Coordinate arbitrary Magnetic Field Control System for driving an Externally Powered and Geared Endoscopy Capsule Motor

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Abstract
Magnetically Guided Capsule Endoscopy is a recent advancement in Capsule Endoscopy. Precise control of the capsule is however usually limited to manual steering. The work presented here demonstrates the embedding of a 3D magnetic sensor for establishing a coordinate arbitrary Magnetic Field Control System for use in driving a capsule motor system externally. A concept and prototype for a motor and gearing system is also provided together with simulation and test data from the sensor, model and prototype.

1 Introduction
Capsule Endoscopy (CE) is continually demonstrating that it has significant advantages\(^[[1][2][3][4]]\) over alternate available techniques for detecting problems such as sources of bleeding in the gastrointestinal (GI) tract, but it still does not achieve 100% detection. Until recently the capsule was not controllable and moved passively through the GI tract recording images. Ishiyama and colleagues proposed the use of a magnetic field in driving the capsule endoscope. \(^[5]\) thus allowing doctors the ability to better visualise any suspicious lesions.

Magnetically Guided Capsule Endoscopy (MGCE) is a recent advancement in Capsule Endoscopy. It offers the same advantages as normal capsule endoscopy as a minimal invasive procedure compared to conventional endoscopy, but extends the benefits by providing an ability for the doctor to control the capsule as the capsule moves through the stomach. This means a doctor is not required to search through large quantities of data recordings, but can direct the capsule and concentrate the diagnostic procedure and image collection where the problem is. The results of the first clinical study have been published here \(^[4]\).

As previously mentioned, the system is presently limited to the stomach, where an amount of water drunk by the patient, allows a capsule to swim easily with relatively low magnetic fields. These low magnetic fields and gradients, with the resulting low forces restrict the concept from being employed further along the gastrointestinal tract. Here more complex movement concepts are required.

There are a number of projects developing robots capable of such movement for the small and large intestines. Examples of such robots are the 12-legged capsule with slot-follower/lead screw mechanism by KIST (South Korea), Johns Hopkins University (USA) and the CRIM Lab (Italy) \(^[6]\) or the Paddling based Microbot by KIST (South Korea) \(^[7]\). These systems show the capability of moving through the GI tract, but are generally hampered by the requirement to carry not only the motors for controlling such movement, but also the batteries needed to drive these motors. An alternative concept proposed by the ETH (Switzerland) in 2008 was for a swimming Capsule Endoscope operating inside an MRI using the static and RF magnetic fields for propulsion \(^[8]\).

In the work by Wang et al. \(^[9]\) they discuss the use of an MGCE system built with three orthogonal circular coil pairs for pushing and pulling endoscopic capsules. However, the work is limited to require the position and orientation of the magnetic seed. The work by Hong et al. \(^[10]\) does make an estimation of the position and angle, but with errors up to 15 degrees, and no closed loop
control, they only test their model in a fixed frequency modulated field.

This paper presents a method for using the MGCE system to control a capsule with a multitude of possible movement mechanisms. Without implying the use of one specific movement or traction concept, this work focuses on the development of this control system necessary for adapting any possible drive system. The complexity and requirements for externally controlling a motor, possibly including multiple geared drive shafts is outlined in section 2. Section 3 outlines the construction of a prototype geared system, the control algorithm, the simulation environment, and description of the test MGCE System. Section 4 provides the simulation and experimentation results including their comparison. Section 5 discusses the implications of the results, and outlines the future work for pushing the capability forward.

2 Problem Background

2.1 MGCE Systems

An MGCE system includes a series of coils surrounding a patient table, and capable of generating dynamic magnetic fields in three-dimensional space, nearly homogenous over an area approximating that of the human stomach. The vector of this field can be controlled in terms of direction and of magnitude. The system operates at significantly lower field strengths compared with that of an MRI. The MGCE system is also capable of generating a gradient of this field in a second arbitrarily chosen vector.

2.2 System Constraints and Considerations

As a comparison between the generated B-Field and gradient, the B-Field is considerably stronger than the gradient and more influential. To magnetic items placed within the system, the implication is that a strong torque can be applied to the magnet, but only very limited force. The engineering implication of this statement is that directly pushing a push-rod or other drive item is not effective, but the conversion of the torques through levers and threads, while requiring more space, can yield significantly larger gains.

