A Magnetic Tracking System based on Highly Sensitive Integrated Hall Sensors*

Vincent SCHLAGETER**, Predrag DRLJACA**,
Radiwoje S. POPOVIC** and Pavel KUČERA***

A tracking system with five degrees of freedom based on a 2D-array of 16 Hall sensors and a permanent magnet is presented in this paper. The sensitivity of the Hall sensors is increased by integrated micro- and external macro-flux-concentrators. Detection distance larger than 20 cm (during one hour without calibration) is achieved using a magnet of 0.2 cm³. This corresponds to a resolution of the sensors of 0.05 μT_{rms} . The position and orientation of the marker is displayed in real time at least 20 times per second. The sensing system is small enough to be hand-held and can be used in a normal environment. This presented tracking system has been successfully applied to follow a small swallowed magnet through the entire human digestive tube. This approach is extremely promising as a new non-invasive diagnostic technique in gastro-enterology.

Key Words: Magnetic Field Sensors, Magnetic Pill, Gastro-intestinal Motility

1. Introduction

Magnetic field sensors are often used for positional sensing system with the advantage of non-contact operation. The range of possible applications is wide and the number of degrees of freedom (dof) of the magnetic marker can vary from one up to five^{(1)–(3)}. The marker is a magnetic dipole, either a permanent magnet⁽⁴⁾ or a high frequency electromagnetic signal emitted by a coil⁽⁵⁾. The main advantage of the coil is the elimination of external noise, while the advantage of the permanent magnet is the simplicity of the system since no external excitation is required. For a number of dof larger than three, only expensive and cumbersome systems have been used up to now.

In a recent paper, we have described a tracking system with 16 Hall sensors and a permanent mag-

net⁽⁶⁾. The main limitation was the low frequency $1/f^\alpha$ noise of the sensors. In this paper, two approaches are presented to improve the accuracy of this system still based on highly sensitive integrated Hall sensors. The first improvement is gain in sensitivity by means of macro-flux-concentrators. The second is the reduction of the $1/f$ noise using the spinning-current method.

We also present a new medical application of such an improved tracking system, namely, the tracking of a small magnet along the entire human digestive system. This approach is very promising as it allows to obtain by using a single and totally non-invasive technique anatomical as well as functional information concerning gastro-intestinal motility.

2. Material and Methods

2.1 Description of the tracking system

Our tracking system consists of four components, as shown in Figs. 1 and 2. The marker is a rare earth cylindrical magnet, $\varnothing 6 \times 7$ mm, with a magnetic moment $m=0.2$ Am². The sensing system itself is a 4×4 -array of Hall sensors with flux-concentrators. The sensors are described in details in Results and

* Received 16th July, 2002 (No. 02-5096)

** EPFL-FSTI-IMM, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland

*** Institute of Physiology, Medical Faculty, University of Lausanne, Rue du Bugnon 7, CH-1005 Lausanne, Switzerland. E-mail: pkucera@physiol.unil.ch

Fig. 1 Photograph of the tracking system. On the screen is shown an on-line 3D display of a recorded trajectory of the marker (circular movements of the hand holding the magnet over the detection matrix; the side of the cube = 10 cm; the sampling frequency = 20 Hz).

Fig. 2 Block diagram of the whole system

Discussion. Each sensor measures one component of the magnetic field in the plane of the matrix, the x - for one half of them and the y -component for the other half (Fig. 3). The signal of each sensor is then amplified with a low-noise hybrid electronic circuitry designed for this specific application. Conventional acquisition electronics convert the analogue amplified signals to digital signals and sends them to a computer

Fig. 3 Definition of the coordinates system. The position of the magnet is defined by five coordinates, x , y , z and two angles θ and φ .

for further processing. The computer implements an iterative algorithm to recalculate the position of the magnet with respect to the sensors array.

