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Diamagnetically stabilized levitation control of an intraluminal magnetic capsule

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Abstract

Controlled navigation promotes full utilization of capsule endoscopy for reliable real-time diagnosis in the gastrointestinal (GI) tract, but intermittent natural peristalsis can disturb the navigational control, destabilize the capsule and take it out of levitation. The focus of the present work was to develop an economical and effective real-time magnetic capsule-guiding system that can operate in the presence of naturally existing peristalsis while retaining navigational control. A real-size magnetic navigation system that can handle peristaltic forces of up to 1.5 N was designed utilizing the computer-aided design (CAD) system Maxwell 3D (Ansoft, Pittsburg, PA) and was verified using a small-size physical experimental setup. The proposed system contains a pair of 50 cm diameter, 10 000-turn copper electromagnets with a 10 cm × 10 cm ferrous core driven by currents of up to 300 A and can successfully maintain position control over the levitating capsule during peristalsis. The addition of bismuth diamagnetic casing for stabilizing the levitating capsule was also studied. A modeled magnetic field around the diamagnetically cased permanent magnet was shown to be redistributed aligning its interaction with the external electromagnets, thus stabilizing the levitating capsule. In summary, a custom-designed diamagnetically facilitated capsule navigation system can successfully steer an intraluminal magnet-carrying capsule.

Keywords: capsule endoscopy, magnetic navigation system, feedback-controlled levitation, stabilization

(Some figures in this article are in colour only in the electronic version)
1. Introduction

Capsule endoscopy is a novel imaging technology for intraluminal examination of the gastrointestinal (GI) tract. This technique was first introduced by Given Imaging Ltd (Yoqneam, Israel) and is presently the most rapidly growing segment in the GI device market with a total value of over $70 million according to a recent report on the US market for gastrointestinal endoscopy (Millennium Research Group 2006). Other major industrial players in this important area include RF System Laboratory (Nagano, Japan), Olympus Corporation (Tokyo, Japan) and Intromedic (Seoul, Korea). Notably, Olympus Corporation has produced a capsule endoscope available with a real-time viewer for live transmission of video images (Olympus Medical Systems 2007).

The capsule endoscope system includes a wireless ingestible pill with built-in microelectronic imager, microlens, light-emitting diodes (LEDs), data transmitter, data receiver and a microcontroller unit, supplied by a miniature battery (Cave 2004). The microelectronic imager is usually located at one or both ends of the capsule and collects sequences of images that are wirelessly transmitted to an external data logger where the images are stored to be examined by gastroenterologists.

The capsule endoscope traverses the GI tract due to natural peristalsis, an organized motility action of the gut during which the circular smooth muscles contract to prevent the backflow of food chime and the longitudinal muscles contract to propel the content down, a mechanism known as ‘the law of the intestine’ (Evans 1956). The force due to peristalsis is usually measured in terms of contact pressure, which when referred to the contact surface area provides the contact force. The pressure measured in different locations along the GI tract may vary. At the area of the upper esophageal sphincter (UES), for example, the pressure in a non-symptomatic patient can be as great as 6.7 kPa. This is equivalent to a force of about 1.5 N acting on the upper hemisphere of a hard-covered capsule with a surface area of 1.57 cm² (Mintchev and Wu 2006). This 1.5 N force is an overestimate of the peristaltic force acting on the capsule, since some of the lateral forces would cancel out (figure 1). Notably, the clinically measured force at 5 cm above the lower esophageal sphincter (LES) for a non-symptomatic patient was 1.23 N ($p < 0.02$) on a sphere with a surface area of 2.65 cm² (Schoen 1977). In this paper, an overestimated peristaltic lateral force of up to 1.5 N is assumed acting on the intra-luminal capsule.
Despite its numerous advantages over traditional endoscopy, at present the capsule endoscope cannot completely replace it because of several shortcomings. First, the camera in the capsule cannot be pointed to a specific direction nor can it be placed at a specific GI site to acquire images because it is passively propelled by natural peristalsis. Second, taking into account the size of the device, it tumbles in large-lumen organs such as the stomach and the large intestine, rendering the images acquired from these organs useless. Third, it cannot perform biopsies, polyp removal or any therapy (Fireman et al. 2004). Fourth, the battery power supply for the capsule lasts only up to 12 h while the complete traversal of the GI tract usually takes 20–48 h, and therefore, it is not possible to obtain video recording of the entire GI tract in one clinical trial (McCracken 1999).

