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ON THE FEASIBILITY OF STEERING SWALLOWABLE MICROSYSTEM CAPSULES USING COMPUTER-AIDED MAGNETIC LEVITATION

Billy T. Wu, Martin P. Mintchev

Abstract: Swallowable capsule endoscopy is used for non-invasive diagnosis of some gastrointestinal (GI) organs. However, control over the position of the capsule is a major unresolved issue. This study presents a design for steering the capsule based on magnetic levitation. The levitation is stabilized with the aid of a computer-aided feedback control system and diamagnetism. Peristaltic and gravitational forces to be overcome were calculated. A levitation setup was built to analyze the feasibility of using Hall Effect sensors to locate the in-vivo capsule. CAD software Maxwell 3D (Ansoft, Pittsburgh, PA) was used to determine the dimensions of the resistive electromagnets required for levitation and the feasibility of building them was examined. Comparison based on design complexity was made between positioning the patient supinely and upright.

Keywords: Computer-Aided Magnetic Levitation, Capsule Endoscopy, Real-Time Image Transmission

ACM Classification Keywords: J.6 Computer-Aided Engineering

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Introduction

Gastrointestinal (GI) disorders, including cancers, are common medical problems which affect up to 35% of the world population [1]. Fiberoptic endoscopy has become a preferred diagnostic method for the early detection of polyps and cancers in the GI tract, and particularly in the colon [2]. However, the invasive nature of this test makes its wide applicability for early screening and prevention purposes difficult, if not impossible [3].

Microsystem Diagnostic Capsules

Swallowable capsule endoscopy (CE) has been suggested as a non-invasive alternative to fiberoptic endoscopy for some GI organs to minimize the discomfort for patients and to enhance screening applicability of the test [4]. A capsule endoscope of the size of a medical pill may contain an imaging device and various sensors for monitoring the characteristics of the examined GI lumen. In addition, it is typically equipped with embedded battery and radio-frequency transmitter for power supply and real-time data transmission, respectively. CE has been utilized for diagnosing small intestinal bleeding and has been recently suggested for detecting abnormalities of the esophageal wall [4]. The relatively small lumens in both organs preclude the capsule from tumbling, and natural peristalsis provides a reasonable means of steering the capsule, albeit in uncontrolled fashion. Steering based on natural peristalsis is not feasible for larger-lumen GI organs, e.g. the stomach and the colon, because the capsule tumbles and correct recognition of the tested area becomes impossible, not to mention the fact that substantial segments of the tested organ could be missed simply because the capsule would fall through cylindrical spaces of larger diameter.

Steering Options

Presently, the movement of the capsule through the GI tract relies on the propulsive contractile activity of the smooth muscles of the given organ. The inability of CE to achieve positional stabilization and to have independent external steering precludes broader applicability of this innovative diagnostic technique, which could become a pivotal screening test for GI polyps and cancers. In addition, controlled steering of the capsule and future developments in the area of micro-electromechanical systems (MEMS) create the possibility for collecting biopsies concurrently with the luminal examination, and even for the removal and the collection of smaller polyps or growths. Therefore, independent, externally-controlled intraluminal steering of the capsule is of pivotal importance for exploiting the full potential of CE not only as a diagnostic, but also as a therapeutic technique.

Forces Acting on the Capsule

In order for the capsule to levitate in the lumen (the esophagus is chosen for this study because of its simple vertical structure), gravitational and peristaltic forces exerted on the capsule have to be overcome. Suppose the capsule is 10 mm in diameter and 25 mm in length. The two ends of the capsule are hemispheres, each with a surface area of 0.000157 m^2. With a miniature magnet, sensors, and circuitry inside, the capsule is estimated to weigh less than 11 g in total. The gravitational force on the capsule would be less than 0.108 N.

Peristaltic pressure is applied on the top of the hemispherical surface of the capsule as the contraction of the smooth muscles pushes the capsule towards the stomach. Table I lists the average and absolute maximum peristaltic forces for both supine and upright positions, calculated based on the hemispherical surface area of the capsule and published pressure data on esophageal contractility [5].

