Magnetic sensor techniques for new intelligent endoscopic capsules

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Abstract: Endoscopic camera capsules for the imaging of the gastrointestinal tract are unrivalled for small bowel examinations, where standard endoscopy is not feasible. Still, capsule cameras have some substantial drawbacks in comparison with endoscopy, since they move only passively with the gastrointestinal motility and their position is not well known with nowadays localization techniques. We introduce AMR sensor (AMR = anisotropic magneto resistive) solutions at first to monitor the anatomical capsule position by use of a highly sensitive and calibrated sensor array from outside of the patients. Secondly, to control the status of legged locomotion at restricted space and energy directly inside the capsule, we use another AMR-sensor with 1 mm pole width.

1. VECTOR - Versatile Endoscopic Capsule for Gastrointestinal Tumor Recognition and Therapy

Within the sixth EU framework program, Sensitec, Innovent and 16 other European partners participate in the VECTOR project [1]. Within this project advanced technologies are being developed to enhance the diagnostic and therapeutic capabilities of video capsules for the gastrointestinal tract. These new developments add robotic features to the capsule, including magnetic and legged active motion, magnetic localization, drug delivery and tissue sampling.

Two techniques employed make use of AMR sensors. For the localization of the capsule, we record the quasi static field which originates from a small NdFeB magnet inside the capsule. Compared to signal or frequency bound localization, our solution needs only little space and no power supply inside the capsule. The magnetostatic field measurement of the slow moving marker allows for low pass filtering and time averaging to suppress environment and sensor noise. We use sensor arrays which measure all three spatial magnetic field components. The arrangement of the sensors has been optimized in order to capture the characteristics of the marker field and thus to maximise the sensitivity of the capsule position detecting algorithm. The AMR sensors are calibrated with respect to sensitivity, temperature dependence and exact measurement direction (onboard). The selectivity of the system to separate the marker field from the earth magnetic field and from man made static and slowly changing field sources and thus the localization accuracy depend on the accuracy of the sensor and sensor array calibration. With 0.1 Am^2 marker strength we realize a localization accuracy of 2-5 mm depending on the marker position.

The legged locomotion of the VECTOR capsule makes use of a miniaturized Namiki motor and a mechanic which translates rotation into movement of the legs. To control the legs positions, we monitor the rotation angle of the gear mechanics. With a LK 29 sensor chip (1 mm pole with) and a magnetic disc (Ø 4.6 mm, 16 poles) we realize an angular resolution of 5.6 °. The disc is made from NdFeB-polymer compound and was micromachined by the VECTOR partner Scuola Superiore Sant´Anna [2]. The magnetisation was done by pulse magnetisation (Sensitec).

2. Magnetic localization

The localization of small permanent magnet markers by use of a sensor field is a method to track small objects, which can not be wired and are optically hidden. Magnetic localization is used for gastrointestinal tracking of different strong markers with different sensitive sensors (Hall, AMRs, SQUIDs) [3], [4], [5]. At Innovent and with our research partners, we have used the technique also to monitor the movements within washing machines and within fluidisation beds. Those applications make use of the possibility to track fast particles, which is only restricted by the AMR measurement and data acquisition speed.
For the localization algorithm, position and orientation constitute five independent marker parameters. If the marker magnetization is not known or is subject to variation during the measurement, the marker strength constitutes a sixth parameter which must be determined. Mathematically spoken, it would be sufficient to use six magnetic sensors in order to determine six unknown marker parameters. In practice, more sensors are used for two reasons: (i) Additional information is needed to determine and separate disturbing fields, and (ii) additional magnetic sensors can provide homogeneous localization sensitivity within the desired measurement volume nearly independent of the orientation of the marker.

The magnetic field of a small marker with magnetisation **M** (vector: strength and direction) and volume *V* matches with the field of a point-like magnetic dipole with moment $\boldsymbol{\mu}$, $\boldsymbol{\mu} = \mathbf{M} \cdot V$. The dipole field is

$$\mathbf{B}(\boldsymbol{\mu},\mathbf{r}) = \frac{\mu_0}{4\pi} \cdot \frac{3(\boldsymbol{\mu}\cdot\mathbf{r})\cdot\mathbf{r} - \boldsymbol{\mu}\cdot r^2}{r^5},$$

with $\mathbf{r}$ and r , $r = |\mathbf{r}|$, being vector and distance of the field point with respect to the marker position. Since we have more sensors than unknown marker parameters, the localization is a least squares optimum search algorithm, which finds the marker (moment $\boldsymbol{\mu}$ and position $\mathbf{r}_m$) whose field fits best the measurement at the sensor positions $\mathbf{r}_s$. The remaining value of the quality function Q is a measure of the quality of the localization:

$$Q = \sum_{i=1}^{N_{sensors}} \left(\mathrm{B}_{meas,i} - \mathrm{B}_{marker,i}\left(\boldsymbol{\mu}, \mathbf{r}_{s,i} - \mathbf{r}_m\right)\right).$$

The figure below shows a measurement system, which is running at the University Hospital Jena. This system is used with passive capsules (no function aside the magnetic marker). The system proved its value by providing a new insight into the human stomach motility [6].