Perhaps the major limitation related to capsule endoscopy is associated with the inability to control the motion of the capsule in the GI tract after ingestion. Control over the capsule’s position can be helpful in retaining the capsule at diagnostically important sites and quickly passing through unimportant areas, saving on battery power (Schoen 1977). In any capsule navigation system, the natural peristaltic force has always been the largest external disturbance precluding the full development of a capsule navigation system. It has been shown that the administration of pharmacological agents can greatly reduce gastric motility and hence the strength of peristaltic contractions, in experimental animals by 20–80% (Mitsuhiro and Yoshitsugu 2000). However, the reduced peristaltic force is still greater than any other forces playing a role in the GI tract. Many research groups have looked independently into developing steering technologies for capsule endoscopy and have arrived at preliminary designs of controlled capsule navigation systems that address this issue (Takeshi 2003, Meng et al. 2004, Wakefield 2004, Olympus Medical Systems 2005, Ries 2005). In particular, a magnetic capsule navigation system is the most extensively studied approach for the external guidance of an intraluminal capsule (Olympus Medical Systems 2005). The use of strong magnetic fields for diagnosis is known to be a safe and painless procedure for the patients (Schenck 2000). Furthermore, a magnetic navigation system known as Stereotaxis has been widely used in the industry, along with different imaging modalities such as real-time fluoroscopy, to guide magnetically tipped intervention devices for accurate positioning in the human body (Leksell and Jernberg 1980). This system has a user-friendly interface and well-established computer software (Stereotaxis Inc. 2008). However, the Stereotaxis system can only guide magnetically tipped intervention devices that are invasively inserted and maneuvered inside the body. This system is not applicable to the free-floating capsule endoscope that has the ability to traverse the entire GI tract and relies fully on the magnetic interaction between the capsule and external electromagnets for position control.

The focus of the present work is to develop an economical and effectively stabilized magnetic capsule navigation system that can operate in the presence of GI peristalsis and define the parameters of such a system in the context of a novel diamagnetic stabilization technique to improve the levitation capabilities of the device.

2. Methodology

2.1. Overview

Many capsule steering systems that involve multiple electromagnets or other complicated designs have been suggested in the past, yet none has been successfully utilized in actual clinical conditions (Takeshi 2003, Meng et al. 2004, Wakefield 2004, Olympus Medical Systems 2005, Ries 2005). The approach taken in the present study is to build a simple, functional magnetic capsule navigation unit and then look at ways to improve the system.
Figure 2. Proposed setup for a magnetic capsule navigation system utilizing a pair of stationary electromagnets, a levitating magnetic capsule with built-in wireless transmitter and a computer feedback control unit. In this implementation, the patient’s bed is movable.

The sacrifice for an easy-to-implement control system is the added complexity to the capsule. In developing a navigation system for the capsule endoscope, several technical issues have to be resolved. First, a control system for the capsule’s position in a Cartesian coordinate system using two electromagnets has to be developed. Second, circumferential imaging in the capsule is mandatory because only three degrees of freedom (three translations in the Cartesian coordinate system: \(x\), \(y\) and \(z\), but no rotations) are possible with the suggested design. Circumferential imaging has been proposed before (Mintchev and Yadid-Pecht 2006) and is currently being incorporated into the latest version of a capsule endoscope manufactured by RF System Laboratory (RF System Lab 2007), a growing industrial company in Japan. Third, the requirements for the real-size navigation system have to be determined.