The second constraint of using an MGCE system for conveying mechanical energy to an internal mechanical component, is that only a single magnetic field can be generated that influences the complete capsule and all magnetic items inside the capsule. It is not possible to have multiple items activated separately without additional complexities. E.g. instead of using permanent magnets in the capsule, electro-magnets can be used to activate separate systems, but this again requires a battery source, requiring again more space, something the system is trying to avoid.

With these two constraints, the concept for this work was to use a single spinning magnet, capable of delivering a controlled torque to an internal mechanical structure. This idea is simple enough but requires that the external magnetic field is rotated around the axis of the capsule’s internal structure. The present MGCE systems however do not include any method of position or orientation tracking.

2.3 Magnetic Field Detection

While it is possible to detect the three dimensional magnetic field with a specific setup and orientation of a hall sensors (many works on 3D Compass applications can be found here), it can not provide a complete orientation alignment between the detected field and the given field. The problem is that the sensed data provides no indication of the rotation around the given field’s axis. I.e. the single vector of the magnetic field does not constrain the orientation of a coordinate frame, there is one free DOF. This is shown diagramatically in Figure 2.
3 Methods

The following section describes the evolution of the testing from the simulation system, with its associated mathematical model, to its physical implementation with the complete MGCE test system, developed sensors, and a prototyped geared system.

3.1 The System Model

The correlation between the static coordinate system of the MGCE system, and the mobile coordinate system of the magnetic sensor is approximated by a single unknown rotation\(^1\) \(q\). The non-linearities of the field due to movement of the capsule away from the homogeneous center zone are ignored. I.e. from the generated \(B\) Field, \(\vec{B}_G\), to the \(B\) Field as detected in the sensor \(\vec{B}_s\), equation 1 is the actual state, where \(\vec{B}_p\) is the sensor calibration vector offset due to the permanent magnet in the capsule.

\[
\vec{B}_s = q(\vec{B}_G) - \vec{B}_p \tag{1}
\]

\(q\) is initially an unknown value, therefore an arbitrary initial guess is provided as \([0 0 0 1]\). Because \(q\) is not known, equation 1 does not hold, and the model works to solve this one unknown. At each simulation or data acquisition step, this guess is updated by rotating \(q\), around the vector \(\vec{u}\) being the cross product of \(\vec{B}_s^\perp\) (the estimate, right side of equation 1) and \(\vec{B}_s\), and by an angle of the inverse cosine of the dot product between \(\vec{B}_s^\perp\) and \(\vec{B}_s\). See equation 2.

\[
\begin{align*}
\vec{B}_s^\perp &= q(\vec{B}_G)q - \vec{B}_p \\
\theta &= \cos(\vec{B}_s^\perp \cdot \vec{B}_s) \\
\vec{u} &= \vec{B}_s^\perp \times \vec{B}_s \\
q' &= q \otimes [\vec{u}\sin(\theta/2)\cos(\theta/2)] \tag{2}
\end{align*}
\]

In order to increase the bandwidth of the \(q'\) estimator in tracking a spinning magnetic field, a PI controller was tuned as a function of the \(\theta\). It is not possible to use a standard PI filter here, because the dot product has the effect that its output will always be positive and any integrator component would continually climb to infinity, therefore a leaky integrator was used.

The generated \(B\) Field \(\vec{B}_G\) is then updated to \(\vec{B}_G'\) in each simulation or data acquisition step based on the difference between a desired \(B\) Field \(\vec{B}_D\) and the measured \(B\) Field \(\vec{B}_s\), again less the offset from the permanent magnet. This resultant error is rotated through the current estimation of the rotation, and added to the current generated \(B\) Field. See equation 3.

\[
\vec{B}_G' = \vec{B}_G - q(\vec{B}_D - \vec{B}_s - \vec{B}_p)q \tag{3}
\]

3.1.1 Noise in simulator and real system

The noise measured on the sensor was confirmed to match that of the issued data sheet (see section 3.3), with a standard deviation of 38 \(\mu\)T per measurement and a maximum deviation of 77 \(\mu\)T per measurement. This was matched in the simulation with noise generators.

3.1.2 Simulator Startup

As discussed in section 2.3, the guess of the rotation can not perfectly detect or know the complete rotation of the coordinate fields because the twist around the \(B\) Field is lost. In order to ensure additional information is gathered, the startup involves the generation of a series of random \(B\) Fields, preferably (but not essentially) orthogonal to each other. The changes between these fields must occur faster than the bandwidth of the system. If these changes occur too slowly, the magnet attached to the sensor can move with the field, and maintain an unchanged \(B\) Field vector. For this reason, step input changes are provided at random times and to random values.

