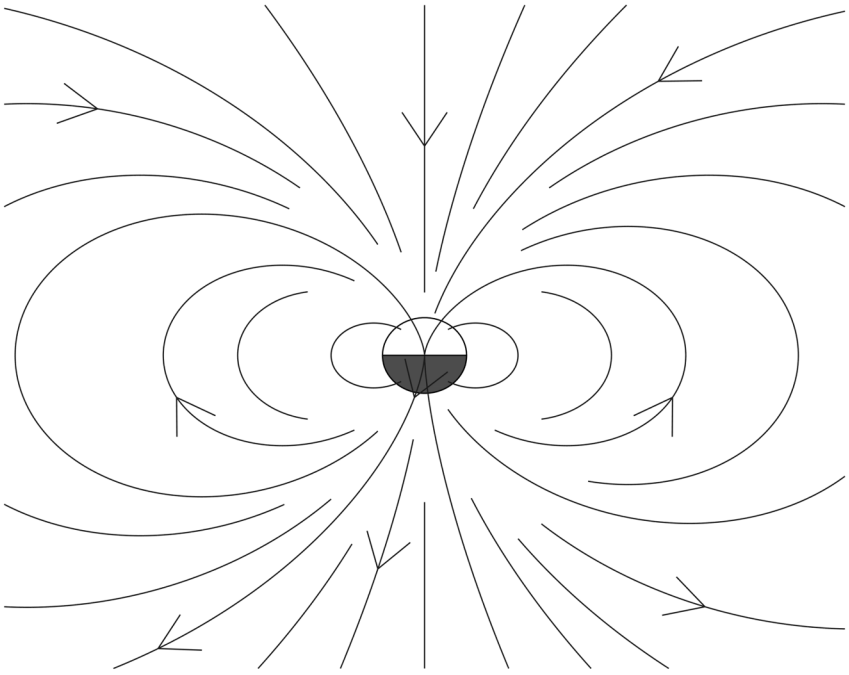
Magnetic actuation of endoscopy capsules for enhanced gastrointestinal tract imaging



Weihao Chen

Bachelorassignment
Biomedische technologie
Surgical Robotics Lab (SRL)
University of Twente

Examination Committee:
Prof. Dr. ir. P. Jonkheijm
Dr. I.S.M. Khalil
Dr. D. Wasserberg
Dr. ir. K. Constantinos
July 22, 2024

Contents

Abstract

Capsule endoscopy involves the patient swallowing a capsule that travels through the gastrointestinal tract while capturing interior images. The capsule usually passes the body. However, in patients with irritable bowel disease, the capsule has a chance to become lodged due to bowel constrictions. This complication requires surgical removal, turning a non-invasive procedure into an invasive one. To prevent such an outcome, magnetic actuation can maneuver a capsule past constrictions. To test the feasibility of this, capsules were controlled within a Bowel Phantom with constrictions. Results showed that the capsule managed to maneuver through the Bowel Phantom, indicating that controlled navigation within the bowel is feasible. This result could decrease the likelihood of the capsule becoming lodged, making it a preferable option over passive capsule endoscopy.

1 Introduction

Conventional endoscopy involves imaging the digestive tract by inserting an endoscope orally, often causing discomfort for around 30% of patients [1, 2, 3]. Consequently, some patients refuse this procedure. Capsule endoscopy, a less invasive method, involves a patient swallowing a capsule that travels through the digestive tract and captures images of the patient's gastrointestinal (GI) tract. The capsule could be used to image the entire tract; however, it mainly images the small intestines, since those are difficult to reach with conventional endoscopy [4].

Usually, the capsule travels smoothly through the GI tract. Nevertheless, it may become lodged due to constriction within the bowel [5] by some diseases, particularly in patients with Crohn's disease. These constrictions prevent the peristaltic movement from moving the capsule past an obstruction. Capsule retention, where the capsule remains in the GI tract for two weeks or longer, occurs in about 1.9% of cases [5, 6, 7], which increases to around 3% [8, 9] for people with Crohn's disease. However, it decreases to 2.88% when a patency capsule [8], a soluble capsule used to assess the risk of capsule retention in the patient, is utilized. Generally, the consequence of capsule retention will be surgical removal of the capsule [2, 10]. Furthermore, surgical procedure would nullify the non-invasive nature of capsule endoscopy. Thus, it is crucial to decrease chances of capsule retention further. A potential solution to this problem is using magnets to manipulate the movements of the capsule to move past an obstruction. Besides solving the problem of immobilization, the clinician may adjust the camera to image points of interest from multiple angles within the GI tract of the patient.

In addition to the immobilization issue, there is an issue specific to the upper GI tract. Nonmagnetic capsules cannot be used for gastroscopy [11] due to the anatomy of the stomach. The capsule would pass the stomach without any opportunity to image anything within it. Nonetheless, if the capsule becomes magnetically controllable, the clinician may control what is imaged within the stomach and control when the capsule passes the stomach, allowing for gastroscopy.

Preliminary tests were done to test the viability of moving the capsule through the large intestines. Nonetheless, since the capsule is not magnetic, it needs a casing where magnets can be added. The entire experiment took around two hours, during which the endoscopy capsule did not move past the first haustrum, which Figure 1 shows. Therefore, the original casing cannot aid the capsule to move through the Bowel Phantom. The failure to move could imply that the capsule does not gain enough traction to move through the Bowel Phantom or does not react strongly to the RPM. The experiments were done using the original casing. Since the casing did not manage to move inside the Bowel Phantom, shown in Section 3, the capsule needs to change to allow the capsule to maneuver through the large intestines. Hence, this report will focus on improving the capsule to allow movement inside the Bowel Phantom.

Currently, the bulk of research around capsule endoscopy is focusing on automated robots controlling the capsule and assessing its safety for clinical use [12, 13], comparing it to conventional methods such as the endoscope [2, 3]. This article will add to the bulk of the research by seeing the feasibility of moving a capsule past a constriction, which simulates an irritable bowel disease, without the aid of peristaltic movements.

Thus, this article will research how the movement of the control magnet may control the movement of the capsule and how specific parameters, like the magnetic dipole moment, change the control of the capsule. Therefore, the research question is: "How can the movement of a capsule be controlled within the GI tract with the help of an extracorporeal magnet?"

2 Theory

To understand how the magnetic capsule is controlled, the physics needs to be understood. Permanent magnets, or ferromagnets, inherently create a magnetic field. This field depends on the shape of the magnet and the material. However, to simplify the calculations in this paper, the magnets used in experiments are approximated, assuming that the magnet is a point dipole. This approximation becomes more accurate when the magnetic field is assessed at a distance further away from the magnet, as opposed to directly next to the magnet [14]. The magnetic field of a magnetic point dipole can be constructed with the following formula [15]:

$$\mathbf{h} = \frac{||m_a||}{4\pi||p||^3} \times \mathbf{D}(\hat{\mathbf{p}})\hat{\mathbf{m_a}}, \tag{1}$$

where $\mathbf{h}$ represents the magnetic field produced by a magnetic point dipole. Furthermore, m_a signifies the dipole moment and p represents the distance from the middle of the RPM to the middle of the capsule, with $\mathbf{p} = \mathbf{pc} - \mathbf{pa}$ where pc stands for the middle of the capsule and pa stands for the middle of the Rotating Permanent Magnet(RPM). This can be seen in Figure 1.