The design of the proposed magnetic capsule navigation system includes a pair of electromagnets, a free-floating (levitating) magnetic capsule with wireless transmission capabilities and a computer feedback control unit. It should be noted that levitation only occurs in large lumens of the GI tract such as the stomach and the large intestine where the capsule endoscope tumbles a lot. In contrast, capsule endoscopy without the need for magnetic levitation has been successful for the small intestine, since its walls encompass relatively tightly the capsule (Linagpunsakul et al 2004). The electromagnets act as external magnetic sources that guide the intraluminal magnetic capsule along the GI tract. They operate at a low current state during normal steering operations and at a high current state in the event of GI peristalsis, thus conserving power. The current required during the high current state depends on the magnitude of the expected lateral external disturbance force. The permanent magnet may be embedded at either end of the capsule, while circumferential imaging is located at its center. Utilizing a Hall-effect sensor (Graumann 2005, Kuth 2007), the computer control unit can locate and control the position of the magnetic capsule and take it to the desired location via an apparatus similar to a joystick for directional control (figure 2). The choice of a Hall-effect sensor was based on its size and cost, but more importantly, on the simplicity and practicality in utilizing it as part of a feedback control mechanism in the small-size experimental setup. The type of sensor utilized in a real-size design should be a subject of similar optimization based on the size, dimensions and particularities of the specific new system.
In addition, the focus of this development has been to study the measures needed to effectively stabilize the levitating magnetic capsule in order to maximize its ability to withstand the impact of external peristaltic forces attempting to take the device out of levitation control and propel it along the GI tract as a food chime. Previous studies have demonstrated that diamagnetic substances under a strong magnetic field exhibit characteristic behavior that helps to stabilize a levitating permanent magnet embedded in them (Geim and Simon 2000, Geim et al 2001). Diamagnetism is a form of magnetism that opposes to the gathering of and spreads out magnetic field lines in materials. Under normal circumstances, the diamagnetic phenomenon is overpowered by other forms of magnetism such as ferromagnetism and paramagnetism (Parasnis 1961). The diamagnetic effect can most easily be seen in the presence of large external magnetic fields in substances that display mostly or solely diamagnetic behavior. These are known as diamagnetic materials and include graphite, water, protein, wood, bismuth, silver, diamonds and gold (Geim et al 2001). Bismuth and graphite are among the strongest diamagnetic materials. They exert a diamagnetic force about 20 times higher than that of water (Geim et al 2001). A design idea that distinguishes the proposed system from others that have been already explored (Takeshi 2003, Meng et al 2004, Wakefield 2004, Olympus Medical Systems 2005, Ries 2005) is the incorporation of the concept of diamagnetism in the capsule casing to stabilize the levitating permanent magnet embedded in the capsule that is still relatively free to move inside the capsule volume, thus providing an enhanced resistance of the device to the possibility of being taken out of levitation control by the natural peristaltic forces.

A starting point of the proposed design was the development of a small-size experimental setup of a capsule navigation system using a hard-covered plastic capsule embedding four miniature magnets. Due to current and size limitations related to the external electromagnets available for the small-size experimental setup, the magnetic strength of the levitating capsule was enhanced with the incorporation of four such miniature magnets instead of one as proposed in the real-size navigation system. This physical setup was subsequently utilized to verify a matching computer model developed using the Maxwell 3D Computer Aided Design (CAD) software package (Ansoft, Pittsburg, CO). Upon the verification by the CAD modeling software, the design was generalized to determine the anticipated requirements for a real-size navigation system.

In the small-size experimental setup, the capsule was levitated primarily through a current-based feedback control circuit. The levitating capsule was not stable horizontally, and it was noted that the capsule wobbled during levitation. Theoretically, when the capsule is aligned with the central axis, the external electromagnets generate a magnetic force on the free-floating capsule in the vertical plane only. If the capsule moves away from the central axis due to external disturbances, the electromagnets would apply a force that pulls the capsule back toward the central axis as illustrated in figure 3. For this reason, the capsule should be stable in the horizontal plane. Similar considerations apply if the central axis of the electromagnets is horizontal rather than vertical, so in our model we considered only one case. The important practical limitation of this type of levitation is that regardless of the position of the central axis of the external electromagnets, because of the time-varying nature of the currents in the electromagnets in the feedback control circuit, the capsule wobbles in the air and the stabilization becomes an issue (Geim and Simon 2000). Therefore, the stabilizing effect of incorporating diamagnetic materials into the capsule casing was examined. First, the theoretical condition required for diamagnetic stabilization of the levitating permanent magnets was investigated (Geim et al 2001). Second, the effects on the levitating capsule in the small-size experimental setup when using bismuth for diamagnetic capsule casing and Teflon for regular capsule casing were quantified using a custom-designed vibration assessment...
Figure 3. The forces acting on the levitating capsule are in the vertical plane only when the capsule is positioned on the central axis, directly below and above the centers of the two electromagnets (left). The application of an external disturbance force causes the capsule to move away from its position on the central axis (center). Away from the central axis, magnetic forces are generated to bring the capsule back to its original position (right).

setup. Third, CAD modeling software simulations were performed for validating the results, which were later extended to the real-size navigation system.