Fig. 1: Magnetic monitoring system MAGMA at the University Hospital Jena, with passive capsules.

2.1 Suppression of disturbing fields

The field of the magnetic marker is overlaid with steady and time varying fields of different shape. Steady fields result from the earth magnetic field and its deformations by iron structures (e.g. concrete reinforcement). If those structures move (cars, elevators, hospital beds etc.), the respective fields change in time. Slowly changing fields may also origin from tramways, which work with DC current and build a large coil

between rails and overhead wire, with changing length and current. The homogeneity of disturbing fields depends on the distance of the field source, near sources produce more inhomogeneous fields.
The suppression of steady fields works by taking a baseline prior to the measurement. Homogeneous time varying fields are handled by homogeneous field suppression algorithm. If size and shape of the sensor field provide enough information, also inhomogeneous time changing field sources may be separated by adaptation of the multipole expansion method [7].

2.2 Optimal arrangement of AMRs

In the following section, we show the possibility to compute the localization error depending on sensor geometry, marker location and sensor noise, and the possibility to optimize sensor geometries with these simulated localization errors.
For precise and stable magnetic marker localization, the number and arrangement of the sensors used to measure the magnetic field of the VECTOR pill is relevant. The sensors are arranged in an array, which is intended to capture the magnetic field as completely as possible. The sensor array is composed of two to four sensor board modules. During the redesign of the boards, we used the chance to modify the sensor positions in order to optimize the localization performance of one single module.
Each board carries three sensor triplets, which measure x-, y- and z-component of the magnetic field.

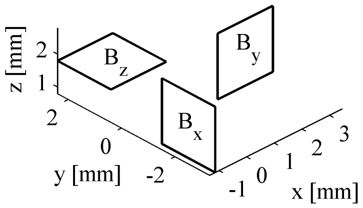

Fig. 2: Sensor Triplet with Three Sensor Apertures to Measure the X-, Y- and Z-Component of the Magnetic Field.

We compare an initial sensor design (Fig. 3 A) which has been realized for the MAGMA system with a modified (Fig. 3 B) sensor design. The modified design moves the middle triplet out of the symmetry axis and thus does span a triangle between the three triplets.

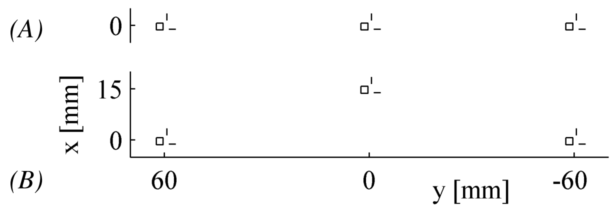

Fig. 3: (A) Existing Sensor Design, (B) Modified Sensor Design.

As a model for the magnetic noise and the intrinsic AMR noise we use a white independent noise process of 10 nT (standard deviation) for all sensors. This sensor noise causes a localization noise which is a white Gaussian process, too. Its standard deviation marks the localization error to be expected. The relation between sensor noise $B_{n,std\,i}$ in sensor i and the noise process Δx (localization error) is

$$\Delta x_{off,std\,j} = \sqrt{\sum_{i=1}^{N_s} \left(J^{+}_{j,i} \cdot B_{n,std\,i} \right)^2} \text{, with } J_{i,j} = -\frac{\partial B_{d\,i}}{\partial x_j} \text{, } J \text{ being the Jacobi matrix.}$$

The localization error depends on the marker position and its magnetic orientation. At any specific marker position and orientation, the localization error may be described by a spheroid, which gives the different sensitivity of the localization in different spatial directions. Those spheroids can be used to visualize the probability region around the localization result within our online software.
To define one single parameter from this spheroid, we use the vector sum of its principle axis, which gives the localization error in unknown direction. This parameter is compared for old and new sensor board design in the figure below. The three planes yield for the three main marker directions. Each plane maps the area perpendicular above the sensor board, coincident with the working region of the boards.