The Levenberg-Marquardt optimisation algorithm⁽⁷⁾ is based on the equation of an ideal dipole

$$\vec{B}(\vec{m}, \vec{r}) = \frac{\mu_0}{4\pi} \frac{r^2 \cdot \vec{m} - 3 \cdot \vec{r} \cdot (\vec{r} \cdot \vec{m})}{r^5} \quad (1)$$

where the magnetic dipole m produces a magnetic field B at a distance r . The Levenberg-Marquardt algorithm is an iterative algorithm using a trust region method: smooth transition from steepest descent direction to the Newton direction (quadratic model) in a way that gives the global convergence properties of the steepest descent and the fast local convergence of Newton's method. The calculated position, five coordinates (x , y , z , θ , φ) as defined in Fig. 3, is then visualised in 2D vs. time or in 3D in real time up to 50 Hz.

3. Results and Discussion

3.1 Improvement of sensors

3.1.1 Improvement of sensitivity: flux-concentrators The concept of integrated twin magnetic flux-concentrators^{(8),(9)} is illustrated in Fig. 4. The idea is inspired by the conventional configuration of the combination of Hall magnetic sensor and rod-like magnetic concentrators (MC). The key difference is, however, that now the Hall element is placed not in, but near the air gap and under the concentrators. In this way, we can use conventional planar integrated Hall elements and we can define by photolithography the shape of MCs and the mutual positions in the system between MCs and Hall elements.

The integrated magnetic flux-concentrators consist of a high permeability and low coercive field (very soft) ferromagnetic layer bonded on the Hall sensor chip surface. The layer is structured so that a narrow

Fig. 4 (a) Integrated combination of Hall magnetic sensor and magnetic flux-concentrators: two Hall elements are placed under the planar magnetic concentrators⁽¹¹⁾. (b) Result of a two-dimensional simulation of twin planar MCs exposed to a homogenous magnetic field parallel with the MC-plane.

air gap is created approximately in the middle of the chip. Figure 4 shows the distribution of the magnetic field lines around the MCs. The MCs "suck in" the magnetic field lines and convert locally the magnetic field parallel with chip surface into a magnetic field perpendicular to the chip surface. The perpendicular component of the magnetic field is the strongest near the gap. There we place the Hall elements. We use two Hall elements because two equivalent places are available. The Hall plates below the different concentrators "sense" the useful magnetic field in opposite directions. Thus, the system is insensitive to an external field component perpendicular to the chip surface⁽¹⁰⁾ which results in increased signal-to-noise ratio.

We shall now estimate the main characteristics of the magnetic flux concentrator, which are the magnetic gain and the saturation field. We assume that integrated and macro magnetic flux concentrators are layer-like (the planar dimensions of an MC are much larger than its thickness t). Moreover, since in practice we work only with very high-permeability materials, such as amorphous metals with relative permea-

Fig. 5 The values of the factor K deduced from two-dimensional simulation of twin planar MCs

bility $\mu_r > 10^5$, we assume $\mu_r \rightarrow \infty$.

Magnetic gain

The magnetic gain of an MC is the ratio

$$G_{XY} = B_{HE}/B_0 \quad (2)$$

Here B_{HE} is the (perpendicular) component of the magnetic induction "seen" by the planar Hall element (HE) at a position (X, Y) (see Fig. 4) and B_0 is the magnetic induction component parallel with the axis of the MC faraway from the MC.

The magnetic scalar potential difference (i.e. the equivalent excitation current I_{ex}) acting between the two adjacent MCs may be expressed in the following way:

$$I_{ex} = KH_0(2L + g) \quad (3)$$

Here H_0 is the magnitude of the magnetic field vector H_0 before introducing the MC, $H_0 = B_0/\mu_0$. K is a numerical factor defined by $K = \int H_g dl / H_0(2L + g)$, where H_g is the magnetic field in the gap and the integration is done over the gap. K tells us which part of the theoretically available equivalent excitation current along the whole length of the MC we can really use around the air gap. From physical arguments we estimate the limits for K in the two-dimensional case, with $L \gg t$, as follows:

when $g/t \rightarrow 0$, then $K \approx g/t \rightarrow 0$; when $L \gg g \gg t$, then $K \approx 1/2$.