2.2. Small-size experimental setup

In order to develop this miniature physical model of the real-size navigation system, two copper electromagnets were wound, each having an 11 cm diameter, 5000-turn continuous AWG 19 (0.91 mm) copper wire, around an 8 mm × 8 mm ferrous core. A Hall-effect sensor (SS495 A, Honeywell Sensing and Control, Morristown, NJ) external to the capsule was employed to determine the position of the levitating hard-covered plastic capsule (12 mm in diameter × 35 mm in length), which embedded four 7 mm NdFeB magnets (Kinetic MicroScience, Los Gatos, CA).

The overall weight of the capsule was 15 g with the added modeling clay to imitate the weight of other components in a functional capsule endoscope. The electromagnets in the system operated in two distinct states, a high current state and a low current state. Under normal operation, the electromagnets were at a low current state of 100 mA sufficient to levitate and navigate the magnetic capsule in the presence of small disturbance forces similar to bowel movements. In the event of a large sudden external lateral disturbance such as peristalsis marked by a large displacement of the capsule, the Hall-effect sensor that locates the position of the capsule sends a signal to the feedback control circuit to increase the currents in the electromagnets. Within the system’s characteristic response time, the electromagnets switch from their low current state to high current state of 500 mA in order to regain control over the magnetic capsule.

The capsule was levitated vertically, concentric with the central axis due to difficulties in achieving a high level of symmetry in the capsule to levitate it horizontally in the small-size
Figure 4. Small-size experimental setup for levitating the magnetic capsule (left) and the interrogating force actuator (right). The force actuator system contains a miniature force sensor that controlled the force applied to the levitating capsule.

experimental setup. This limitation was related to the power of the small electromagnets. In the real-size navigation setup, however, the orientation of the capsule should not be an issue, since a single embedded permanent magnetic ball would interact with much stronger electromagnets.

For the purpose of assessing the requirements for the navigation system to sustain position control over the capsule, known lateral forces were applied to the levitating capsule in the small-size experimental setup to mimic GI peristalsis. A miniature force actuator (MD-2 Motor Control System, Arrick Robotics, Tyler, TX) integrated with a force sensor (FSL1500, Honeywell, Morristown, NJ) attached to its end was used to apply and measure the lateral force acting on the levitating capsule (figure 4). The minimum force that could take the capsule out of levitation causing the feedback system to lose levitation control was recorded. The experimental results were then compared with the advanced computer simulations of the same scenario using the CAD modeling software.

2.3. Condition for diamagnetic stabilization

According to Geim et al (2001), the condition for diamagnetic stabilization occurs when the potential energy, \( U \), of the levitating magnet as shown in equation (1) is at a local minimum. The additional potential energy due to the presence of cylindrical diamagnetic casing, \( U_{\text{dia}} \), can be represented as \( U_{\text{dia}} = C_r r^2 + C_z z^2 \) in the cylindrical coordinates:

\[
U = -\mathbf{M} \cdot \mathbf{B} + mgz + U_{\text{dia}}
\]

(1)

where \( \mathbf{M} \) is the dipole moment vector of the levitating magnet, \( \mathbf{B} \) is the external magnetic field vector, \( m \) is the mass of the levitating magnet, \( g \) is the gravitational constant and \( z \) is the position of the capsule in the geometry system. For the potential energy of the levitating magnet, \( U \), to be at a local minimum, its second derivative must be greater than zero. This
gives rise to the inequality in equation (2), where horizontal stability is achieved when the term in front of \( r^2 \) is greater than zero:

\[
C_r + \frac{1}{4} \frac{m^2 g^2}{2MB_0} > 0
\]

where \( B_0 \) is the external field strength at the point of levitation and \( C_r \) is the radial component of the diamagnetic potential energy term. From a dipole approximation of \( C_r \) as shown in equation (3), the inequality can now be represented as in equation (4):