Table I. Average and absolute maximum pressures and peristaltic forces anticipated during a normal esophageal contraction.

	Supine	Upright
Average Pressure (kPa)	6.67	5.33
Absolute Max. Pressure (kPa)	10.5	8.66
Average Force (N)	1.05	0.837
Absolute Max. Force (N)	1.65	1.36

Methods for Magnetic Levitation

Earnshaw's theorem implies that a permanent magnet cannot maintain levitation in a magnetostatic field [6]. However, although magnetic levitation is intrinsically unstable, this does not necessarily mean that it cannot be artificially stabilized using external aiding sources such as particular sensors and/or diamagnetism.

Diamagnetic materials, including water and living tissues, develop persistent atomic or molecular currents which oppose externally applied magnetic fields. Even though the diamagnetic stabilizing force is much weaker than the magnetic lifting force, diamagnetically stabilized levitation of a miniature permanent magnet has been demonstrated [6]. The walls of the GI organ encompassing the capsule can fulfill the role of diamagnetic stabilizer, which can be supported further by shelling the capsule with an appropriate diamagnetic material (e.g. bismuth or pyrolytic graphite) [6].

If the position of the capsule (or the levitating magnet inside) can be determined in real time, the field of the electromagnets can be continuously adjusted via a feedback control system to keep the capsule in the desired position. A levitation kit [7] demonstrating this method of levitation is commercially available. It uses a Hall Effect sensor to detect the position of the levitating magnet, as the sensor produces a signal based on the field strength of the magnet. This signal controls the current supplied to the coil, which in turn determines the strength of the field.

A combination of these two levitation-aiding techniques can be utilized in steerable CE.

Aim of the Study

The aim of this study is to explore the feasibility of steering an endoscopic capsule and holding it at areas of interest in the GI tract using aided magnetic levitation. A conceptual design for controlling the movement of the capsule and for affixing it at particular locations is presented. Magnetic levitation is achieved by using powerful resistive electromagnets at least 30 cm apart, situated at the front and back sides of the patient. The levitation is stabilized with the aid of a feedback control system and diamagnetism. The feasibility of designing such system for a patient in supine and upright positions is examined.

Methods

The patient can be arranged in two possible positions, supine and upright, as depicted in Fig. 1.

Modeling Setup

The force between two permanent magnets or between a permanent magnet and an electromagnet is the result of non-uniform magnetic field [8]. Force calculations dealing with non-uniform magnetic fields and permanent magnets are complex, and involve finite element analysis. Software simulations were created using the computer-aided-design (CAD) system Maxwell 3D (Ansoft, Pittsburgh, PA) to determine the size and the arrangement of the electromagnets.

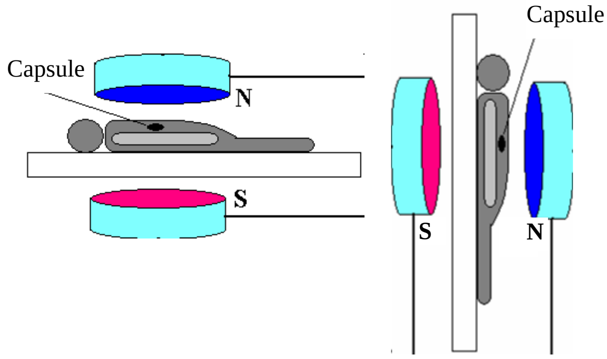

Fig. 1. Options for positioning the patient during diagnosis, supine (left) and upright (right).

Experimental Setup

A levitation kit [7], which can be thought of as a micro-model of a patient in supine position, was utilized to build a complete electronically-controlled system for establishing stable levitation with feedback control. The purpose of this setup was to analyze the detection of the magnet position and compare the experimental findings to the CAD system modeling. A hand-wound coil was used as the electromagnet, with roughly 5000 turns of American-wire-gauge (AWG) 20 copper wire. The core of the coil was a 1018-stainless-steel bolt. A spherical NdFeB permanent magnet was placed in a clay-filled capsule to give a combined mass of 10.9 g. The Hall Effect sensor was positioned directly below the coil on the center axis. The equilibrium position of the magnet at which it levitated was about 10 mm below the Hall Effect sensor for a coil current of 158 mA.