The values of K deduced from numerical simulations, Fig. 5, support these estimations.

By inspecting Fig. 4 we see that the magnetic field lines below the MC and close to the gap have approximately a circular form. This is always the case for high-permeability MCs and narrow gaps. Using this fact we find now the magnetic gain of a twin MC for a HE placed at (X, Y) :

$$G_{XY} = \frac{K(2L+g)X}{\pi(X^2+Y^2)} \quad (4)$$

for $X > g/2$, $g \approx t$ and $\mu_r \gg 1$

With an optimal layout of MC, for given t , L and g , one can further increase K and so the magnetic gain G_{XY} up to a factor of $2^{(12)}$. The realistic values of G_{XY} for an integrated sensor are between 5 and 10. But adding external MCs, this can be easily increased to about $100^{(11)}$.

Saturation field

By inspecting Fig. 4 we notice that the magnetic field lines have the highest density in the magnetic concentrators somewhere between the middle of each concentrator and the gap. We find the corresponding maximal magnetic flux density by calculating the total flux entering into an MC as follows:

$$B_{\max} \approx \mu_0 \frac{KH_0(2L+g)}{g} \left(1 + \frac{2}{\pi} \frac{g}{t} \ln(L/g) \right) \quad (5)$$

When this induction reaches the saturation induction B_{sat} of the MC material, our magnetic sensor shows a strong decrease in its magnetic sensitivity. The external magnetic field induction at the onset of the saturation is given by

$$B_{0sat} \approx B_{sat} g \left[K(2L+g) \left(1 + \frac{2}{\pi} \frac{g}{t} \ln(L/g) \right) \right]^{-1} \quad (6)$$

for $g \approx t$ and $\mu_r \gg 1$

For a sensor with the MCs of the total length $2L+g = 2$ mm, $t=g=20$ μ m and $B_{sat}=1$ T, we obtain $B_{0sat} \approx 10$ mT. By choosing an optimal form of the MC for given t , L and g , one can increase the saturation field up to a factor of $2^{(10)}$. In the next section, integrated micro- and macro-flux-concentrators are used to improve the sensitivity of the tracking system.

3.1.2 Implementation: cylindrical Hall device

In our first tracking system⁽⁶⁾, cylindrical Hall sensors with integrated flux-concentrators were used⁽¹³⁾. The noise of the sensors for the frequency range of interest (integration of the noise from 0.1 s to 1 h) was $2 \mu T_{rms}$.

We have now improved the sensors by adding macro-flux-concentrators with the length $L=8$ mm, glued on top of the integrated concentrators. We obtained the magnetic gain of 10. We can compare this value with the theoretical one, which is $L_{macro}/L_{integrated}=8/0.5=16$. The difference between the two values is mainly due to the air gap (glue gap) between the macro- and micro-concentrators.

The macro-concentrators do not add detectable noise, so the detectivity is improved by a factor 10 as well: now the noise of the sensor is $0.2 \mu T_{rms}$. Figure 7 compares the noise spectra of the sensors discussed in this paper.

For our application, the length of the macro-concentrators is limited by two factors. The first one is the saturation field, which will decrease if we keep

Fig. 6 Block diagram of the cylindrical Hall sensor module

increasing the length⁽⁶⁾. The second limit is due to the fact that we are not measuring a homogenous field and, if the concentrators are too long, we may deteriorate spatial resolution. This second point is certainly the limiting factor for the tracking application, that is the reason why further simulations are under way to better determine the limit for the length of MCs.

