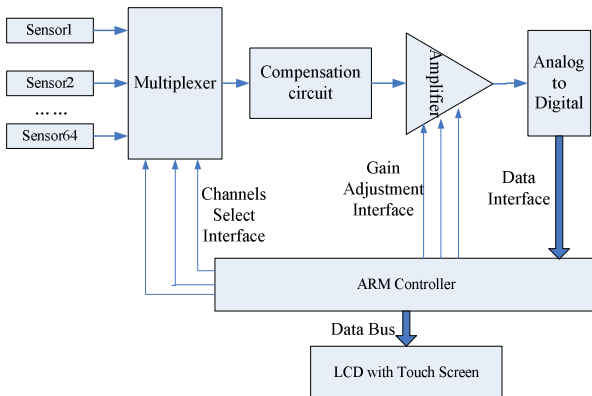


Fig.1 Block diagram of hardware system.

III. COMPENSATION FOR MAGNETIC SENSOR

To realize such a magnetic localization and orientation system, a sound sensing system is necessary. This system must

have high tracking accuracy, high robustness, and easy realization. Nevertheless, it should work continuously in real-time mode [5].

We considered many types of magnetic sensors, and finally choose the Honeywell magnetic sensor, HMC1043, because of its high sensitivity and anti-interference ability. It is a 3-axis AMR (Anisotropic Magneto-resistive) sensor, which has a resolution of $100\mu\text{Gauss}$ and a full range of $\pm 6\text{Gauss}$ [8]. Fig.2 shows its schematic diagram and pin configuration. In the sensor, each of the axes has four resistors made by thin films on the silicon base. These four resistors work in a differential mode. The resistance in two of them (in the opposite side) increases, while that of other two resistance decreases, with the input magnetic intensity, and this differential resistance variation will linearly produce a voltage output change in the Wheatstone bridge.

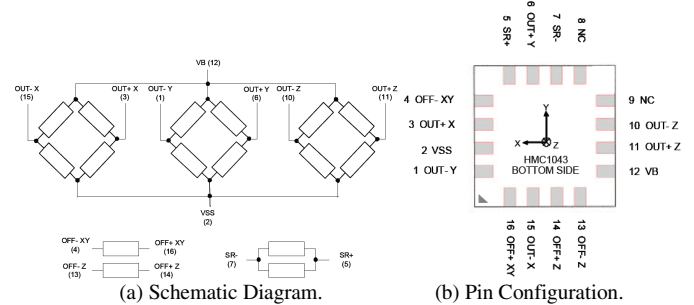


Fig.2 Honeywell 3-axis sensor HMC1043.

A. Output Signal Range of Sensor

The sensitivity of HMC1043 is 1mV/Gauss/V . That is, if it exposes in its minimum resolution magnet field of $100\mu\text{Gauss}$, the sensor bridge output due to the field with V_b of 5V is $0.5\mu\text{V}$. It's a pretty small signal. On the other hand, if it is in the full range of $\pm 6\text{Gauss}$ and supply with 5V , its output voltage reaches to $\pm 30\text{mV}$.

B. Balance Adjustment of Wheat-stone Bridge

The Wheat-stone Bridge offers many advantages, however, it also generates an undesired output voltage without any external magnetic stimulus, it is known as an offset voltage. This is the disbalance of Wheat-stone Bridge. Offset voltage is result of the difference in voltages of the output nodes, V_{o+} and V_{o-} as show in Fig.3. The bridge offset voltage is primarily caused by inexact resistance values of each bridge arm. Even an error of a fraction of one Ohm can create a sizable offset voltage.

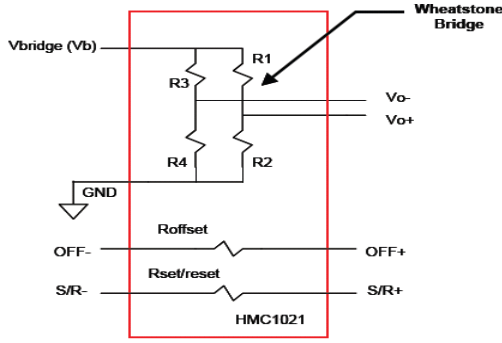


Fig.3 Bridge circuit of sensor.