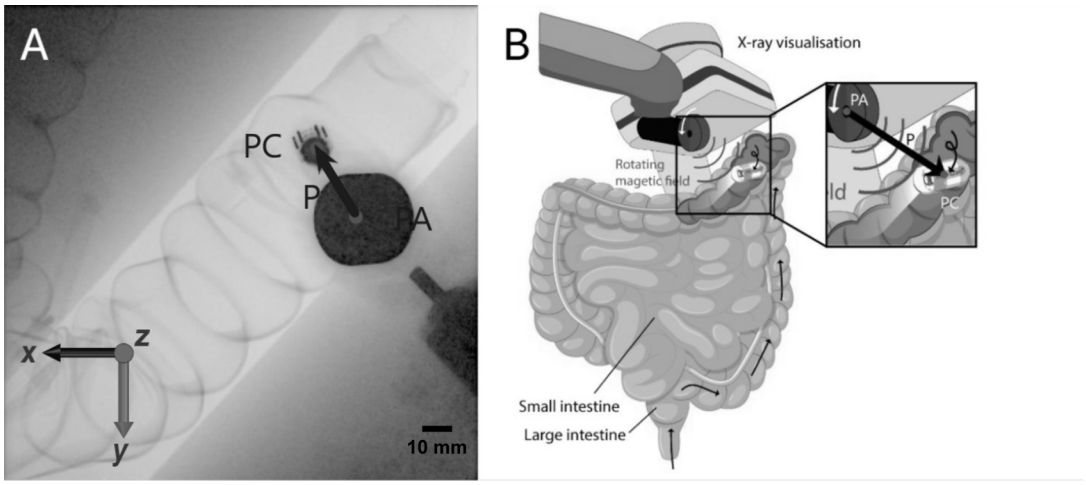


Figure 1: A) The capsule inside the Bowel Phantom, stuck in the first haustrum. B) The capsule is being magnetically controlled by the Rotating Permanent Magnet(RPM). During control of the capsule, the capsule will be able to send images to the clinician, aiding them in control of the capsule. The distance, $\mathbf{P}$, between the points in space **pa** and **pc**, where **pa** stands for the middle of the RPM and **pc** stands for the middle of the capsule.

In the formula, the magnitude and the vectors of m_a and p are separated. Meaning that $\hat{\mathbf{m_a}}$ and $\hat{\mathbf{p}}$ are the unit vectors of p and m_a. $\hat{\mathbf{m_a}}$ shows the direction of the magnetic dipole moment from the magnet. Finally, $\mathbf{D}(\hat{\mathbf{p}})=3 * \hat{\mathbf{p}}\hat{\mathbf{p}}^T - I$, where I is the identity matrix for a 3D space. Formula 1 is used to assess the magnetic field direction. This is useful knowledge because the magnets will try to align their magnetic dipole moment with the other's magnetic field. However, since the RPM is fixed in place rotationally and positionally, only the capsule will try to align itself with the magnetic field of the RPM.

Torque affects the capsule due to interactions between the magnetic fields of the RPM and the capsule's magnetic dipole moment. This formula is a modified version of Formula 1. By multiplying Formula 1 with $\mu_0 m_c$ and the dipole moment vector of the capsule $\hat{\mathbf{m_c}}$ and its absolute value, $\mathbf{m_c}$, the following formula is obtained:

$$\boldsymbol{\tau_m} = \frac{\mu_0||\boldsymbol{m_a}||\,||\boldsymbol{m_c}||}{4\pi||p||^3}\hat{\mathbf{m_c}} \times \mathbf{D}(\hat{\mathbf{p}})\hat{\mathbf{m_a}}. \tag{2}$$

Figure 2 illustrates the magnetic field of the RPM, with the capsule depicted within the RPM's magnetic field. Since the capsule is not aligned with the RPM, which has a stronger magnetic dipole moment, it would be reasonable to predict the capsule to align itself with the RPM's magnetic field. Therefore, the capsule will experience a negative torque, which would cause the capsule to rotate counter-clockwise. The calculations in Appendix 6.1 support this, as this situation was found to have a torque of -1.28E-05 Nm. If this torque is strong enough, the capsule will stay aligned with the RPM, a phenomenon called coupling. Conversely, if the torque is not strong enough, the capsule will not be able to stay aligned, which is referred to as decoupling.

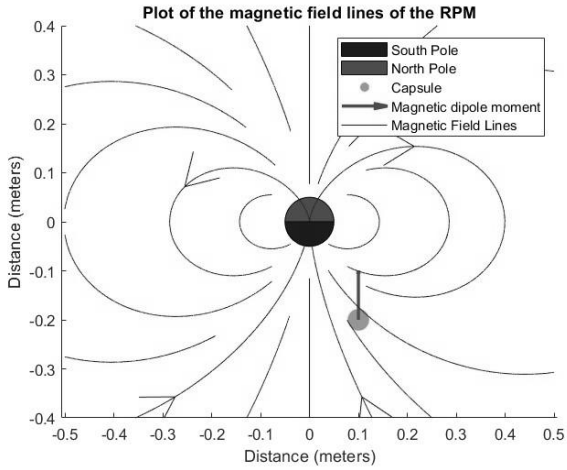


Figure 2: Figure2 depicts the capsule within the magnetic field of the RPM.

Using the magnetic field generated in Figure 2, and the kinematics equations, a small simulation can be generated. The calculations used to generate these simulations are explained in Section 6.2. In this simulation, the RPM remains stationary while it rotates at a rate of one rotation per second. Consequently, the capsule rotates in reaction to the magnetic field, causing it to roll. Figure 3 illustrates this movement at an interval of 1.25 seconds. This interval was chosen to clearly demonstrate the capsule traveling, while the RPM is rotating.

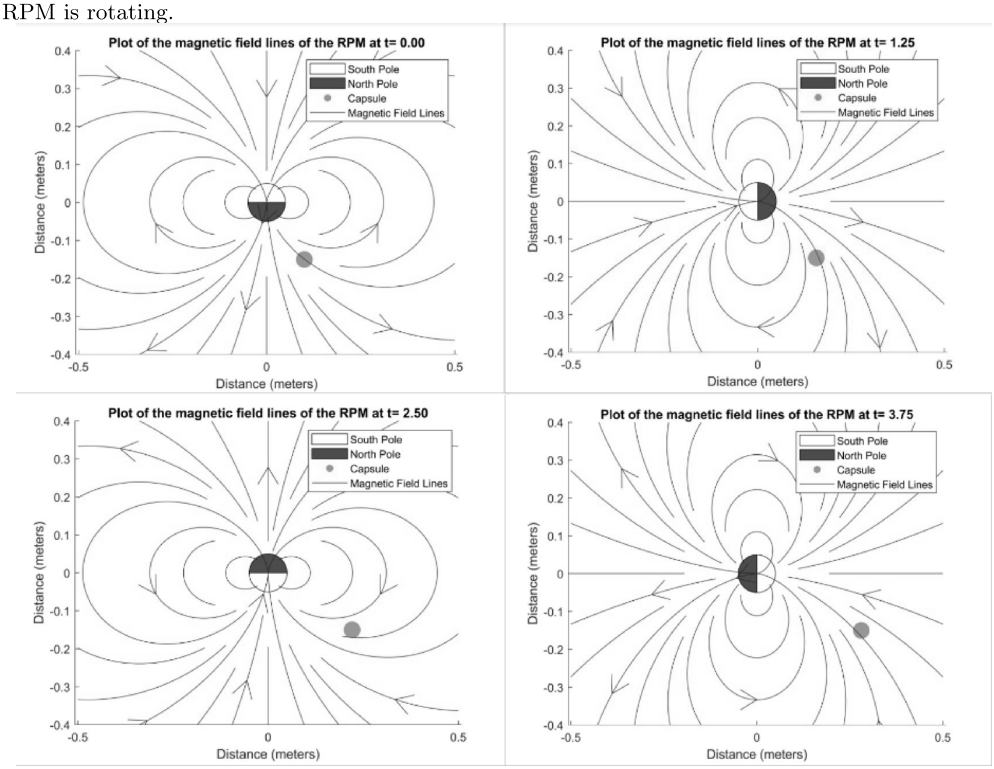


Figure 3: This figure depicts how the capsule reacts when the RPM rotates. The figure shows the location of the capsule at a 1.25 second interval.

3 Methods

For the experiments, an endoscopy trainer (Kyoto Kagaku, Japan) of the large intestine, shown in Figure 4 A, and not the small intestine, will be used because the first tests are going to be a proof of concept. If testing is successful, testing can move to the small intestine to see if this concept will work in a more narrow space. The capsule will have to move over the plicae semilunares in this phantom.