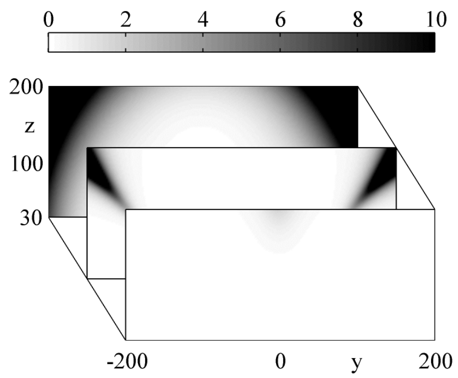

Fig. 4: Decrease of the Localization Error (mm) Perpendicular to the Module (Z-Direction), Modified vs. Existing Design, X-, Y-, Z-Directed Marker (Rear, Center, Ahead).

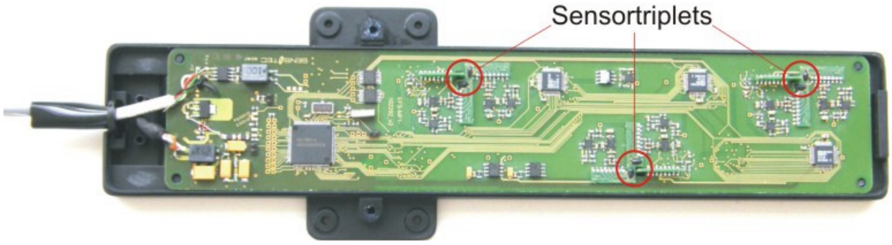

Fig. 5: Optimized Sensor Board Module with Three Sensor Triplets (SENSITEC)

2.3 Sensor calibration

We use a 3-axial Helmholtz coil to calibrate for each sensor sensitivity and its temperature dependence plus exact onboard measurement direction (0.5 ° accuracy). To avoid inaccuracies with the spatial allocation of the modules, we use an optical system (EasyTrack 200, Atracsys).

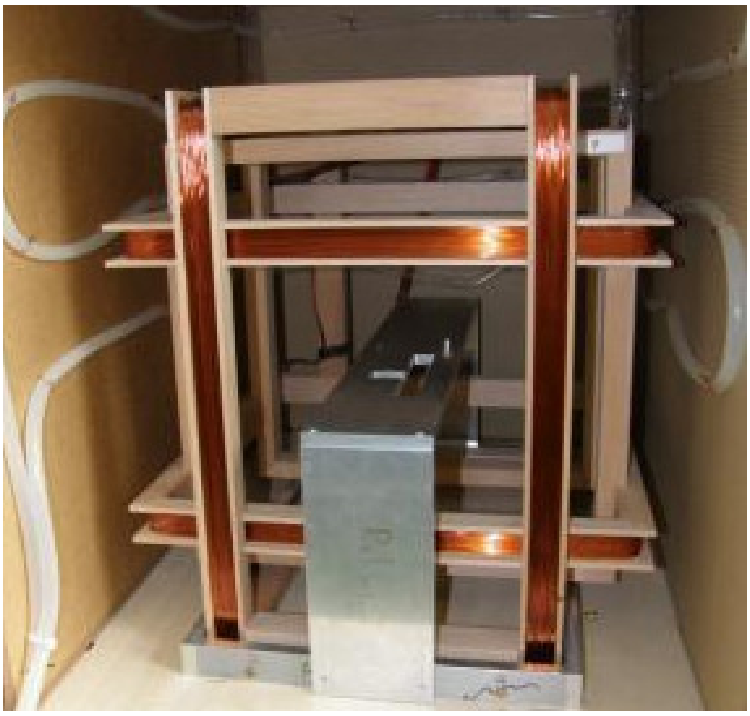

Fig. 6: Optimized Sensor Board Module with Three Sensor Triplets (SENSITEC)

3. Angular encoder (Sensitec / SSSA [2])

The legged locomotion of the VECTOR capsule makes use of a miniaturized Namiki motor and a mechanics which translates rotation into movement of the legs. This mechanics is worked by the secondary gear in the figure below. To control the legs positions, the rotation angle of the gear mechanics is monitored with an LK 29 sensor chip (1 mm pole with).