Steering in Supine Position

A simulation CAD model (Fig. 2) was created to verify the experimental setup. The upward force on the magnet given by Maxwell 3D was 0.106 N, which was the weight of the capsule. The second side of electromagnet and the peristaltic force were not considered at this time in order to simplify the experimental setup.

Ideally, the sensor should only detect the field from the magnet, but the magnetic field of the coil was inevitably picked up by the sensor as well. In the designed experimental setup, the magnet contributed much more to the magnetic field of the system compared to the contribution of the coil. This demonstrates the effectiveness of positioning the Hall Effect sensor directly below the coil.

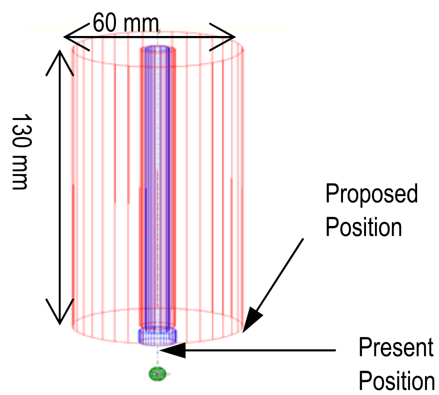

Fig. 2. Experimental Setup for the present and the proposed position of the Hall Effect sensor.

However, in an actual application, the distance between the coil and the levitating magnet should be far greater than 10 mm. The size of the coil and the current flowing through it would increase significantly as well. The present position of the Hall Effect sensor would not be applicable because the coil would produce a much greater magnetic field. Moving the sensor to the side at the bottom of the coil (proposed position in Fig. 2) was examined with simulation models. The respective contributions of the magnetic sources (the coil and the magnet) at the proposed position were studied.

Steering in Upright Position

Following the validation of the CAD model with the small-scale experimental setup, a different approach was pursued in the CAD modeling for the upright position. Rather than parameterizing a physical micro-model, the simulation CAD model was constructed based on the requirements of an actual application, i.e. actual maximal peristaltic force and a 30-centimeter separation between the electromagnets were utilized as parameters. This ensured that the electromagnets were of feasible size before more time and effort was spent on details of the feedback control system.

After some refining, the model in Fig. 3 was determined to be capable of producing an upward force greater than 1.47 N on the levitating magnet to counter the gravitational and peristaltic forces (0.108 N + 1.36 N).

In the model, the resistive electromagnets were designed using copper wire. The electromagnet on each side was separated into inner and outer coils. To keep things simple, the wire current (in amperes) and the wire gauge of the inner and outer coils were considered to be the same. The currents of each inner coil and each outer coil were 144,000 ampere-turns and 256,000 ampere-turns, respectively. Even with the additional costs of a power supply with precise regulation and a cooling system, resistive electromagnets were determined to be generally much cheaper and simpler to build than superconducting magnets [9]. Soft iron cores were used to concentrate the magnetic field generated.

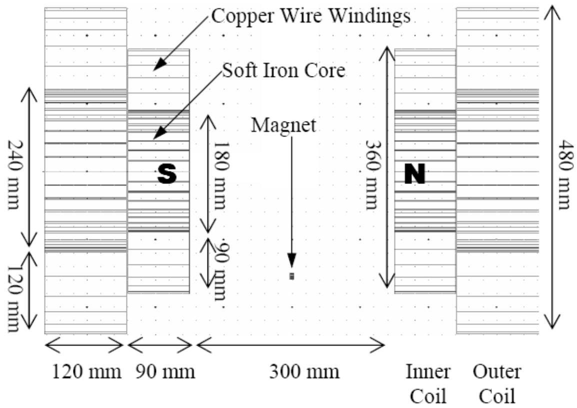

Fig. 3. Cross-sectional view of the simulation model for upright position in an actual application.