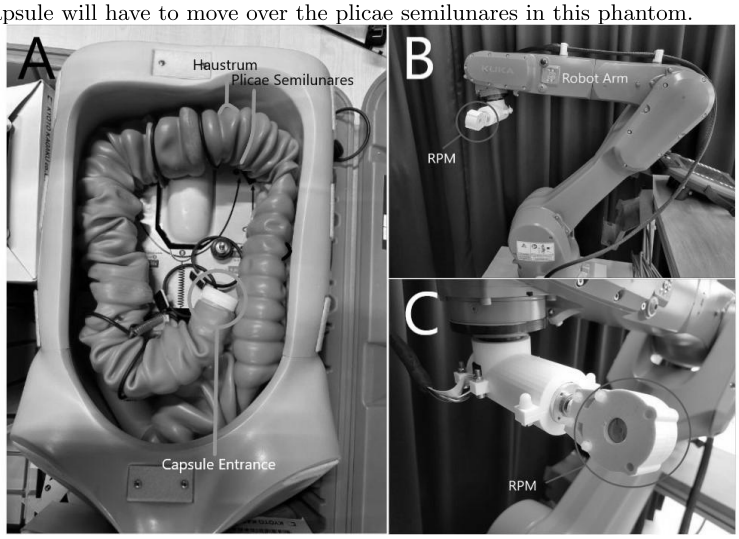


Figure 4: A) The Bowel Phantom used, is a colonoscope trainer from Kyoto Kagaku. B) The KUKA robot used for the experiments. C) The Rotating Permanent Magnet, which controls the capsule.

3.1 Rotating permanent magnet (RPM)

During the tests conducted, there were two magnets: The rotating Permanent Magnet (RPM) and the casing magnets. The RPM, shown in Figure 4 C, is used to control the casing's movement and orientation by orientation and movement in 3D space. The specific robot arm in this article is the KUKA KR10 R1100-2 (KUKA, Germany), shown in Figure 4 B. The robot allows control over the magnet with six DOF. Additionally, a motor is attached to the end effector of the KUKA-arm to allow for the spinning of the magnet, hence the name rotating permanent magnet.

3.2 Capsule and casing

The endoscopy capsule used for experiments is named "MiroCam MC1600". This capsule, also seen in Figure 5 A, is 24 mm in length and 11 mm in diameter. The capsule has a depth of field between 0 and 30 mm and can image 170° in the forward direction at 6fps and flashes light at a similar tempo. The weight of Mirocam MC1600 is 3.38 g. The capsule activates upon removal from the container, immediately capturing images. These images are stored within a Mirocam receiver and transmitted to the desired computer during the procedure and at the end. A company called IntroMedic (Korea) created the capsule and the transceiver [16].

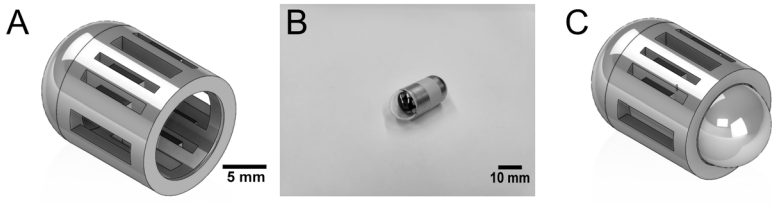


Figure 5: Figures showcasing the capsule casing and how the capsule casing should be attached to the capsule. A) An endoscopy capsule used to image the GI-tract of a patient. B) Capsule casing to hold the magnets. C) Capsule with the casing.

Since the capsule is not magnetic, it is not controllable with the RPM. Hence, a casing has been created to hold magnets. The casing, shown in Figure 5 B, referred to as "capsule casing", is made from ABS-Like 2.0 Photopolymer Resin from Elegoo. Resin printing is preferred, since it allows for more detailed printing over Fused Deposition Modeling, also known as conventional 3D printing. The capsule casing weighs 1.51 grams, has a density of 1.195 g/cm^3, has a diameter of 15.4 mm, and is 20.5 mm long. The purpose of the capsule casing is to hold $1.5 \times 1 \times 5$ mm N45 magnets within its eight slots, which have a magnetic dipole moment of 0.007878 $m^2 \cdot A$. Therefore, a capsule casing with eight magnets has a dipole moment of 0.063 $m^2 \cdot A$. With a density of 8 g/cm^3, these magnets weigh 0.06 g. The total weight adds up to 5.37 g, including capsule and casing. Also, there are extra slots, which are wider than the magnet slots. These serve the purpose of decreasing the total weight of the capsule casing. After having fit the capsule casing with eight magnets, it allows for magnetic control of the endoscopy capsule with the aid of an external magnet. Lastly, the capsule is put into the casing as in Figure 5 C, allowing the capsule to still image 170° inside the casing. Due to the casing stopping before the transparent part of the capsule, the casing does not limit the field of view of the capsule.

Nonetheless, during preliminary testing, this capsule casing version showed instability and uncontrollability in the form of right or left drift. The drift is likely caused by the RPM when the capsule is not perfectly perpendicular to the RPM, which can be calculated using Formula 2. And since the capsule is never perfectly parallel to the RPM, the capsule experiences forces opposing straight motion. Thus, to improve the controllability of the capsule, a redesign is necessary. For this purpose, three designs have been made. Of the redesigns, the designs in A, shown in Figure 5, are fit with bumps, while the design in B has an increase in magnet slot size. The reasoning behind the bumps is that they form a threshold against small forces, which push the capsule off the straight path. Therefore, an increase in speed would be expected as a result. The slot size increase allows for more magnets to fit within. Resulting in an increase of the overall stability of the casing, since the current capsule casing is likely unstable due to a low magnetic dipole moment. A low magnetic dipole moment can cause the capsule to oscillate between being coupled and decoupled with the RPM. While the capsule is decoupled, the RPM's forces can cause the capsule to move erratically. Nevertheless, it will also increase the weight of the casing, which could cause 'climbing' over the semilunares plicae to be more difficult. Therefore, it is paramount to understand if more magnets will increase the controllability of the casing and if the increase in weight in trade for controllability is beneficial. There are going to be three designs for the redesigns. Design one increases the size of the magnet slots, design two has four bumps on each side of the casing, and design three has eight bumps on each side of the casing, for a total of eight and sixteen bumps respectively. Figure 5 illustrates the redesigns of the capsule casings.

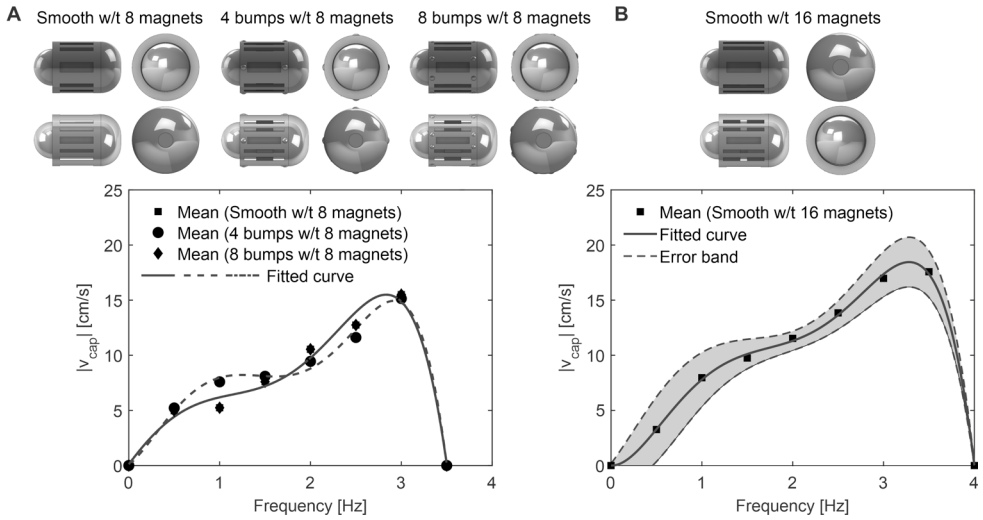


Figure 6: Figures showcasing the capsule casing redesigns from different views. Moreover, the frequency response of the respective capsule is shown underneath the designs. A) shows the capsules with eight magnets, these are smooth, four bumps, and eight bumps, respectively. While, B) shows the design of the sixteen magnet casing. Additionally, this figure displays the frequency responses of different capsule casings, with the y-axis being the speed in cm/s, and x-axis displaying the rotational speed of the RPM in RPS. Overall, the graphs look similar, except for the frequency response of the sixteen magnet casing, which manages to move at an RPS of 3.5.