As shown in Fig.3, the bridge element resistors R1, R2, R3, and R4 are nominally 1100Ω each. Thus the positive bridge output node voltage (Vo+) will be:

$$V_{O+} = V_b [R_2 / (R_1 + R_2)] \quad (1)$$

The negative bridge output node voltage (Vo-) will be:

$$V_{O-} = V_b [R_4 / (R_3 + R_4)] \quad (2)$$

So, the resulting bridge offset voltage will be:

$$V_{off} = (V_{O+} - V_{O-}) = V_b \{ [R_2 / (R_1 + R_2)] - [R_4 / (R_3 + R_4)] \} \quad (3)$$

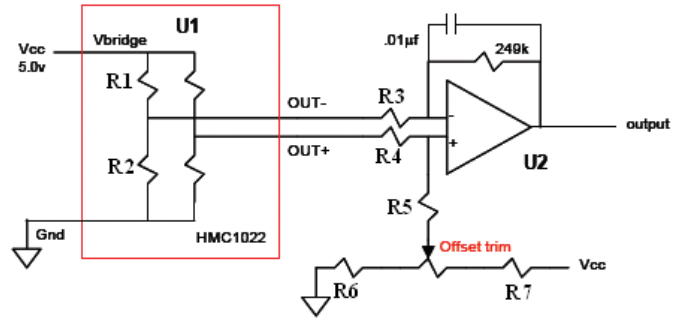
If R1 and R4 are 1101Ω with R2 and R3 remaining at 1100Ω, with $V_b = 5V$, then, according to (3), $V_{off} = -0.00227V$ or $V_{off} = -2.27mV$. Comparing with the minimum resolution of sensor, 0.5μV, it is a pretty large voltage.

However, all of these resistors keep the same values over the whole application life of the sensor. Moreover, the offset voltage is proportional to bridge supply voltage. Considering these two aforementioned characteristics, we can use them to reduce the influences of offset voltage.

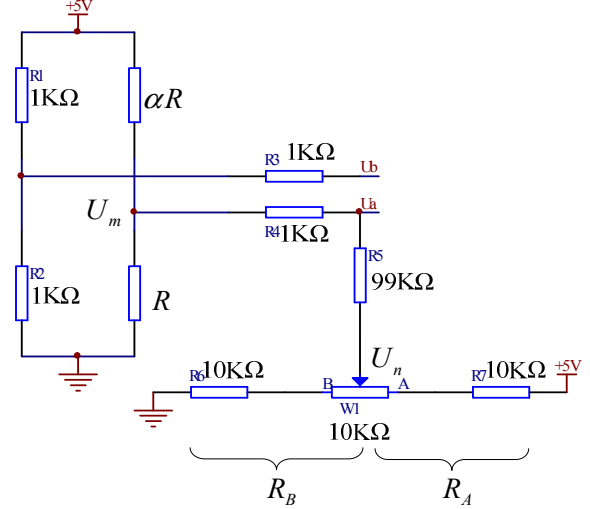
C. Analysis of the Compensation Circuit

There are several methods can be used to counteract the influence of bridge's offset voltage. In this paper, we present an "amplifier bias zero adjustment" method, as shows in Fig.4 (a). If $R1 \neq R2$ and $R3 = R4$, Out- will not equal to Out+. Therefore, there is an offset voltage between the positive and negative input of amplifier. Adjusting the potentiometer (offset trim) can reduce the error to zero.

From Fig. 1, we can see that all analog channels use one common compensation circuit. But, the offset voltage of each analog channel is not same. Each analog channel corresponds with a potentiometer value. That is, the traditional mechanical potentiometer is not suitable for this application. A linear taper digital potentiometer is chosen to do adjustment, and it is controlled by the digital interface from microcontroller.



(a) Amplifier bias zero adjustment.



(b) Simply model.

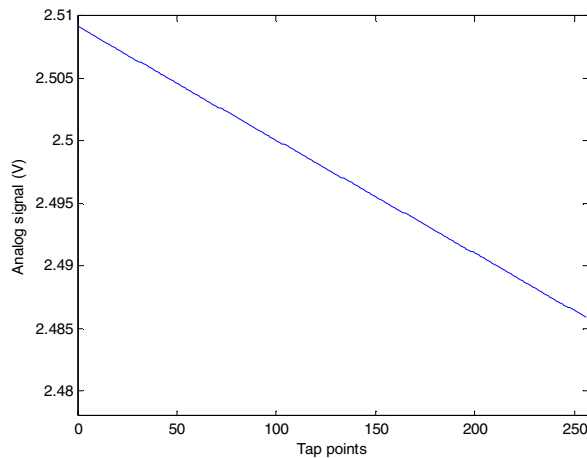
Fig.4 Compensation model.