\[
C_r = \frac{45 \mu_0 |X| M^2}{16} \left\{ \frac{45 \mu_0 B_0 M^3 |X|}{2 \frac{m^2 g^2}{\mu_0 \rho g}} \right\}^{1/5} > D
\]

where \( \mu_0 \) is the permeability of free space, \( X \) is the diamagnetic coefficient of the material for casing and \( D \) is the inner diameter of the hollow cylindrical diamagnetic casing. It is also known that the magnetic dipole moment, \( M \), for a spherical NdFeB magnet with a diameter, \( d \), and a remnant field, \( B_r \), is \( M = (\Pi/4\mu_0)B_rd^3 \). Consequently, the theoretical condition for diamagnetic stabilization of a levitating permanent magnet based purely on mathematic derivations is described to be (Geim et al. 2001)

\[
A \left( \frac{|X_b|LB_r^2 d^3}{\mu_0 \rho g} \right)^{1/5} > D > d
\]

where \( A \) is the geometric constant; \( X_b \) is the diamagnetic coefficient of bismuth; \( L \) is the characteristic length and ranges from \( R \) (short solenoid) to \( 1.2R \) (long solenoid) with \( R \) being the radius of the solenoid (Geim et al. 2001); \( B_r \) is the remnant field of the NdFeB magnet; \( d \) is the diameter of the NdFeB magnet; \( \mu_0 \) is the permeability of free space; \( \rho \) is the density of the NdFeB magnet; \( g \) is the gravitational constant and \( D \) is the inner diameter of the hollow cylindrical diamagnetic casing. The term ‘solenoid’ refers to the external electromagnets used in the magnetic levitation setup. \( D - d \) is the clearance gap between the levitating ball magnet and the diamagnetic wall. The clearance gap is kept small for successful levitation of the ball magnet. As an initial confirmation of the concept, the parameters used in the small-size experimental setup and the real-size navigation system were tested against the theoretical condition for diamagnetic stabilization. The experimental setting was similar to the one described earlier (Geim et al. 2001), since there was instability in the horizontal direction, and diamagnetic casing was employed to stabilize the levitating permanent magnet, which was relatively free to move with respect to the diamagnetic casing under a strong external magnetic field.

2.4. Diamagnetic casing and the vibration assessment setup

The modeling clay in the hard-covered plastic capsule was replaced first with a cylindrical bismuth casing and then with Teflon casing of the same weight and shape. The magnetic field distributions for both casings were measured using a Gaussmeter (DC Magnetometer, Alpha Lab Electromagnetic Instruments, Salt Lake City, UT) and agreed with the CAD modeling simulations for the correct range of values. However, it was impractical to distinguish the magnetic field distribution difference between the diamagnetic bismuth-cased capsule and the regular Teflon-cased capsule, as this difference was small compared to the resolution of the Gaussmeter. Therefore, the lateral vibrations of the levitating capsule in the small-size experimental setup were measured via an array of optical sensors to determine the effect
Figure 5. Data acquisition setup for measuring the projected vibration motions of the levitating capsule via a class III laser beam and an array of eight photodiodes. The ‘wobbling’ motion of the Teflon-cased and bismuth-cased levitating capsules can then be quantified.

of diamagnetic stabilization on these vibrations. Eight photodiodes (PDBV6122, Advanced Photonix Inc., Camarillo, CA) were spaced out equidistantly at 0.5 cm on a flat surface to detect the vibrations of the levitating capsule. A class III laser beam tailored around 940 nm was aimed at the levitating capsule (figure 5). The laser beam was then reflected off a 15 mm × 25 mm mirror surface attached to the capsule onto the photodiode array. The resulting signals coming from the photodiodes were processed to determine the amplitude of vibrations of the levitating capsule. The signal at the output of each photodiode unit varied from −0.7 V (laser beam not present) to 5 V (laser beam present) and was used to monitor the status of each photodiode sensor. This signal was utilized to light up an LED for visual display. Together with the array of photodiodes, this setup was employed to determine the amplitude of the projected vibrations of the levitating capsule with a resolution of up to 0.5 cm, limited by the width of each sensor. Z-score repeatability tests (Christensen 1977) were applied to the results obtained, with a level of significance of $p < 0.05$ (two-tailed).