3.3 Experiment

Experimentation is done in two parts. First, the redesigns will be tested and compared. Secondly, the chosen capsule casing will move through the Bowel Phantom.

3.3.1 Pre-experiment testing

The capsule will move in a straight line during the first experiment, and the RPM controlling the capsule will follow while it rotates at different frequencies. This will be recorded as videos to then derive the velocity of the capsule by using a tracking software called Tracker by Physlet. The data garnered from the experiments are plotted, with velocity on the y-axis and frequency on the y-axis, to create the frequency response. The frequency response curve will be used to determine ideal rotations per second and will aid in choosing the right redesign, since a higher cutoff frequency means that the capsule casing can keep up with the high rotational speeds of the RPM, which implies a better coupling to the RPM. The expectation for the eight magnet capsules with bumps is that they cause an increase in speed due to moving in a straighter path than the original capsule. Also, the expectation for the sixteen magnet capsule would also be an increase in speed, but caused by better coupling to the RPM.

3.3.2 frequency response

With this experiment, the capsule casings have been characterized. Figure 5 shows that the capsule casing with sixteen magnets moves in reaction to the RPM spinning at a rate of 3.5 RPS. The other capsule casings did not react to the RPM. with linear movement at a RPS of 3.5. The capsules with bumps reacted by spinning in place or rolling in the opposite direction. These types of movement are not productive in moving the capsule. Consequently, the frequency, where the capsule casings responses undesirably, are considered to be zero.

The frequency responses in Figure 6 show that the sixteen magnet casing caused the capsule to react at 3.5 RPS. Thus, this suggests that the sixteen magnet casing has better coupling to the RPM. While the other capsule casings do not show improvements over the original capsule casing. Furthermore, while it appears the eight bump capsule and smooth capsule have the same data points, they do vary slightly. Also, the frequency response of the sixteen magnet casing shows a gradual increase in velocity, opposed to the plateauing experienced by the casings with eight magnets. Therefore, the sixteen magnet design is used during the experimental phase. The eight magnets redesigns also did not any improvements over the original capsule. For example, the eight bump casing appears to react almost exactly the same way the smooth capsule does, and the four bump capsule only has slight deviations compared to the smooth capsule and eight bump capsule.

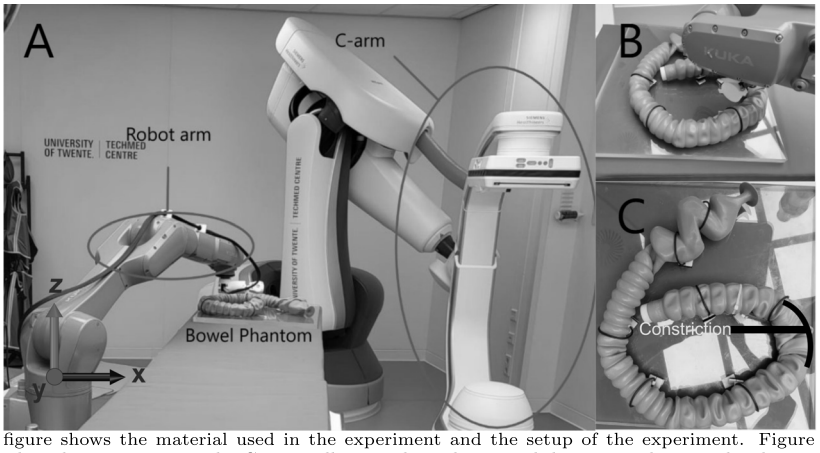


Figure 7: The figure shows the material used in the experiment and the setup of the experiment. Figure 7 A shows the KUKA-arms used in the experiment. The C-arm will move the radiator and detector to be straight above and beneath the Bowel Phantom, respectively. Then, the C-arm will turn 30 °so that the RPM does not block the capsule in the images. Additionally, this prevents the robot from ever hitting the C-arm on accident. Figure 7 B shows the KUKA-arm to be directly above the Bowel Phantom. The KUKA-arm should be close enough to allow control, but also prevent the capsule casing from being pulled into the RPM. Lastly, Figure 7 C shows the position in which the Bowel Phantom is placed for the experiments. Also, the figure shows the constricted area, between the eighth and fourteenth haustra

3.4 Experiment

In Section 3.4, the experiments will be divided into two sessions with different plans, since time with the ARTIS pheno is limited.

3.4.1 Session 1

In session 1, the capsule traverses from the white cap of the Bowel phantom (Figure 7). An operator controls the RPM both manually and autonomously. The RPM is controlled autonomously by predetermining what path the RPM follows during the procedure. Since the amount of sessions and time with the ARTIS pheno is limited, autonomous and manual control are combined. The operator controls the RPM manually during the straight parts of the bowel, while the RPM is controlled autonomously during turns, since the number of buttons that are used simultaneously makes turning manually difficult. Furthermore, the area between the eighth and fourteenth haustra is constricted to simulate an irritable bowel disease. During this experiment, the measured parameters are the time taken from the Ileocecal valve to the right before the capsule enters the rectum. Moreover, the distance traveled through the intestines is measured every 30 seconds. The distance measured is based on which of the 41 haustra the capsule is in. Since the Bowel Phantom is not transparent, X-ray Fluoroscopy is used to image the capsule. The device used is the ARTIS pheno (Siemens, Germany)

3.4.2 Session 2

The experiments of session 1 are going to be divided in individual experiments in session 2. Since the operator now has more experience setting up and adjusting the KUKA-arm decreasing time wasted. Thus, session 2 has two experiments, one involving manual control and the other autonomous control. Also, during Session 1, it was observed that if the RPM is too close to the Bowel Phantom, the capsule will be attracted to the RPM, consequently lifting and twisting the Bowel Phantom. The decision was made to tape the Bowel Phantom down, which is acceptable, since this complication cannot happen in vivo. The tape was applied in a way that did not cause any additional constrictions. This can be seen in Figure 11 in the appendix.

3.4.3 Experiments without the ARTIS pheno

Since the sessions and time with the ARTIS pheno device are limited, further experimentation is done without the ARTIS pheno device to gain an appropriate amount of data. The setup remains mostly the same, but without the X-ray view of the capsule, a different method is deployed to ascertain the capsule's position. A flashlight is used to cast the capsule's shadows on the Bowel Phantom's walls. Furthermore, this allows the visualization of the capsule without X-ray fluoroscopy and without disturbing the capsule. While this is not a method a clinician could employ during capsule endoscopy, it is a method that can let the capsule go undisturbed from outside influences aside from the RPM. Another change is that the time constraint is lifted. Consequently, there is enough time to experiment with autonomous and manual control. These will be separated in different experiments of either pure autonomous control or pure manual control. During autonomous control, the distance between RPM and Bowel Phantom is changed between attempts to see its effects on how far the capsule manages to get.