Since the cylindrical Hall device is a discrete device, all the electronics is discrete. Figure 6 shows the electronics needed for each of the 16 sensor modules. Often the Hall sensors are biased by a current source to ensure a stable sensitivity (reminder: the sensitivity is proportional to the current), but in our case a stabilised voltage source is the best choice. This is because the offset of the sensor is higher than the measured magnetic field (reminder: a large part of the offset due to geometrical dissymmetry is proportional to the input voltage). The amplification electronics does not add significant noise.

The improvement of accuracy of the tracking system is straightforward related with the improvement of the detectivity of the sensor. The equation of an ideal dipole (1) shows that the magnetic field decreases with the distance r with the power 3. So, if we can measure a 10 times smaller field, we will be able to track the same magnet at a distance $10^{1/3} \approx 2$ times larger, and increase the distance between the sensors by the same factor. This is true if we can neglect all external noise, and other errors; for instance, the approximation that we are measuring a field homogenous in the area of the concentrators (as discussed above). The real detection distance of the new tracking system is 1.5 times greater than the first one: 20 cm instead of 14 cm. Based on simulations⁽⁶⁾ we can also say that an improvement of the signal to noise ratio by a factor 10 will increase the accuracy of the position of the magnet more or less by the same factor.

3.1.3 Reduction of noise: Hall device with spinning current

In this section, we compare two sensors, the vertical Hall device presented in the previous section with a Hall ASIC realised in CMOS

Fig. 7 Noise spectrum of the cylindrical Hall device (CYH) with macro-concentrators (magnetic gain of 10), and of the spinning-current Hall device (ISA-1M) with and without macro-concentrators. Note the different slope of the $1/f^\alpha$ noise: $\alpha=1.0$ for the ISA-1M, and $\alpha=1.85$ for the CYH.

technology using the so-called spinning-current method. This method, which consists in periodic supply- and output-contact permutations, is widely used to reduce the offset and the low frequency noise of Hall sensors⁽¹⁰⁾. The spinning-current Hall device we used also combines integrated flux-concentrators (Type 1SA-1M, Sentron AG, Zug, Switzerland), and also gives the possibility to add external macro-concentrators. The magnetic sensitivity of the microsystem without macro-concentrator is 300 V/T and the equivalent offset field is 0.05 mT.

The noise spectra of both sensors are given for comparison in Fig. 7 which shows that there is still $1/f$ noise in the spinning-current device. This is due to the large $1/f$ noise of the CMOS technology, and especially the noise of the buffer, which is not chopper stabilised. However, if we integrate the noise in the frequency range of interest, we find a value of $0.45 \mu\text{T}_{\text{rms}}$ (without macro-concentrators) which is 5 times lower than for the cylindrical Hall. One might expect a more significant improvement thanks to the spinning-current method. Actually, a dedicated technology with very low noise was possible for the CYH sensor⁽¹³⁾, with the drawback that electronics needed for spinning-current cannot be integrated.

Once again, the use of macro-concentrators enables us to gain a factor 10 in the signal-to-noise ratio (Fig. 7). Accordingly, a similar further improvement in the detectivity of the tracking system as that described in the previous section can be achieved.

3.2 Medical application

The magnet tracing described above has been used to study the integrated motility of the human

Fig. 8 Photograph of a volunteer with the matrix of 4×4 sensors above the abdomen. The matrix with the acquisition card is connected to a laptop computer and a power supply (not shown).

digestive system. Ten volunteers were recruited for this study. They were lying back on the bed and the detection matrix was positioned over their abdomen with respect to surface anatomical landmarks (Fig. 8). The matrix is positioned as close as possible to the abdomen (1 to 2 cm), without touching the subject. The detection distance of 20 cm is large enough to track the magnet through all gastro-intestinal tract in most people. However, for overweighed subjects, an improved detectivity is still desirable. The magnet, as a pill coated with silicone, was swallowed and its position within the digestive tube was followed with short interruptions for 2 days⁽¹⁴⁾. There was no complication or complaint and all magnets were recovered within 3 days.