A cylindrical magnet with a diameter of 9.55 mm and a height of 5 mm was selected for levitation. It was larger and heavier than the spherical magnet used in the supine case, but the extra weight was much smaller compared to the peristaltic force. The trade-off of using a larger levitating magnet was the size reduction of the electromagnets required to achieve levitation.

It should be mentioned also, that additional stabilization of the capsule in both steering modalities can be facilitated by the organ walls (providing their proximity to the capsule is reasonable), or by implementing the entire or part of the outer shell of the capsule using diamagnetic material [6]. This stabilization aid can substantially ease the sensitivity requirements for the Hall Effect sensors.

Results

Steering in Supine Position

Fig. 4 shows that the field of the magnet was minimal at the proposed position and was overwhelmed by the coil field. The situation would worsen when the coil is enlarged with its field greatly increased in an actual application. Thus, keeping the Hall Effect sensor at a position immediately under the coil is not feasible.

The fundamental problem of detecting the magnet position is not in finding an appropriate location for the sensor. Instead, it is the field of the magnet decreasing significantly with distance. If locating the magnet is to be based on magnetic field detection, the sensor must be in close proximity to the magnet.

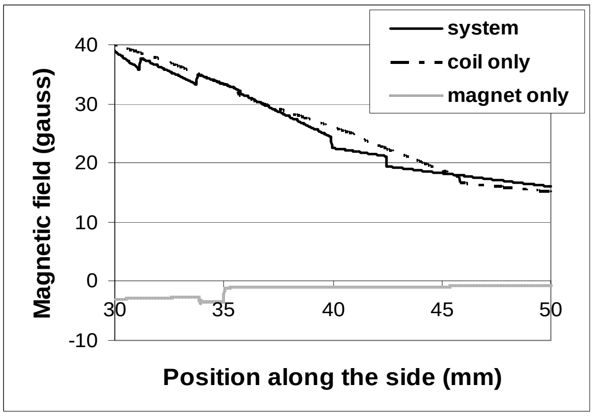

Fig. 4. Breakdown of the field contributions near the proposed position (supine case).

An alternative would be to measure the magnetic field of the coil from inside the capsule. With the coil field at a fixed location outside the body serving as a reference, the capsule can be located with respect to the coil. This two-sensor design is illustrated in Fig. 5.

The unprocessed signal from sensor #1 consists of contributions from the magnet and the coil. Since the magnet and sensor #1 are both inside the capsule, the field from the magnet remains the same with respect to sensor #1, regardless of the capsule position. Thus the field contribution of the coil inside the capsule can be obtained by adaptively subtracting a constant from the unprocessed signal.

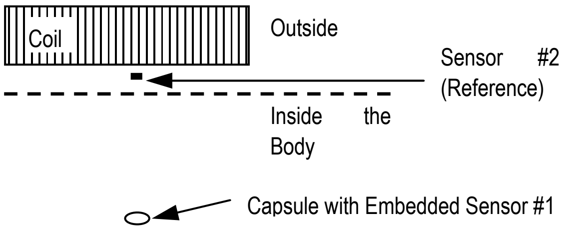

Fig. 5. Two-sensor concept for supine position.

Steering in Upright Position

In the developed simulation model, the magnetic field produced by the electromagnets was about 2.1 T at the pole faces of the inner coils, and 0.5 T at the point of levitation.

The size of the electromagnets was considered acceptable. In order to show the feasibility of building such electromagnets, it is necessary to determine their weights and heating rate. These two factors are dictated by the wire gauge selection, since the dimensions of the electromagnets have been predicted using simulation. Equations (1) and (2) for designing MRI resistive electromagnets [9] were utilized:

$$dT/dt \approx \frac{1}{c_p \rho \sigma} \left(\frac{I_w}{A_w} \right)^2 \tag{1}$$

where dT/dt is the rate of temperature increase in °C/s, I_w is the current of each winding, and A_w is the cross-sectional area of the wire. The parameters c_p, ρ, and σ are the specific heat, density, and the electrical conductivity of copper, respectively.