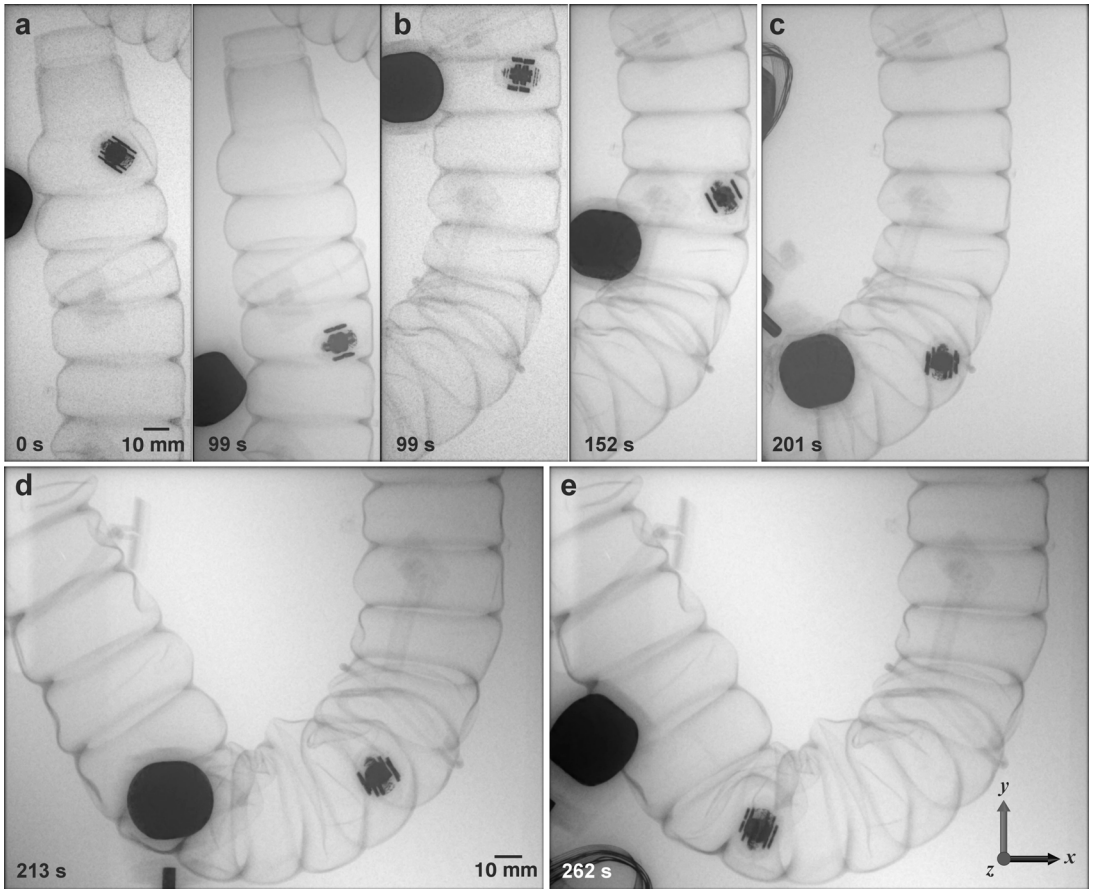


Figure 8: This figure is obtained from the experiments with the C-arm. The figure gives an impression that the RPM is beside the capsule. However, the RPM is actually directly above the capsule.

4 Results

4.1 Session 1

The experimentation with the X-ray fluoroscopy started with a straight path. Thus, the operator controlled the RPM manually for the first part. As depicted in Figure 8 a, b, and c, the fourth haustrum was reached by 1:39 minute and the sixth haustrum by 2:32 minutes. Once the capsule reached haustrum ten, the control switched from manual to autonomous. During autonomous control, Figure 8 d & e, the capsule managed to move at a similar pace as the manual control until the capsule became stuck. Multiple attempts were made using autonomous control, but the capsule did not budge. The RPM was lowered to use a stronger field to control the capsule. The magnetic field of the RPM got strong enough to lift the capsule into itself, which caused the Bowel Phantom to twist. The capsule reached the thirteenth haustrum before the Bowel Phantom became twisted. Therefore, the capsule managed to traverse 31.7% of Bowel Phantom.

4.2 Session 2

In session 2 both manual, and autonomous control managed to completely move through the Bowel Phantom. Though manual control was faster, with a time of 11 minutes and 5 seconds, while the autonomous control took around 7 minutes and 54 seconds. However, this time is only made up of the KUKA-arm maneuvering the capsule. This will be discussed more in detail in Section 5.

4.2.1 Autonomous Control

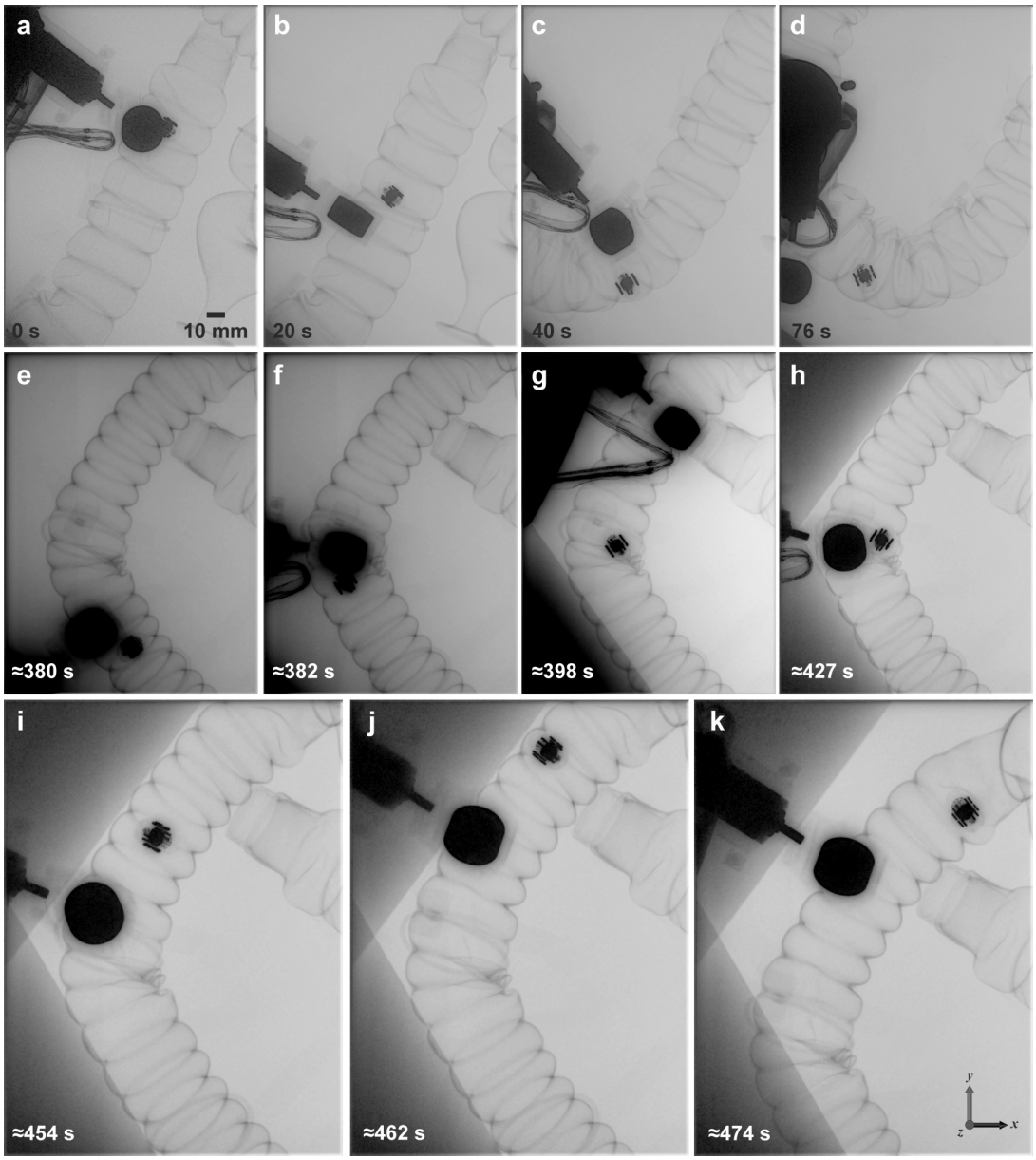


Figure 9: This figure is obtained from the experiments with the C-arm. The figure gives an impression that the RPM is beside the capsule. However, the RPM is actually directly above the capsule.

The videos for a part of the autonomous control became inaccessible due to corruption, which was supposed to be after Figure 9 d. Consequently, the time from Figure 9 e is an estimate, since the time was not recorded in another way. In the autonomous control, once the capsule coupled with the RPM, the capsule moved faster compared to manual control. The speed can be seen in Figure 9 d. It managed to maneuver through the constriction at 76 seconds. While the manual control became lodged there.