2.5. Generalization of the CAD model

In order to verify the reliability of the simulation data from the CAD modeling, experimental results obtained for the maximal sustainable lateral force and for the diamagnetic stabilization of the bismuth-cased capsule in the small-size experimental system were compared to CAD modeling simulation results employing the same design.

Based on the conformity of the results from the small-size experimental setup and from the computer simulations of the same scenario, the design of the capsule navigation system was extended to real size. The initial design of the real-size navigation system started with the basic requirement of 15 cm distance between the levitating capsule and each external electromagnet, with the symmetry of the capsule positioning between the external electromagnets preserved. Subsequently, iterative adjustments were performed by manipulating the geometries, the materials and the current consumption of the electromagnets for the system to sustain lateral forces of up to 1.5 N experienced by the capsule during peristalsis. The CAD model of
the real-size navigation system also studied the effect of diamagnetic stabilization on the bismuth-cased capsule.

3. Results

3.1. Force analysis in the small-size experimental setup

A lateral force of 0.42 N applied to the levitating capsule in the small-size experimental model was sufficient for the system to lose control over the capsule. This experiment had been repeated twice, 30 times each in 2 separate days, delivering a total of 60 data points. Z-score tests were applied to the results, revealing statistically significant repeatability ($p < 0.05$).

3.2. Effect of diamagnetic casing on the small-size experimental setup

The condition for diamagnetic stabilization for a single NdFeB permanent magnet (7 mm in diameter) levitating in a magnetic field created by a pair of electromagnets (11 cm in diameter) becomes

$$A' \left( \frac{|X_b|D'_{\text{solenoid}}B^2d^3}{\mu_0\rho g} \right)^{1/5} > D' > d'$$

where $A' = 1.73$, $D'_{\text{solenoid}} = 11$ cm, $D' = 11$ mm and $d' = 7$ mm. Results from Matlab (The Mathworks, Natick, MA) computations showed that the inequality was valid (17.5 mm > 11 mm). The above inequality implies that if the levitating magnet were unstable horizontally, under the right conditions the diamagnetic effect for stabilizing the levitating magnet could take place. In the present study, this mathematical derivation was based on the use of a single 7 mm embedded magnet compared to a 4 mm embedded magnet utilized before (Geim et al 2001), a bismuth cylinder with an inner diameter of 11 mm compared to 8 mm in Geim et al (2001), and a ball magnet with a remnant field of 1.22 T compared to 1.4 T in Geim et al (2001). The clearance gap between the levitating magnet ball and the diamagnetic wall was 4 mm, same as in Geim et al (2001). The condition for diamagnetic stabilization using four such identical magnets in the small-size experimental setup was still valid by the principle of superposition. Similarly, for the real-size navigation system, the parameters in equation (2) became $A' = 1.73$, $D'_{\text{solenoid}} = 50$ cm, $D' = 11$ mm and $d' = 7$ mm and the inequality was shown to be valid (23.8 mm > 11 mm) for a single embedded magnet in the final envisioned real-size navigation system. Hence, diamagnetic stabilization effects were present in addition to the feedback-controlled levitation. Table 1 presents a complete list of the parameters used in the derivation.

Comparing the two setups with Teflon-cased capsule and bismuth-cased capsule, a decrease in the mean lateral vibrations of the levitating capsule from 2.5 cm to 1.5 cm was measured by the vibration assessment setup. The Z-score repeatability test was performed on the vibration data using the two different capsule casings. The two sets of measurements were shown to be statistically different ($p < 0.05$). These results demonstrated that the diamagnetic bismuth casing significantly improved the vibration stability of the levitating capsule in the small-size experimental setup.

3.3. CAD modeling of the small-size experimental setup

CAD modeling of the small-size experimental setup resulted in a theoretically obtained maximal sustainable lateral force of 0.39 N. The very small discrepancy in this result compared to the actual physical measurement demonstrated the reliability of the CAD modeling software.
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Figure 6. The small-size experimental systems for both the regular Teflon-cased capsule (left) and diamagnetic bismuth-cased capsule (right) were simulated in Maxwell 3D. The difference in the magnetic field distribution is denoted by a square.