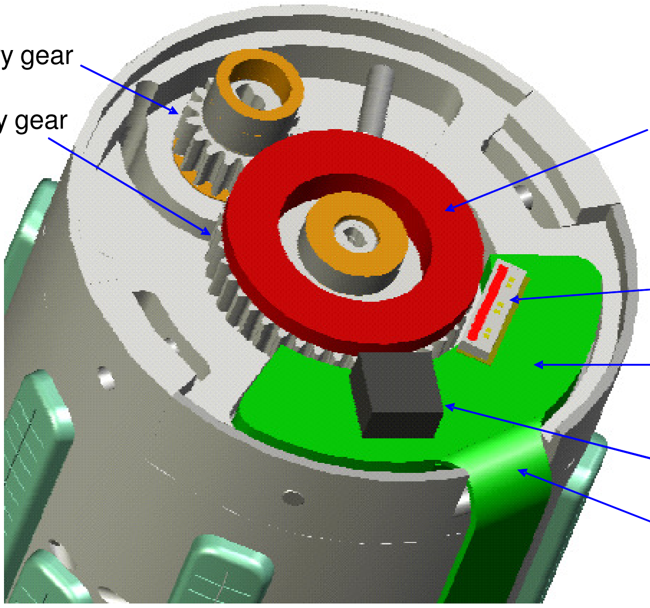

Fig. 7: Components of the magnetic motor encoder

The magnetic discs made from NdFeB-polymer compound were micromachined by the VECTOR partner Scuola Superiore Sant´Anna [2] and pulse magnetized at Sensitec (fig. below). Two discs were produced:

Diameter	Pole number	Number of signals	Resolution
4.6 mm	16	64	5.6°
3.8 mm	12	48	7.5°

Each pole generates a sine and a cosine signal of which a comparator provides 2 flanks each. Thus a resolution of 5.6° and 7.5° with the smaller disc is possible.

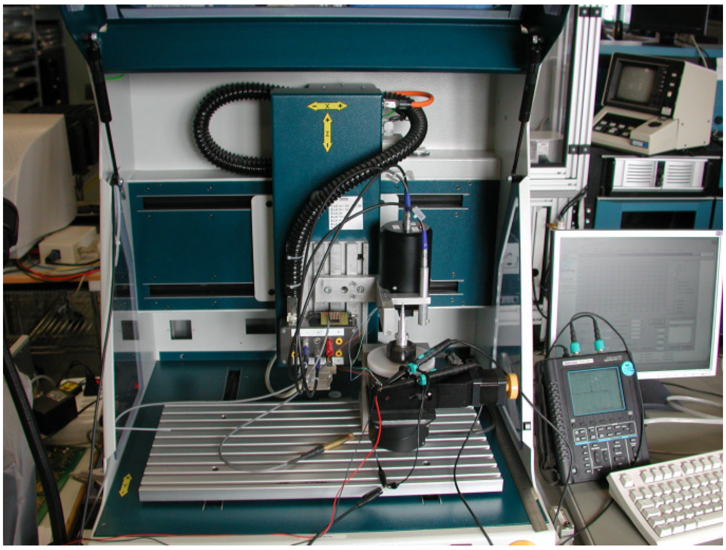

Fig. 8: Components of the magnetic motor encoder

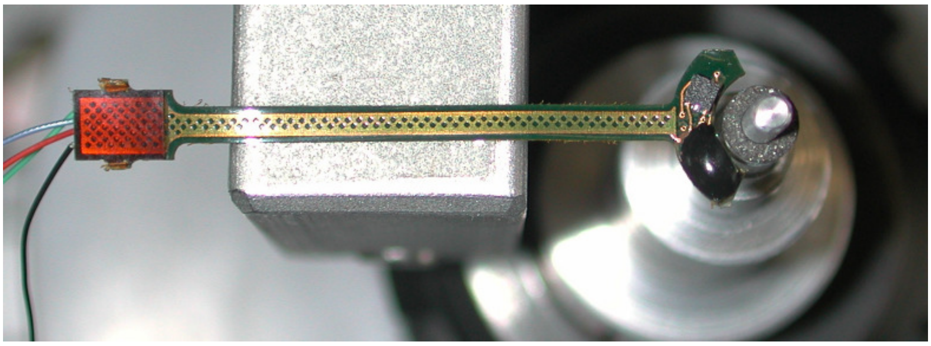

Fig. 9: Sensor pcb with the smaller magnetic disc fixed in the test setup

During the tests all pcbs except one piece were working properly together with the different types of magnetic discs. A graph of the output signals is shown in the fig. below. The good shape of the flanks (90°) and their regularity (constant signal width) should provide a suitable basis for the subsequent motor management electronics.

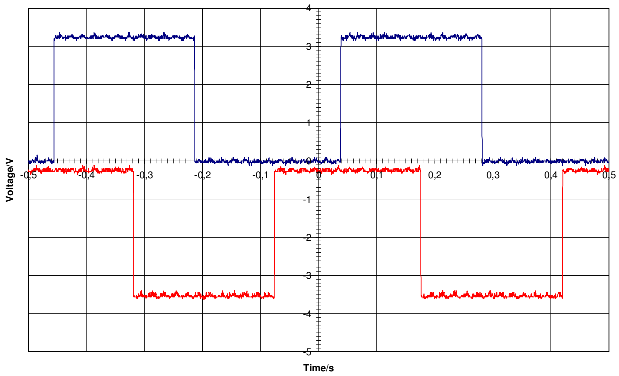

Fig. 10: Output signals of the motor encoder

Literature

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