3.2 The MGCE Test System

The magnetically guided capsule endoscopy system used was jointly developed by Olympus Medical Systems

\(^1\)Quaterians used for rotation space mathematics.
Corporation and Siemens Healthcare; a prototype was built for endoscopic examination of the stomach that included an Olympus capsule endoscope and Siemens magnetic guidance equipment for interactively moving the capsule in the gastric cavity. The system shown in Figure 3 was used in the clinical study [4].

3.3 The Magnetic Field Sensor

The sensor used is a custom version of the AS540x developed by the Fraunhofer IIS using their 3D Hall-nOne patented technology. A preliminary data sheet can be obtained from the address in the footnote. The strength of this sensor for this application, is that the two embedded 3D-Hall cells allow both absolute as well as differential 3D magnetic field measurements. This is essential to effectively remove any offset from the strong permanent magnet sitting directly beside the sensor. In its 14-pin TSSOP package, measuring 4.4x5mm, and capable of operating in an ultra low power mode, it is highly suitable for use inside a future capsule.

2http://www.austriamicrosystems.com/eng/Products/Magnetic-Encoders/3D-Hall-Encoders

Figure 4: System connectivity showing the closed loop from sensor to Field Generators. The SimpliciTI link is a wireless protocol from Texas Instruments.
3.4 Test System Setup

Using the MGCE shown in Figure 3 the sensor and model were interfaced as shown in Figure 4. The sensor acquisition rate, as per the system update rate were both set at 100 Hz.

3.5 Geared Motor Prototype

From the earliest works discussed in the introduction, the most suitable types of movement for extending the capability of the MGCE past the stomach to further sections of the GI Tract are those mentioned in [6][7]. These systems currently have the limitation that they require motors and thus larger batteries to be carried inside the capsule. In order to use the external field control of the MGCE, it was necessary to develop a method for controlling a number of different drive components from only one magnet. This was achieved by placing the magnet with fixated sensor in a tube section, where the magnet is still able to move a few millimetres forwards and backwards. This sliding could be controlled by the external field gradient, requiring only very slight force to move the magnet from one end of the tube to the other. This effect was used as the control of the gearing. On one side of the magnet a saw tooth gear was fixed. This gearing would be able to drive one mechanical component, and works similar to a clutch mechanism (On or Off). The geared system is shown disassembled in Figure 5. By adding additional gearing sections on the opposite side of the magnet later, additional mechanisms can be driven. Such a concept is shown in the lower images of Figure 5. A significant advantage of such a motor concept is the torque to volume ratio. This motor requires the capsule to include no internal electromagnetic coils, no controlling electronics, and importantly no battery power is needed for the motor, thus increasing the operating time by dedicating all the battery power to the camera and wireless transmission. The torques are also considerably large in comparison with other capsule motors used as discussed in the introduction because a single large ring magnet can be used with a radius only marginally smaller than the complete capsule.

3.6 Torque Control Drive Mode

In the work by Wang et al. [9] they attempt to track a sensor while rotating the magnet fields. Outlined in Figure 1 was the idea that to achieve continual efficient control along an arbitrary route, the field must be rotated directly around the rotational axis of the magnet. A more elegant solution here exists, whereby the magnetic field is moved in a closed loop system, slightly off axis from the magnet. In this fashion, the magnet is held stable by the strong field holding it in position, and a set amount of torque is provided by the off axis nature of the field. As the magnet turns due to the torque, the field is again moved off axis from the new position. In this concept the same movement is achieved, but the model reveals two large advantages. Firstly, a torque feedback is achieved by how quickly the motor accelerates. Secondly, a more stable running mode is achieved with the system able to be optimised to 100% of the possible torque of the magnet.

4 Results

4.1 Drift in Simulation

The first set of simulations were designed to verify that the model worked as expected, and in order to tune the control parameters. The first results shown in Figure 6 demonstrate the expected result when a constant B Field force is maintained on the system. After initial
alignment of the coordinate systems, drift continues to occur around the axis of the given B Field, and after a time, the correlation (defined as the dot product of the two quaterian vectors) between the two coordinate systems decreases.

Figure 6: Log of the correlation between the estimated rotations vector and the actual rotations vector in the simulated system. 1.0 indicates complete correlation. The drift about the B Field vector is seen to increase significantly from approximately 9 min.