On-line observations revealed digestive rhythms (Fig. 9) and fast displacements. The recording in Fig. 9 is a typical example of the movement of the magnet in the stomach. 1 min out of a 75 min. acquisition, taken 1 hour after the magnet had been swallowed, is displayed. Three rhythms appears very clearly. Two of them are non-digestive: the heart beats (60/min) appears on the phi angle (A), and the ventilation produces a rhythmic (16/min) translation (B). Both can be filtered out easily. The third rhythm reveals the contractions of the stomach at the well-known 3/min slow wave frequency⁽¹⁵⁾. Notice that most of the time the gastro-intestinal rhythms are clearly seen on the theta angle: although the magnet stays at the same spot, a lot of information about the activity is obtained. Off-line analysis allowed for 3 dimensional reconstructions of the entire digestive tube (from the mouth to the rectum) which were in excellent correspondence with x-rays or CT scans done occasionally. In addition, this technique allowed for a detailed evaluation of the dynamics of luminal content

Fig. 9 Example of an on-line recording of the 5 parameters (x, y, z, θ, ϕ).

The figure shows 3 traces. The top one displays the x and y position of the magnet in mm, the second one shows the depth z in mm, the third one shows the rotations θ and ϕ in degrees. The duration of the display is 1 min. During the first 30 sec, the value of ϕ is out of the display window. The record was taken 1 hour and 14 min after the magnet had been swallowed. The magnet stays at one position (no overall drift of x, y, z) around which it oscillates. The oscillations show 3 rhythms: 60/min heart beats appear as small rotations on ϕ (A), 16/min ventilation on x, y and z (B), and 3/min gastric rhythm on y, z and θ (C).

propulsion (acceleration, speed, resting versus active periods). Figure 10 shows in a 3D manner the passage of the magnet from the terminal stomach to the beginning of the small intestine. Such a display can be of course obtained during the examination. A detailed analysis of this medically oriented study has been submitted to publication in specialized press⁽¹⁵⁾.

4. Conclusions

The results obtained with our first tracking system with 5 dof⁽⁶⁾ allowed us to develop another improved one. The accuracy of the new system was achieved by means of (a) macro-flux-concentrators and (b) the spinning-current method. We obtained a magnetic gain of 10 with macro-concentrators of the length $L=8$ mm without adding significant noise. The use of the spinning-current method reduced the noise in the range time range 1 h to 0.1 s by a factor 5, despite the large $1/f$ noise of the CMOS technology. Altogether the resolution of the sensors is now 50 times better ($0.05 \mu T_{rms}$) than in the first tracking system. It is now possible to track a magnet of 0.2 cm^3 up to a distance larger than 20 cm, in a normal environment.

Fig. 10 Trajectory of the magnet through the gastro-duodenal region.

Left: schematic drawing of the duodenal anatomy. Right: the trajectory of the magnet as recorded in the frontal plane in a healthy volunteer. The position of the magnet (sampled at 10 Hz) is plotted only every second. From such a plot can be derived not only the anatomical conformation and length of the digestive tube but also the dynamics of the gastro-intestinal motility, i.e., rhythmicity, speed and propulsive efficiency. The slow back and forth movements in the terminal antrum correspond to the 3/min rhythm shown in Fig. 8. The gastro-duodenal passage through the pyloric canal takes about 15 s, then the magnet stays for a considerable time in the bulb. Notice that the duodenal propulsion can attain 1 m/min.

Further work is under way to better determine the limit for the length of the flux-concentrators in this special application. A compromise must be found between the magnetic gain on one hand, and the spatial resolution of the sensors as well as the saturation field on the other hand.

The spinning-current method is promising for future improvement. In the first place, the sensor presented in this paper has a large bandwidth, over 100 kHz, which is not optimum for this application: by reducing the bandwidth, one can reduce the $1/f$ noise. In the second place, the use of Hall ASICs is very convenient for low electrical consumption and portable applications.

