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Integration and optimization of propulsion systems in endoscopic capsules

Active capsule endoscopy

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UNIVERSITY OF OSLO

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MASTER THESIS

Integration and optimization of propulsion systems in endoscopic capsules

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Abstract

Capsule endoscopy is used to examine the gastrointestinal tract, primarily the small intestines. The transformation of endoscopic capsules from passive to active systems, will save resources and make capsule endoscopy more applicable. An active endoscopic capsule wants to integrate the possibility for biopsy and smaller gastrointestinal surgeries. For this to be achievable, the robot pill needs a well-working propulsion system.

This thesis work aims to optimize a design for optimum propulsion and realize a prototype. The analysis of the different propulsion systems, researched within this scientific field, shows that the two main groups of systems are expanding and non-expanding design. Expanding systems use features to expand their body, to anchor themselves in the intestinal walls, before they achieve propulsion. To stay within the limits of size and power of an *in vivo* system, this study focuses on the non-expanding systems.

The result is a single actuated, wheeled design.

This prototype outperformed another study in the propulsion testing.
This prototype outperformed another study, "A wireless capsule robot with spiral legs for human intestine" by Chen et al. [1], in the propulsion testing.
This prototype achieved better results than a paper, which made use of an expanding design, in propulsion testing.
This prototype achieved better results in propulsion testing, than a paper that made use of an expanding design.

However, the differences in testing environments, and diameter of intestine specimen, prevents this study to draw an indisputible conclusion onto whether the resulting propulsion system is the optimum. But the results and the space efficient design is a reliable alternative for robot pills. With some further testing, it is reasonable to believe that this system will have an impact on future

endoscopic capsules.

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Abbreviations

ABS	–	Acrylonitrile Butadiene Styrene
ACE	–	Active Capsule Endoscopy
AM	–	Additive Manufactoring
CAD	–	Computer-aided Design
DBE	–	Double Balloon Enteroscopy
DMLS	–	Direct Metal Laser Sintering
EBM	–	Electron Beam
EMI	–	Electromagnetic Inteference
EMS	–	Electrical Musle Stimulation
FDM	–	Fused Deposition Modelling
FFF	–	Freeform Fabrication
GI	–	Gatrointestinal
IPT	–	Inductive Power Transfer
LES	–	The Lower Esophageal Sphincter
MGCE	–	Magnetically guided capsule endoscope
MIS	–	Minimal Invasive Surgery
PLA	–	Polylactic Acid
PM	–	Pacemaker
PMMA	–	Polymethyl Methacrylate
PTO	–	Power Take-Off
SL/SLA	–	Stereolithography
SLS	–	Selective Laser Sintering
SM	–	Subtractive Manufactoring
WCE	–	Wireless Capsule Endoscopy

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Part I

Introduction and Theory

Chapter 1

Introduction

To understand the concept of *active capsule endoscopy* (ACE), one must be familier with its predecessor *(wireless) capsule endoscopy* (WCE), and the need for this technology. It is to be considered a disruptive technoloy aiming to displace other types of endoscopy. It is used as a way to record images of the gastrointestinal (GI) tract. The primarily use of WCE is to examine the small intestines. Since it will pass through the entire digestive tract, it will be able to examine areas of the the intestines that are more inaccessible for other technologies.

Current research in this field are targeting to transform the passive endoscopic capsule to an active tool, by including different types of actuators. This robot pill aims to have systems for propulsion, biopsy, and smaller gastrointestinal surgeries. This kind of pill robot will have many benefits, and might save many lives. All these systems have the same requirement, a well functioning propulsion system. So, before active capsule endoscopy can be a reality, we need a functioning propulsion system. This thesis will examine the need for such a pill robot, as well as develop a propulsion system for this endscopic pill.

1.1 Motivation

From a societal context, this is a very essential topic. In the paper "Long-Term Colorectal-Cancer Incidence and Mortality after Lower Endoscopy" [2] 88,902 participants were followed over a period of 22 years. It was proven that the screening process was associated with reduced cancer mortality. This makes

it desirable to screen complete populations for intestinal cancer. Meaning that when a person reaches a certain age, that person is to be checked for intestinal cancer. This implies the need for an efficient and inexpensive procedure for doing this. If ACE was a reality, one would need fewer and less educated staff members. This is a less resource consuming method than today's approach. When performing other types of endoscopy, one would need a specially trained physician.

Robot design is an efficient method of solving this problem. When designing robots, one strive to perfect previous technologies and/or automate manual tasks. Robot design is a very ecletic discipline that require insight in many fields. One will encounter electronics, physichs, mathematics, informatics, and mechanics. *Surgical robotics* is a commonly used dicipline, such as the da Vinci system made by Intuitive Surgical, Inc[1]. This system is used to perform minimal invasive surgary (MIS) with more degrees of freedom. The robot is implemented on the outside of the body, in contrast to the *in vivo robotics* needed for active capsule endoscopy. In vivo meaning within a living organism [3].

There are many research articles on the topic. Most designs take inspiration from the nature, propulsion systems that mimic worms, small crawling bugs, or other similar movement patterns.