In Fig.4 (a), because of the high input current impedance and low leakage current of instrumentation amplifier, we can simplify Fig.4 (a) to Fig.4 (b). Digital potentiometer W1, MAX5403, has 256-tap points and its total resistance is a 10kΩ. The parameter x is the tap point of potentiometer; it changes from 1 to 256. Resistance R_A includes R6 and $10K \cdot x / 256$; Resistance R_B includes R7 and $(256 - x) \cdot 10K / 256$. Signal α is the tolerance of each bridge arm. Obviously, $U_b = 2.5V$. According to the Kirchhoff's law, the equations are built as follow:

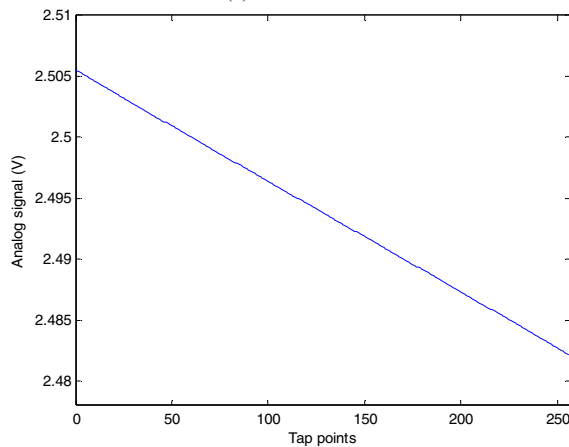
$$\begin{cases} \frac{5V - U_m}{\alpha \cdot R} = \frac{U_m}{R} + \frac{U_m - U_n}{100K} \\ \frac{U_n}{R_B} = \frac{U_m - U_n}{100K} + \frac{5V - U_n}{R_A} \\ U_n + \frac{U_m - U_n}{100K} \times 99K = U_a \\ R_B = 10K + \frac{256 - x}{256} \cdot 10K \\ R_A = 10K + \frac{x}{256} \cdot 10K \end{cases} \quad (4)$$

In (4), supposing $R=1K\Omega$. The relations between U_a and x with $\alpha = 1.002$, $\alpha = 1.005$, and $\alpha = 1.008$ are shown in Fig.5 (a), (b), and (c) respectively. It approaches to linear relation. From Fig.5, we can see that even the tolerance of one bridge in Wheat-stone Bridge is as large as 8%; the offset voltage can be counteracted by compensation circuit to adjust U_a to approach to 2.5V.

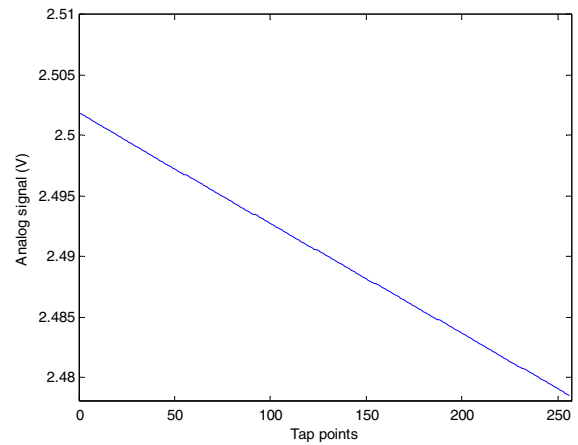
Now, we can analyze the offset voltage when tolerance of one bridge arm is 8% without compensating the circuit. In Fig.3, defining $R_1=1008\Omega$, $R_2=1000\Omega$, $R_3=R_4=1000\Omega$, according to (3), then $U_{off} = -9.96mV$. Referring to the specification of HMC1043, the maximum offset voltage of each bridge is ± 1.25 per volt supply. The maximum offset voltage will reaches to $\pm 6.25mV$ with V_b of 5V; it is within the range which can be effectively adjusted by the compensation circuit.