4.2.2 Manual Control

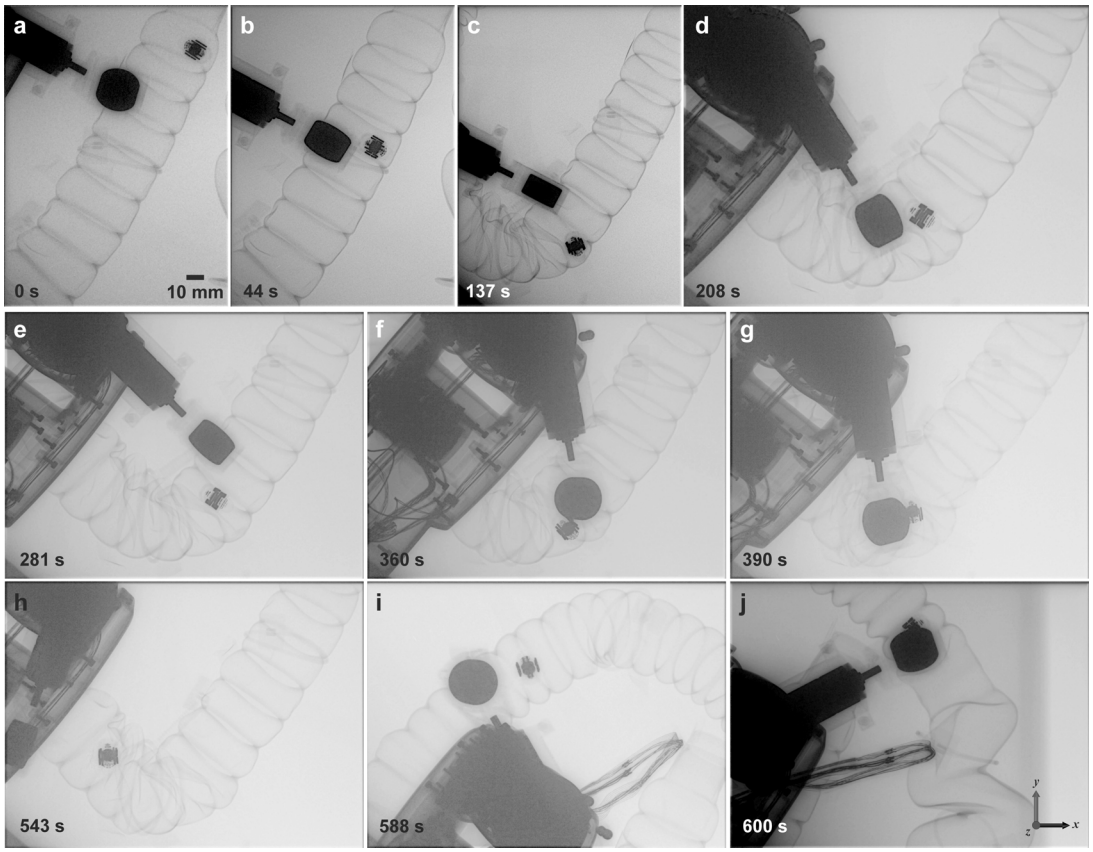


Figure 10: This figure is obtained from the manual control experiments with the C-arm in session 2. It was done by splicing together specific times from the x-ray fluoroscopy videos.

First, the manual control was recorded every moment the KUKA-arm moved. This means that there is some downtime. For example, once the KUKA-arm appeared in Figure 10 d, some time was taken to see if the KUKA-arm was capable of further clock-wise rotation. However, this downtime is not taken into account for time until completion F. Therefore, the time is measured while the KUKA-arm is being controlled by an operator. From the start, in Figure 10 a, the capsule moved continuously until it reached the constricted area. In Figure 10 c, d, e, f, and g the capsule became lodged for approximately 6 minutes and 45 seconds. After the capsule passed the first constriction, it started moving at a consistent pace until it reached the end at the start of the rectum in Figure 10 j.

4.3 Experiments without the ARTIS pheno

Foremost, it is important to understand that these results were achieved before session 2. Thus, the Bowel Phantom was not taped down yet in these experiments.

4.3.1 Autonomous control

The results achieved from the autonomous control experiments are displayed in Table 1. Time taken in Table 1 means the taken before the experiment was aborted. When the capsule becomes trapped, the autonomous controlled RPM does not react, which causes the RPM to move out of range of the capsule. The furthest haustrum the capsule managed to maneuver to was the fourth haustrum. Additionally, during experiments 6 & 7, the distance between the RPM and the Bowel Phantom became so small that the capsule casing got pulled to the RPM, causing the RPM and Bowel Phantom to entangle. Consequently, the data from experiments 6 and 7 have not been recorded.

Experiment number	Time taken (minutes)	Furthest haustrum traveled	Height of the RPM (cm)
1	2	1	5
2	1.5	1	5
3	1.5	1	5
4	1.5	2	5
5	1.5	1	5
6	N/A	N/A	3
7	N/A	N/A	4
8	2	4	4.5
9	1.5	1	4.5
10	1.5	1	4.5
Mean	1.63	1.5	N/A

Table 1: This table contains the data gathered from the experiments with automatically created paths. The table shows the time taken before the experiment was aborted, the furthest haustrum the capsule managed to travel, and the distance between the RPM and the Bowel Phantom during the experiment.

4.3.2 Manual control

The results of the manual procedure are shown in Table 2. The movement of the capsule was often obstructed during experimentation, causing the capsule to become trapped in multiple haustra. Table 2 shows which caused the most trouble for the capsule. The time taken in the manual experiments decreases as the number of attempts increases until attempt number five. Similarly, the longest time spent in a haustrum decreases with more attempts. Moreover, during manual experimentation, the RPM reached a point where it could not continue moving due to limitations set on the KUKA-arm. The time to move the RPM into a position where it could continue was subtracted from the total time taken until completion.

Experiment number	Time taken (minutes)	Haustrum	Longest time spent in Haustrum (minutes)
1	12.5	4 & 16	1.5
2	11	4 & 7	1
3	9	16 & 17	1
4	8	9	3
5	9	11	2
6	13.5	17	3
Mean	10.5	N/A	2

Table 2: This table contains the data from the manual experiments. The table shows time until completion of the Bowel Phantom, the haustrum/haustra, which trapped the capsule the longest and the longest time spent in a single haustrum. The haustra are counted from the capped end.

5 Discussion

The question 'How can the movement of a capsule be controlled within the GI tract with the help of an extracorporeal magnet?' has been answered by rotating the RPM parallel to the capsule, which will roll in a direction perpendicular to the RPM. A problem at the beginning of this project was that the MC1600 Navi are currently not in production. To still be able to carry out experiments, the original capsule casing was created. However, this capsule casing had problems, for example unpredictable movements caused by coupling and decoupling. Therefore, the original capsule casing needed to be redesigned, which resulted in multiple designs. These capsule casings were compared using the frequency response graphs. For example, the capsule casing, from Figure 5 the design with sixteen magnets, showed a peak at a frequency of 3.5 RPS, which suggests that this capsule casing has better coupling to the RPM compared to the other capsule casing designs. Implying, that this design is more stable than the other designs. Also, the eight magnet casing had a similar graph to the original capsule casing. This is possibly due to the amount of bumps, causing the eight bump capsule to react similarly as the original capsule does. Suggesting, the eight bumps to be redundant. Nonetheless, due to the magnets in the capsule casing, the weight of the capsule increased, which made orienting the capsule more difficult. Orientation is still possible, but the capsule needs to roll into position. It cannot rotate in place due to its weight, making orientating the capsule difficult due to the limitation of space. The other designs also had the increase in slot size length, to allow more magnets to be slotted inside the capsule casing. Nevertheless, since these 'dot' designs showed no improvements over the standard capsule casing, further testing using the extra-slotted magnets was discontinued.

The Bowel Phantom is not a one to one substitute for the real bowels, due to the lack of peristaltic movement. Furthermore, peristaltic movement could have made the capsule's movement through the bowels faster. Additionally, inside the bowels of a person, the capsule only has to be controlled if the person executing the procedure needs to stop the capsules' movement due to peristaltic movements, orient the capsule in the direction of a point of interest, or when maneuvering past an obstruction. However, it is possible that the procedure is sped up when the person executing the procedure controls the capsule. Regardless, we found a mean time taken to completion of 10.5 minutes. Due to the experiments not being in vivo. Nevertheless, other articles have reported on small bowel transit time using magnetic actuation, which is around five hours [17, 18]. Implying that large bowel transit time has a high likelihood of being higher.