4.2 Drift Avoidance, Correlation Improvement

In order to improve the rotation estimate, the system was tested with continually changing B Fields, thus providing continually more information about the additional axis. Figure 7 shows how this concept immediately provides more information with the improvement of the correlation factor. After only two changes, the correlation is increased to over 0.996, this equates to an angular discrepancy of < 2°. The poor correlation in the first 0.8 secs is due to the complete absence of any desired B Field.

4.3 Simulation / System Comparison

The model from the Simulation was applied directly to the complete MGCE with only modification to the PD and PI control values. In this setting, the gains were all lowered, to reduce any sudden movements of the magnets in a poorly orientated or oscillating magnetic field. Figure 8 shows two example startups of the system. In these tests the magnetic sensor was placed inside the MGCE system at a random orientation. The location was approximately near the middle. From the data there are two important points to note, firstly that the model appears to work and the system is able to generate the desired magnetic field, in the coordinate system of the sensor. Secondly, the magnetic field approaches the desired field strengths, well before the orientation
estimation approaches a stable solution. Finally, the noise level of the system is slightly lower than the noise level chosen for the simulation.

4.4 Stability of System and Drift in System

During in-system testing there was no evidence of drift occurring after any time period, and no data recordings of such an event could be made. During these tests, the position and orientation of the capsule was moved throughout the working volume of the MGCE, and as shown in the example graphs in Figure 9, the magnetic field in the coordinate system of the capsule remained at the desired level with a standard deviation of $\begin{bmatrix} 0.13 & 0.126 & 0.0527 \end{bmatrix} \text{mT}$.

Figure 8: Real System startup examples from random orientations. The left side shows the startup with low PI coefficients for the orientation estimation. The right side shows alternately low PD coefficients on the Field corrections model. These two graphs thus show a comparison, that even when the orientation estimation is slow to merge, the Fields will still be corrected. However, too sharp a change in the orientation estimation can lead to non-linearities in the Field correction.

4.5 Torque Control Drive Mode Simulation

Figure 10 shows the simulation of the torque controlled drive mode, as described in section 3.6. A strong Z Field holds the magnet steady, and an increasing amount of torque is applied to the magnet around the spinning axis. The desired Magnetic Field of $[\delta \ 0 \ 1]$ provides a rotation around the Y axis. The lag of the B Field around the rotation axis can be seen in the middle graph as being more significant at higher speeds. This lag also provides a measure of the torque required to maintain such a speed. It thus provides useful information on the capability of the system to go faster, or in prototyping, can help with the selection of appropriate gearing.

4.6 Torque Control Drive Mode Tests in System

Example results of the Torque Control mode tests are shown in Figure 11. The results show a significant problem encountered in the testing due to a stick slip friction problem in the prototype. In this trial, a desired torque was selected by the user, noted by the desired 7.5mT in one direction and later 10mT is the reverse direc-
The field rotated around the axis until the first slip occurred with sudden acceleration. Due to this sudden acceleration, the sensor moves, and the field takes a set period of time to realign, building up the torque in the process until the next slip occurs. This was seen to occur in both directions of rotation.

### 4.7 Homogeneity of System

The MGCE system had been previously calibrated to have a homogenous field in the space in which a patient stomach would lie during a diagnostic procedure. As a side effect of the magnetic sensor inclusion in a closed loop system this working volume can be significantly increased without a need for further system calibration. Figure 12.a and b show the measurements made of the system with and without the above described model. It shows over a space of 80cm the standard field of the MGCE changes over 2.5mT, this is 50% of the desired value. Additionally, the orientation of the field change swings by over 4°.

When the closed loop model was applied, the field was stable and consistent for over 650mm. The limitation of the field then occurs due to a software enforced limiting of the field. In the model used in this test, each individual field component was limited to 1.5 times the magnitude of the overall desired field. This was to prevent any excessive currents and overheating should the model become unstable. In future tests, this limitation is likely to be weakened or completely removed, with a high likelihood of extending this working volume considerably more. It is important to note that while this constraint was software enforced, the direction of the vector was continually maintained even into the non-linear region.

### 5 Conclusion

This work has shown how effectively the capsule orientation can be determined through an embedded magnetic sensor. These results show the stable and fast optimisation of the magnetic field into the capsules coordinate system, regardless of startup orientation. This optimisation of the magnetic field also increases the effective working volume of the MGCE system by over 200%. The torque drive mode provides a stable and controllable method for powering a motor inside a future generation of endoscopy capsules. This external drive removes the requirement for additional batteries inside the capsule.

Future work is aimed at including the gradient control...
of the field in the model, this will be key to achieving faster gear changes without loss of a stable field at the capsule’s location and in the appropriate orientation.

References