(a) $\alpha = 1.002$



(b) $\alpha = 1.005$

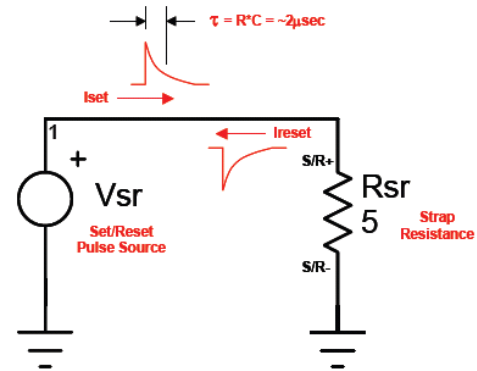


(c) $\alpha = 1.008$

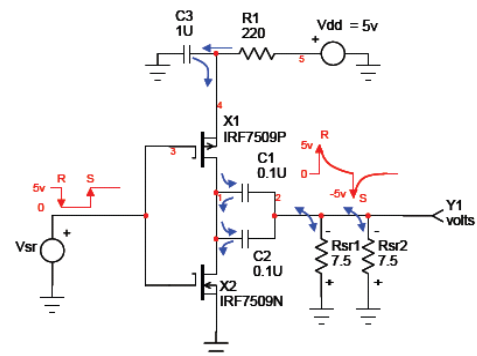
Fig.5 The relation between analog signal (U_a) and tap points(x)

D. Reset/Set Circuit

Honeywell's Anisotropic Magneto-Resistive (AMR) sensors are fabricated with Permalloy (NiFe) a thin film that changes its resistance respect to external magnetic fields. The reasons to perform a set or reset on an AMR sensor are: 1) To recover from a strong external magnetic field that likely has re-magnetized the sensor, 2) to optimize the magnetic domains for most sensitive performance, and 3) to flip the domains for extraction of bridge offset under changing temperature conditions. Fig.6 (a) shows the simplistic schematic "set/reset" circuit, and Fig.6 (b) shows the practical circuit. The control pulse applied on gate electrode of IRF7509 is generated by microcontroller.



(a) Simplistic schematic circuit.



(b) Practical circuit.

Fig.6 Set/Reset Circuit.

In Fig.6 (b), Rsr1 and Rsr2 are the set/reset strap resistors. C1 and C2 are the charge/discharge capacitors. Simply, the equivalent resistor is 3.75Ω , and the equivalent capacitor is $0.2\mu F$. Time constant $\zeta=R*C=0.75\mu sec$, the peak current through Rsr1 and Rsr2 is $1.33A$. It satisfies the demand of reset/set current.

IV. AMPLIFIERS FOR WEAK SIGNAL

The amplifier is a key component in hardware system. It amplifies weak signal to enough amplitude to fix the input range of analog-to-digital converter. Therefore, the amplifier must have some performance conditions, such as: high performance, high input impedance, low noise, and etc. Comparing to other amplifiers, AD8251/3 not only has the aforementioned characters, but also its digital programmable gain.

From the analysis of output range of sensor in section II part A, we can see that the range of analog output of sensor is from $\pm 0.5\mu V$ to $\pm 30mV$ with $5V$ supply. Supposing that all analog signals are amplified to $4.5V$, for the smallest signal, $0.5\mu V$, gain should be $9,000,000$; for the largest signal, $30mV$, gain should be 150 . As we know, there is not any amplifier can provide such large gain. Therefore, we must use polystage amplifiers to get enough gain for the weak analog input signal.

Programmable gains of AD8251: 1, 2, 4, and 8 [9].

Programmable gains of AD8253: 1, 10, 100, and 1000.

The available amplifier gain combination is shown in table I.

TABLE I
AMPLIFIER GAIN COMBINATION

Analog input range	Amplified amplitude	Total gain	AD8251	AD8253
$0.5\mu V \sim 0.5mV$	$4mV \sim 4V$	8000	8	1000
$0.5mV \sim 2mV$	$1V \sim 4V$	2000	2	1000
$2mV \sim 10mV$	$0.8V \sim 4V$	400	4	100
$10mV \sim 30mV$	$1V \sim 3V$	100	1	100

V. EXPERIMENTAL RESULTS

To verify the performance of hardware system, we measure two group data. The first one is measured without compensation circuit, and the second one is measured with compensation circuit. Both the measures are under the same conditions: 1) the distance between permanent magnet and magnetic sensor is $30cm$; 2) the gains are set at 8000 , that is the gain of AD8251 is 8 and the gain of AD8253 is 1000 ; 3) making the magnetic line of force parallel with the X axis of magnetic sensor, the direction of magnetic line of force is as same as the positive direction of X axis of magnetic sensor; 4) set and reset the sensor before testing.

A. Measure without Compensation Circuit

In this experiment, we used 3 sensors to measure the output voltages which were magnified with 8000 times. The results are listed in the second column of table II.