The time measured in this article includes only the operation of the KUKA-arm. excluding the time for positioning and setup corrections, since the KUKA-arm has positional limitations set. Nonetheless, the time taken to set up, and correcting the autonomous control were excluded from the time taken until completion. Resulting in a lower time than it took in total to maneuver the capsule through the Bowel Phantom. Manual control had minimal downtime, with a total time of approximately 30 minutes. However, autonomous control required more manual correcting of the path. Resulting in a total time of approximately three hours.

Regardless, the experiments suggest that it is possible to maneuver the capsule past the large intestine with high possibility of success with manual control. Moreover, autonomous control managed to move through the intestines at a much lower probability of success. Also, results showed that moving past a constriction is possible, even though it takes longer to move past them. The capsule moving past the constricted area supports this, since these were compressed to simulate a constriction in the large intestines. Experiments 6 & 7 might have caused shifting of the Bowel Phantom, causing the obstacles to change. Due to the lifting of the capsule while the RPM was spinning, which caused the Bowel Phantom to entangle with the RPM. Possibly, causing following experiments with the Bowel Phantom to have different results, due to shifting of the set-up. Therefore, only autonomous attempts eight, nine, and ten can be compared to manual control. Since these were done right after the autonomous control experiments. Furthermore, the manual experiments have shown a decrease in time taken when the number of attempts increases until the fifth attempt, which suggests that the operator can improve their control over the RPM. Nonetheless, these results only come from the manually controlled experiments. While, the automatically controlled RPM experiments have managed to maneuver the capsule past the Bowel Phantom. The RPM appears to be moving either too fast for the capsule to keep up or too slow for meaningful progress. A possible solution would be to allow the operator to take control over the RPM when they deem it necessary or to create a feedback system, which changes the RPM's movement based on the location of the capsule relative to the RPM, rather than using a preset path. The mix of manual and autonomous control is however not possible with how the KUKA KR1100-2 was operated during the experiments. The KUKA-arm was programmed to be either in manual or autonomous control, but not both simultaneously. For this reason, using autonomous in conjunction with a feedback loop would likely be a better solution.
Future research could investigate creating a feedback system that allows the tracking of the capsule in space and let the RPM react accordingly to move the capsule forward. Otherwise, investigating the feasibility of using this capsule inside the small intestines would also be interesting.

References

[1] Jinqing Ou et al. “A self-assessment tool for predicting discomfort and tolerance in Chinese patients undergoing esophagogastroduodenoscopy.” In: *BMC gastroenterology* 22.1 (June 2022), p. 287. ISSN: 1471-230X. DOI: 10.1186/s12876-022-02364-0.

[2] Hua-Sheng Lai et al. “Standing-type magnetically guided capsule endoscopy versus gastroscopy for gastric examination: multicenter blinded comparative trial.” In: *Digestive endoscopy : official journal of the Japan Gastroenterological Endoscopy Society* 32.4 (May 2020), pp. 557–564. ISSN: 1443-1661 0915-5635. DOI: 10.1111/den.13520.

[3] Ulrike W. Denzer et al. “Magnetically Guided Capsule Versus Conventional Gastroscopy for Upper Abdominal Complaints: A Prospective Blinded Study”. In: *Journal of Clinical Gastroenterology* 49.2 (2015). ISSN: 0192-0790. DOI: 10.1097/MCG.0000000000000110.

[4] Georgios Geropoulos et al. “Magnetically Controlled Capsule Endoscopy Versus Conventional Gastroscopy: A Systematic Review and Meta-Analysis”. In: *Journal of Clinical Gastroenterology* 55.7 (2021). ISSN: 0192-0790. DOI: 10.1097/MCG.0000000000001540.

[5] Mona Rezapour, Chidi Amadi, and Lauren B. Gerson. “Retention associated with video capsule endoscopy: systematic review and meta-analysis”. In: *Gastrointestinal Endoscopy* 85.6 (2017), 1157–1168.e2. ISSN: 0016-5107. DOI: 10.1016/j.gie.2016.12.024.

[6] Yun Jeong Lim et al. “Indications for Detection, Completion, and Retention Rates of Small Bowel Capsule Endoscopy Based on the 10-Year Data from the Korean Capsule Endoscopy Registry.” In: *Clinical endoscopy* 48.5 (Sept. 2015), pp. 399–404. ISSN: 2234-2400 2234-2443. DOI: 10.5946/ce.2015.48.5.399.

[7] Ignacio Fernández-Urién et al. “Incidence, clinical outcomes, and therapeutic approaches of capsule endoscopy-related adverse events in a large study population.” In: *Revista espanola de enfermedades digestivas* 107.12 (Dec. 2015), pp. 745–752. ISSN: 1130-0108. DOI: 10.17235/reed.2015.3820/2015.

[8] Shabana F Pasha et al. “Capsule Retention in Crohn’s Disease: A Meta-analysis”. In: *Inflammatory Bowel Diseases* 26.1 (Jan. 2020), pp. 33–42. ISSN: 1078-0998. DOI: 10.1093/ibd/izz083.

[9] Seiji Kawano et al. “Safety and efficacy of capsule endoscopy for patients with newly diagnosed Crohn’s disease: A multicenter retrospective study.” In: *Medicine* 101.50 (Dec. 2022), e32424. ISSN: 1536-5964 0025-7974. DOI: 10.1097/MD.0000000000032424.

[10] Mankanwal S. Sachdev et al. “A prospective study of the utility of abdominal radiographs after capsule endoscopy for the diagnosis of capsule retention”. In: *Gastrointestinal Endoscopy* 66.5 (Nov. 2007), pp. 894–900. ISSN: 0016-5107. DOI: 10.1016/j.gie.2007.06.066.

[11] Wen-Bin Zou et al. “Magnetic-controlled capsule endoscopy vs. gastroscopy for gastric diseases: a two-center self-controlled comparative trial.” In: *Endoscopy* 47.6 (June 2015), pp. 525–528. ISSN: 1438-8812 0013-726X. DOI: 10.1055/s-0034-1391123.

[12] Yu-Feng Xiao et al. “Fully automated magnetically controlled capsule endoscopy for examination of the stomach and small bowel: a prospective, feasibility, two-centre study”. In: *The Lancet Gastroenterology & Hepatology* 6.11 (Nov. 2021), pp. 914–921. ISSN: 2468-1253. DOI: 10.1016/S2468-1253(21)00274-0.

[13] Dong Jun Oh et al. “Efficacy and safety of three-dimensional magnetically assisted capsule endoscopy for upper gastrointestinal and small bowel examination.” In: *PloS one* 19.5 (2024), e0295774. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0295774.

[14] A. J. Petruska and J. J. Abbott. “Optimal Permanent-Magnet Geometries for Dipole Field Approximation”. In: *IEEE Transactions on Magnetics* 49.2 (Feb. 2013), pp. 811–819. ISSN: 1941-0069. DOI: 10.1109/TMAG.2012.2205014.

[15] Arthur W. Mahoney and Jake J. Abbott. “Five-degree-of-freedom manipulation of an untethered magnetic device in fluid using a single permanent magnet with application in stomach capsule endoscopy”. In: *The International Journal of Robotics Research* 35.1-3 (Jan. 2016). Publisher: SAGE Publications Ltd STM, pp. 129–147. ISSN: 0278-3649. DOI: 10.1177/0278364914558006.

[16] Maria Manuela Estevinho et al. “Capsule Enteroscopy Using the Mirocam(®) versus OMOM(®) Systems: A Matched Case-Control Study.” In: *Life (Basel, Switzerland)* 13.9 (Aug. 2023). ISSN: 2075-1729. DOI: 10.3390/life13091809.