Table 1. List of symbols and values used in the mathematical condition for diamagnetic stabilization.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
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</thead>
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</tr>
<tr>
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<td>Radius of solenoid</td>
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<td></td>
<td></td>
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<td>0.055 (small size)</td>
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<td></td>
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<td>0.110 (small size)</td>
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<td>Length of solenoid</td>
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<td>1.000 (real size)</td>
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<td></td>
<td></td>
<td>m</td>
<td>0.220 (small size)</td>
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</tr>
<tr>
<td>Inner diameter of the diamagnetic shell</td>
<td>( D )</td>
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<td>0.011</td>
</tr>
<tr>
<td>Remnant field of the NdFeB magnet</td>
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<tr>
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<tr>
<td>Gravitation constant</td>
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<td>( R - 1.2R )</td>
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<td>Geometric constant</td>
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in estimating the sustainable lateral disturbance force acting on the system. Thus, the CAD modeling approach was extended to a real-size navigation system aiming at handling peristaltic forces of up to 1.5 N.

Magnetic field distributions for the bismuth-cased capsule and the Teflon-cased capsule in the CAD model of the small-size experimental setup were not very different when the external magnetic field was weak (figure 6). However, a detailed study of the simulation graphs revealed that the magnetic field lines near the top of the capsule casing were more curved for the Teflon-cased capsule compared to the bismuth-cased capsule because of their realignments due to the diamagnetic casing.
3.4. Generalization of the CAD model

An iterative method for system parameter adjustments in the CAD process for real-size navigation was utilized, which resulted in a set of real-size navigation system parameters of 50 cm diameter, 10,000-turn copper electromagnets having a 10 cm $\times$ 10 cm ferrous core and a single 7 mm diameter NdFeB magnet embedded in a capsule levitating at 15 cm vertical distance from each of the external electromagnets. At the low current state, a 6 A current was shown to levitate the capsule against the force of gravity and at the high current state, a 300 A current was shown to successfully sustain a 1.5 N lateral peristaltic force and hence, maintain levitation control of the capsule in the event of peristalsis. The strength of the magnetic fields involved in the real-size navigation system operating at 6 A and 300 A was simulated as well (figure 7). It was important to note that the parameters selected were not unique. Other combinations of system geometries, materials and current consumptions could accomplish the same task.

For such a large current, power dissipation for the electromagnets must be considered. Peristalsis is an intermittent event and, in fact, can be significantly reduced pharmacologically for the purpose of this specific test (Gilani et al 2005). Therefore, the heating of the electromagnets can be significant but only for a short period of time. The electromagnets are to be filled with transformer oil to dissipate heat energy. In the manufacturing process of the real-size electromagnets, some adjustments to the parameters have to be made related to the availability of materials and their characteristic properties. For example, using thinner wires but increasing the number of turns can reduce the wire current. The parameters suggested in this paper provide a general idea of the field strength required and the interaction between the electromagnet and the levitating capsule. The temperature dependence of the magnetic field, however, cannot be modeled in the simulation program. Also, it should be noted that the 6 T magnetic field, as shown in figure 7, does not directly apply to the capsule. From the simulation graphs it is evident that only 3 T would be required at the capsule navigation area. Previous experience in MRI (Schenck 2000) clearly indicates that employing such strong electromagnets is completely realistic and safe.
Figure 8. Simulations of a real-size system with 50 cm diameter, 10 000-turn electromagnets operating at 6 A, focusing on the area near the center of figure 7 (left). The magnetic field lines of the magnet in the bismuth-cased capsule (right) were better realigned forming a stronger bond with the external magnetic field, compared to the Teflon capsule casing (left). This effect occurs only locally around the 7 mm levitating magnet.

The effect of diamagnetic capsule casing was simulated with the parameters of the proposed real-size system. These CAD simulations clearly demonstrated that the magnetic field lines were realigned when bismuth capsule casing was modeled (figure 8). The effect of the realignment of the magnetic field lines due to bismuth capsule casing was more prominent in simulations of the real-size navigation system compared to the small-size experimental setup due to the higher magnetic field strength involved.