B. Measure with Compensation Circuit

There are 2 steps in this experiment.

Firstly, the permanent magnet was removed. Then, the digital potentiometer is adjusted to make the output voltage of amplifier equal to zero. This step is called the "calibration".

Secondly, the permanent magnet is put at the same position as in former experiment. In the current experiment, we use 3 sensors too. The output voltages of amplifier are listed in third column of table II.

TABLE II
TEST RESULTS OF HARDWARE SYSTEM

Sensor Num	Output voltage(V), without compensation circuit	Output voltage(V), with compensation circuit
Sensor 1	0.274	0.928
Sensor 2	-3.85	0.957
Sensor 3	1.072	0.920

C. Analysis of Data

Comparing the second column to the third column in table II, we can see that the data in the second column are higher random. On the contrary, the data in the third column is more regular. The reason is that each data of the second column is composed by 2 parts: the offset voltage of sensor and the valid voltage that is excited by the permanent magnet. The data in third column are valid voltages. That is, if it subtracts the data in the third column from the corresponding data in the second column, the result is offset voltage.

VI. CONCLUSION

A new hardware system that is efficiently applied in magnetic localization and orientation system is presented in this paper. Considering the output signal of magnetic sensor HMC1043, the detected magnetic signal is pretty weak and has a large variation range. To reduce the errors of sensor signals and enhance the input range of amplifier, we emphasize on the compensation circuit of sensor and the adjustment of the amplifier gains, the compensation circuit is suitable for the magnetic sensor even it is under the worst condition. After the system is built, we tested the output voltages of amplifier with the compensation circuit and without compensation circuit respectively, and the results show that the hardware system can counteract the error which is brought by the offset voltage effectively.

In addition, the test distance between target magnet and sensor is $30cm$. If a target capsule which contains a permanent magnet is placed at the center of a measurement cube, the shortest distance between magnet and sensor is $25cm$. Therefore, our system can be effectively applied for the cubic measurement space of $0.5m \times 0.5m \times 0.5m$.

REFERENCES

- [1] Wei Wang, "A Study on RF Based Wireless Capsule Endoscope", *Proceedings of the 2006 IEEE International Conference on Mechatronics and Automation*, June 25-28, 2006, pp.1663-1667.
- [2] Max Q.-H. Meng, Tao Mei, Jiexin Pu, Chao Hu, Xiaona Wang, Yawen Chan, "Wireless Robotic Capsule Endoscopy: State-of-the-Art and Challenges", *Proceedings of the 5th World Congress on Intelligent Control and Automation*, June 15-19, 2004, pp.5561-5565.
- [3] Wilfried Andra, Henri Danan, Walter Kimbe, Hans-Helmar Kramer, Pieter Saupe, Rainer Schmieg, and Matthias E Bellemann, "A novel method for real-time magnetic marker monitoring in the gastrointestinal tract", *Physics in Medicine and Biology*, 45(2000), 3081-3093.

- [4] W.Weitschies, J.Wedmeyer, R.Stehr, and L.Trahms, "Magnetic Markers as a noninvasive tool to monitor gastrointestinal transit", *IEEE transactions on biomedical engineering*, Vol.41, No.2, 1994, pp.192-195.
- [5] Chao Hu, Max Q.-H. Meng, Mrinal Mandal, Xiaona Wang, "3-Axis Magnetic Sensor Array System for Tracking Magnet's Position and Orientation", *Proceedings of the 6th World Congress on Intelligent Control and Automation*, June 21-23, 2006, pp.5304-5308.
- [6] Chao Hu, Max Q.-H. Meng, Mrinal Mandal, "The Calibration of 3-Axis Magnetic Sensor Array System for Tracking Wireless Capsule Endoscope", *Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China*, October 9-15, 2006, pp.162-167
- [7] Chao Hu, Tongxing Ma, Max Q.-H. Meng, "Sensor Arrangement Optimization of Magnetic Localization and Orientation system", *Proceedings of the 2007 IEEE International Conference on Integration Technology*, March 20-24, 2007, pp.311-315.
- [8] Magnetic Sensors Products application [online].
<http://www.ssec.honeywell.com/magnetic/products.html>
- [9] Programmable Gain Instrumentation Amplifier Application [online].
<http://www.analog.com/zh/amplifiers-and-comparators/instrumentation-amplifiers/ad8251/products/product.html>.