[17] Yuan-Yuan Luo et al. “Magnetic Steering of Capsule Endoscopy Improves Small Bowel Capsule Endoscopy Completion Rate.” In: *Digestive diseases and sciences* 64.7 (July 2019), pp. 1908–1915. ISSN: 1573-2568 0163-2116. DOI: 10.1007/s10620-019-5479-z.

[18] Xi Jiang et al. “Small-sized versus standard magnetic capsule endoscopy in adults: a two-center, double-blinded randomized controlled trial.” In: *Endoscopy* 55.1 (Jan. 2023), pp. 52–57. ISSN: 1438-8812 0013-726X. DOI: 10.1055/a-1881-4369.

6 Appendix

6.1 Calculations

- **pc** $=\begin{bmatrix} 0.1 \\ 0 \\ -0.2 \end{bmatrix}$
- **pa**$=\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$
- m_c=0.0630272 $m^2 \cdot A$
- m_a=18.89 $m^2 \cdot A$
- $\hat{\mathbf{m}}_\mathbf{c}=\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$
- $\hat{\mathbf{m}}_\mathbf{a}=\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$
- $\mu 0 = 4 * \pi * 1E-7$

We can calculate that $\mathbf{p}=\begin{bmatrix} 0.1 \\ 0 \\ -0.2 \end{bmatrix}$ of which $\hat{\mathbf{p}}=\begin{bmatrix} \frac{0.1}{\sqrt{0.05}} \\ 0 \\ \frac{-0.2}{\sqrt{0.05}} \end{bmatrix}$ is the unit vector. Then, we calculate $\mathbf{D}(\hat{\mathbf{p}})$ by filling $\hat{\mathbf{p}}$ into $3 \cdot \hat{\mathbf{p}}\hat{\mathbf{p}}^T - I$, where I is the identity matrix, which equals to $\begin{bmatrix} -.4 & 0 & -1.2 \\ 0 & -1 & 0 \\ -1.2 & 0 & 1.4 \end{bmatrix}$. Then, we start calculating the constant part of the equation by filling $\frac{\mu_0 ||m_a|| \, ||m_c||}{4\pi ||p||^3}$ with constants. Resulting in $\frac{4*\pi*1E-7||\mathbf{18.89}|| \, ||\mathbf{0.0630272}||}{4\pi||\sqrt{0.05}||^3}$. Finally, filling this into the formula for torque gives $\frac{4*\pi*1E-7||\mathbf{18.89}|| \, ||\mathbf{0.0630272}||}{4\pi||\sqrt{0.05}||^3} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \times \begin{bmatrix} -.4 & 0 & -1.2 \\ 0 & -1 & 0 \\ -1.2 & 0 & 1.4 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$, which results in $\begin{bmatrix} 0 \\ -1.28E-05 \\ 0 \end{bmatrix}$ in Nm

6.2 Kinematics equations

The results, in Section 6.2, were gathered from MATLAB. The formulas are run within a for-loop. Therefore, the iterations here mean a single iteration of said for loop.

First, to calculate what distance the capsule will travel as a reaction to the RPM, we need to calculate the acceleration caused by the torque it generates. To do this we need to know how much the capsule rotates, this can be used to calculate the distance the capsule travels. This was done through the Kinematics equations. To start, Newton's second law of rotation is used, which is also shown in Equation 3,

$$\alpha = \frac{\tau}{I} \tag{3}$$

where τ is the torque on the capsule generated by the magnetic field, Formula 2, and I is the Moment of Inertia of the capsule. The rotational acceleration, α, is used then used to calculate rotational speed, ω, in Formula 4.

$$\omega = \omega_{previous} + \alpha * dt \tag{4}$$

In Formula 4, $\omega_{previous}$ is the rotational velocity in the previous loop iteration. This replaces the ω in the original formula, which would be ω_0. Therefore, $\omega_{previous}$ replaces the role of starting rotational speed by taking the rotational speed of the previous iteration. The dt signifies the time step between iterations.

$$\theta = \theta_{previous} + \omega_{previous} + 0.5 * \alpha * dt^2 \tag{5}$$

Finally, in Formula 5 ω and α of the previous formulas are used to calculate the θ, which is how much the capsule has rotated within an iteration. Here, θ works on the same principles as ω The θ calculated using Formula 5 is then used to calculate the distance the capsule has traveled within the time step of the iteration.

$$d = r * \theta \tag{6}$$

Here, d stands for the distance traveled, r is the radius of the capsule, and θ is how much the capsule has rotated in an iteration. This is then added to **pc**, after which the entire iteration start anew.

6.3 Figures

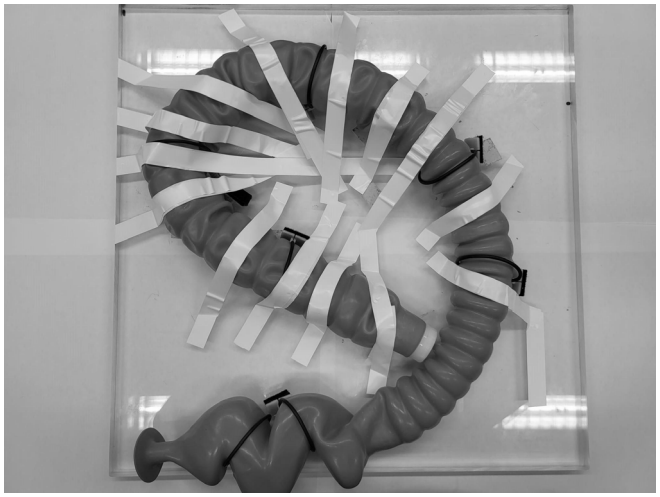


Figure 11: This is the taped down version of the Bowel Phantom. This was done to prevent the capsule from lifting the Bowel Phantom into the RPM. The tape was done in a way that prevents the Bowel Phantom from lifting into the RPM, while not constricting any of the haustra.

6.4 Chat-GPT

Chat-GPT was used in this article to write more concise, and check for grammatical errors. In the early stages, it was also used as a tool to understand certain concepts like the magnetic dipole moment.

6.5 Dutch abstract

Bij capsule endoscopie slikt een patiënt een capsule, die door het maag-darmkanaal gaat en beelden vastlegt. De capsule reist meestal zonder problemen het lichaam door, maar in patiënten met inflammatoire darmziekten heeft de capsule de kans om vast te raken. Als de capsule langer dan twee weken vast zit, dan wordt er gebruik gemaakt van chirurgie om de capsule te verwijderen. Dit zorgt ervoor dat de procedure van non-invasief naar invasief verandert. Om deze uitkomst te vermijden wordt magnetische controle gebruikt om de capsule langs verdikkingen in de darm te manoeuvreren. Om te testen haalbaarheid van deze methode te testen zal de capsule in een "Bowel Phantom" met verdikkingen gecontroleerd worden/ Volgens de resultaten van deze experimenten kon de capsule zich langs verdikkingen manoeuvreren in de "Bowel Phantom", wat laat zien dat magnetische controle in de darmen mogelijk is. Magnetische controle zou de kans dat de capsule vast komt te zitten kunnen verminderen. Met als gevolg is deze methode beter dan passieve capsule endoscopie.

6.6 Acknowledgements

Khalil, I for being the supervisor and helping with whenever there were questions, and thinking along when decisions had to be made.

Ligtenberg, L.W. for creating the script that creates the path, which the KUKA arm follows during experiments.

Mijle Meijer, J.K. van der. for creating the original design of the capsule.

Boer, M.C.J. de, Liefers. R, for processing the fluoroscopy videos into more manageable videos.

Saavedra Castano, S. for printing the original capsule.

Boer, M.C.J. de, Liefers. R, and Mijle Meijer. J.K. van der for doing the initial testing, which provided information about the stability of the original capsule. And for providing Figure 1.

Bester, E. for working together for the most of the project, and helping each other out when one would need it. Also, for his contribution to Tables 1 % 2, and Figures 6 % 8

Mulder, I. for providing the artwork for Figure 1 B.

Baat, H. for providing the opportunity to test this model inside the MST hospital and allowing us to use the equipment used in a capsule endoscopy.

Remco, L. for allowing and aiding in the use of the C-arm. And for his contribution to Figure 4.