3.5. Vision for the overall system design

The established vision of the overall capsule navigation system that can maintain control in the presence of peristaltic forces of up to 1.5 N includes a pair of 50 cm, 10 000-turn copper electromagnets with a 10 cm $\times$ 10 cm ferrous core, a Hall-effect position sensor, a microcontroller unit and a microelectronic capsule with an embedded 7 mm NdFeB magnet, circumferential imaging and diamagnetic bismuth capsule casing for improved vibration stability during levitation. The electromagnets act as an external magnetic source that guides the intraluminal magnetic capsule along the GI tract. They operate in two states: a low current state of 6 A and a high current state of 300 A to conserve power. Utilizing the Hall-effect sensor and the microcontroller unit, the capsule can be moved and held at different locations of the GI tract via an apparatus similar to a joystick. A suggested Hall-effect sensor that can be used in strong magnetic fields is the HSU-1 (Cryomagnetics, TN, USA) with a sensitivity of 10 mV T$^{-1}$ that can detect field changes of less than 40 G for millimeter-resolution control of the magnetic capsule’s position. This Hall-effect sensor should be contained inside the capsule to report its physical location.

4. Discussion

This paper discussed the vision of a magnetic capsule feedback navigation system with diamagnetic stabilization capabilities. A magnetic capsule was designed to be navigated in the GI tract using external magnetic sources and a feedback control unit. A simplistic approach
with only two electromagnets as external magnetic control sources was taken. The present
design alleviates many of the complicated issues involved in angular and altitude control of the
capsule, making the system more suitable for implementation. The feasibility of the system
design had been demonstrated in a small-size experimental setup and via CAD modeling of
the same scenario. These results were extended to a plausible real-size design with a 50 cm
copper electromagnet operating at a maximum current of 300 A. The described system was
shown to sustain a lateral disturbance force of up to 1.5 N. The simplicity in the design of the
present magnetic guidance system resulted in a high current requirement for it. Nevertheless,
the 300 A is an overestimate of the current needed for the magnetic navigation system, since
pharmacological avenues to reduce gastric motility have not been considered.

The diamagnetic capsule casing was incorporated into the capsule design to stabilize the
feedback-controlled levitation. The described systems were shown to meet the requirement
for diamagnetic stabilization (5) when levitating a permanent magnet. In the small-size
experimental setup, a statistically significant decrease in the capsule vibrations was also
measured ($p < 0.05$) for a diamagnetic bismuth-cased capsule compared to a regular Teflon-
cased capsule. In the CAD modeling of the same scenario, the diamagnetic capsule casing
demonstrated magnetic field lines realignment around the levitating capsule, creating a
stronger interaction with the external electromagnets, thus stabilizing the levitating capsule.
Simulations extended to a real-size system revealed that the magnetic field lines around the
levitating permanent magnet were better realigned for the diamagnetic bismuth-cased capsule
compared to its Teflon-cased equivalent. Altogether, this study illustrated the feasibility of a
real-size intraluminal capsule navigation system in the presence of natural GI peristalsis.

The diamagnetically facilitated capsule navigation system is now in its infancy stage, and
many related issues await further studies. For instance, the magnetic force may cause damage
to the intestinal walls if the capsule accidentally goes out of levitation. Hence, pressure
sensors should be added to the capsule in the testing stage of the real-size system to prevent
possible lesions the intestinal wall and help quantifying the peristaltic force. The real-size
electromagnets should also include a proper cooling system. In addition, intraluminal studies
on animals should be performed to confirm the findings reported in the present study.

5. Conclusion

A custom-designed diamagnetically facilitated capsule navigation system was shown to
successfully steer an intraluminal magnet-carrying capsule in a small-size experimental setup
and in computer-aided models. The real-size system parameters selected can sustain stable
levitation in the presence of an estimated peristaltic force of 1.5 N. The added stabilization
feature enhances the capsule’s ability to remain under levitation control during peristalsis.
This was demonstrated theoretically in a small-size experimental setup and in corresponding
CAD models. A real-size capsule navigation system using diamagnetic stabilization is a
feasible diagnostic modality. This paper explores the potential problems associated with a
diamagnetically facilitated magnetic capsule navigation system and explicitly outlines the
requirements for such a system. The results can be regarded as a first step toward the
development of a real-size capsule navigation system.

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