Given a coil with N turns, the mass is:

$$m = V\rho = 2\pi A_w \rho \sum_{n=1}^{N} a_n \tag{2}$$

where V is the volume of the coil (with copper windings), and a_n is the average radius of the n^{th} winding. Since the cross-sectional area is a square matrix of coil windings, N_S can be defined as the number of turns per side, where $N_S = \sqrt{N}$. a_n can be quantified as:

$$a_n = a_{n-1} + d_w = a_{n-2} + 2d_w = ... = a_1 + (n-1)d_w \quad (3)$$

where d_w is the diameter of the wire and a_1 is the radius of the innermost winding. Then the mass of the coil is:

$$m = 2\pi A_w \rho N_S \sum_{n=1}^{N_S} (a_1 + (n-1)d_w) \quad (4)$$

$$m = 2\pi A_w \rho N_S \left[N_S (a_1 - d_w) + d_w \sum_{n=1}^{N_S} n \right] \quad (5)$$

The masses of the soft iron cores can be estimated using the density of iron. AWG 14 wire was selected because of the reasonable balance between the winding current and the heating rate. The winding current was calculated to be 53 A, while the heating rate was 3.15°C/s. The heating rate is significant, but this value is for the case when the electromagnets are running at full capacity (i.e., when there is a contraction). The contraction only lasts few seconds [5], then the current will drop back to a much lower value. Air or water cooling will probably be required. The number of turns and the masses of each coil and core are listed in Table II.

Table.II Electromagnet characteristics for upright position in an actual application.

	Inner	Outer
# of Turns	52	70
Coil Mass (kg)	42.3	102.6
Core Mass (kg)	17.9	42.3

Discussion

In the search for optimal computer-aided magnetic levitation for capsule endoscopy, the proposed two-sensor, diamagnetically-enhanced concept for the supine position could be implemented for the upright position as well. A magnetic measurement device capable of measuring substantial field with considerable precision, such as a NMR gaussmeter, should replace sensor #2, because the field at the location of sensor #2 is much greater in an actual application. An additional magnetic measurement device outside the body would be required for the second electromagnet at the back side of the patient. The control circuit would adjust the currents of the inner coils with the magnetic sensing system. A contraction could be detected with pressure sensors mounted on each end of the capsule. Depending on the pressure exerted on the capsule, the currents of the outer coils could be increased accordingly to maintain levitation.

When the second side of the electromagnet and the peristaltic force are taken into account for the supine position, the magnetic forces are not symmetrical because the gravitational and peristaltic forces are in orthogonal directions. The design for controlling the asymmetrical field strength of the electromagnets would be complicated and not very feasible. When the patient is positioned upright, the peristaltic and gravitational forces are in the same direction, leading to symmetrical magnetic forces. This simplifies the design of the field control system.

Utilization of this diagnostic technique in larger-lumen organs of the GI tract (e.g. in the colon) is highly feasible. Although colonic pressures are complex and variable, the maximum peristaltic force in the colon is not significantly greater compared to that in the esophagus [5], [10]. In addition, pharmacological agents for reducing colonic contractility could temporarily be used during the CE test.

An interesting discussion point is the potential mechanical resistance of a collapsed organ wall to the controlled steering of the capsule in the absence of contractile activity. Similarly to present-day fiberoptic endoscopy, this problem can be easily bypassed by appropriately inflating the investigated organ with air prior to the test. However, this procedure itself could jeopardize the non-invasive nature of the test. Thus, additional work is needed to estimate the related forces and incorporate them into the design. The issue of the maximal steering velocity of the capsule and its relationship to the levitation characteristics needs quantification as well.

Conclusion

Simulation models demonstrated that electromagnets in a set of inner and outer coils with soft iron cores can be built to levitate an endoscopic capsule and to counteract the peristaltic force. Stabilization can be achieved with the aid of a computer-aided feedback control system and diamagnetism.

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