The tracing of a small magnet throughout the human digestive tube is an extremely promising application as it allows to determine not only the anatomical configuration but also evaluate the dynamics of the gastro-intestinal motility. This new approach is completely non-invasive and hence usable for long term and repetitive examinations which are not possible with the routine existing clinical exploratory methods.

Acknowledgements

We thank Dr. B. Meyrat from the Pediatric sur-

gery, University Hospital in Lausanne, for his expertise and help with the definition of experimental protocol used in the study with volunteers.

References

- (1) Baba, M., Shimizu, Y., Kenny, R., Maenaka, K. and Maeda, M., A Study of a Three-Dimensional Positional Sensing System based on an Analogue Neural Network with Three Inputs, Technical Digest of the 14th Sensor Symposium, (1996), pp. 289-292.
- (2) Jenks, W.G., Sadeghi, S.S. and Wikswo, J.P., SQUIDS for Non-destructive Evaluation, Review Article, J. Phys.(D), Vol. 30 (1997), pp. 293-323.
- (3) Weitsches, W., Kötitz, R., Cordini, D. and Trahms, L., High-Resolution Monitoring of the Gastro-intestinal Transit of a Magnetically Marked Capsule, J. Pharm. Sci., Vol. 86, No. 11 (1997), pp. 1218-1222.
- (4) Haynor, D.R., Somogyi, Ch.P. and Golden, R.N., System and Method to Determine the Location and Orientation of an Indwelling Medical Device, Patent US 5879297, 1999.
- (5) Dumoulin, Ch.L., Darrow, R.D., Schenk, J.F. and Souza, S.P., Tracking System to Follow the Position and Orientation of a Device with Radiofrequency Field Gradients, Patent US 5211165, 1993.
- (6) Schlageter, V., Besse, P.-A., Popovic, R.S. and Kucera, P., Tracking System with Five Degrees of Freedom Using a 2D-array of Hall Sensors and a Permanent Magnet, Sensors and Actuators A, Vol. 92 (2001), pp. 37-42.
- (7) Kelly, C.T., Iterative Methods for Optimization, (1999), SIAM, Philadelphia.
- (8) Popovic, R.S. et al., Magnetic Field and Current and/or Energy Sensor, Swiss Patent Application CH 030062/95, 1995.
- (9) Popovic, R.S., Drljaca, P., Schott, C. and Racz, R., Integrated Hall Sensor/Flux Concentrator Microsystems, 37th International Conference On Microelectronics, Devices and Materials, MIDEM 01, Bohinj, Slovenia, Oct. 2001.
- (10) Popovic, R.S. et al., Integrated Hall-effect Magnetic Sensors, Sensors and Actuators A, Vol. 91 (2001), pp. 46-50.
- (11) Drljaca, P. et al., High Sensitivity Hall Magnetic Sensors Using Planar Micro and Macro Flux Concentrators, Transducers '01, Munich, Germany, June 2001.
- (12) Drljaca, P., Vincent, F., Besse, P.-A. and Popovic, R.S., Design of Planar Magnetic Concentrators for High Sensitivity Hall Devices, Sensors and Actuators A, Vol. 97 (2002), pp. 10-14.
- (13) Blanchard, H., Chiesi, L. and Popovic, R.S., Cylindrical Hall Device, Technical Digest IEDM, (1996), pp. 541-544, IEEE.
- (14) Stathopoulos, E., Schlageter, V., Meyrat, B., Gudinchet, F., Popovic, R.S. and Kucera, P., Spatial and Temporal Analysis of Human Gastro-intestinal Motility by Using a Magnetic Tracer, Neurogastroenterology and Motility, Vol. 13 (2001), pp. 433-444.
- (15) Stathopoulos, E., Schlageter, V., Meyrat, B., de Ribaupierre, Y., Popovic, R.S. and Kucera, P., Examination of Human GI Motility by Using Magnetic Pill, submitted.