1.2 Structure of thesis

Comparison of different research articles shows the outline of the general mindset and, maybe more important, what is commonly tested. Diversity is important to aquire new knowledge. By using *the scientific method* for investigating different robot designs, one will compare observations from multiple research teams. This will again, hopefully, lead to the best possible propulsion system.

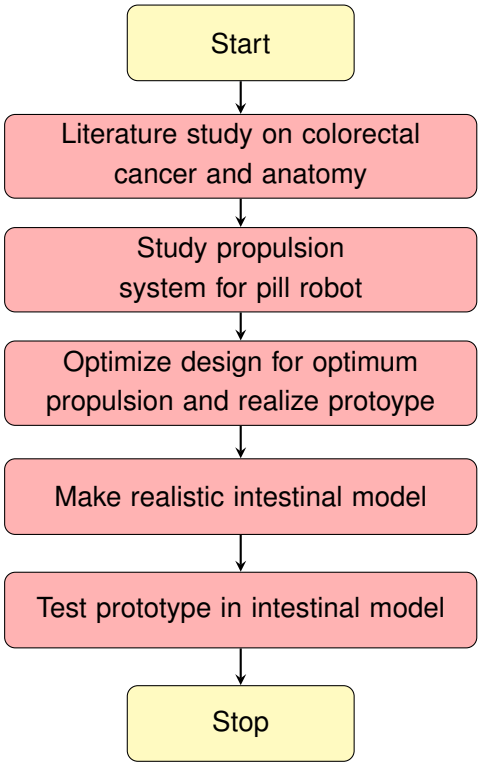
A literature study on colorectal cancer will give input on how the diagnosis of colorectal cancer/diseases and treatments in the intestines are done today. This will further expand the knowledge of which features is expected from a robot pill.

By investigating different propulsion systems available and what is currently

[1] http://www.davincisurgery.com/

being researched, one can get inspiration for how to design a well-working propulsion system. The different ideas must further be optimized for optimum propulsion.

The realized prototypes needs to be tested in an intestinal environment. Studies on the intestines will give an indication on how to make a realistic intestinal model. Experiments will also be done with a *in vitro* study. In vitro means doing studies, on e.g. intestines, outside the living organism in an artificial environment [4].



Outline

- **Chapter 1** gives a light introduction to the thesis and its content.
- **Chapter 2** contains background material, and the necessary theoretical groundwork. This includes the study on anatomy of the intestines, procedures to detect colorectal cancer/diseases and the use of robotics in medicine, especially their propulsion systems.

- **Chapter 3** describes the physical work done, and tools used. How 3D models are realized, which components are used, and how the prototypes will be tested.
- **Chapter 4** introduces the different prototypes for robot pills and synthetic intestinal models. The evaluation of them is done in an iterative process, which includes mechanical testing and redesigning.
- **Chapter 5** shows how the experiments are conducted, and the results of the experiments.
- **Chapter 6** analyzes the results from the experimentes, discuss the solution, presents the conclusion, and looks closer at what further work can be done.

Chapter 2

Background

2.1 Anatomy of the human intestines

The intestines (bowel) are a long, continuous tube running from the stomach to the anus. It is a part of the body's digestive system. This is where the body removes and processes nutrients (vitamins, minerals, carbohydrates, fats, proteins, and water) from foods. It is also a means to pass waste material from the body. The intestines includes the small intestine, large intestine (colon), and rectum.

The different parts of the intestine has different tasks. The first part is the small intestine, and absorbs most nutrients. The colon is shorter, only about 1.5 meter, but is wider in diameter. The colon absorbs water from the waste material, creating stool. When stool enters the rectum, nerves activate, and create, the urge to defecate.

This thesis focus on the small intestines, because this is where active capsule endoscopy is relevant. The wider diameter in the colon creates a completely different environment, and is therefore not the main focus when developing a propulsion system. The small intestine is about 6.7 to 7.6 meters long and 2.5-3 cm. in diameter [5]. It is fed gastrict chyme, partially digested food mass, through the *pyloric sphincter*. It acts as valve and lets very small amounts of chyme enter the intestine at one time. The small intestine is divided in three parts [6].

Duodenum constitutes the first 23-28 cm. and has the widest diameter of the

small intestine It recieves gastrict chyme from the stomach. Bile emulsifies fat, and digestive enzymes from the pancreas breaks down carbohydrates, proteins and the emulsified fat. These secretions, and bicarbonate from the pancreas, neutralizes the stomach acid contained in the gastric chyme.

Jejunum is about 2-3 meter long, and contains the *plicae circulares*. Which are folds that cover one-half to whole of its circumference. The biggest fold are about 8.0 mm. deep, but most of them are smaller. They also dimish considerably in size further down the intestines, and are almost completely disappeared in the lower part of ileum. They slows the passage of the gastric chyme and increases surface for absorption. Each fold are covered in *villus*, approximately 0.5-1.6 mm. long finger-like projections. Which again is covered with microville. They efficiently absorb products of digestion (sugars, amino acids, and fatty acids) into the bloodstream. They also help the chyme move along.

Ileum is the last part of the small intestine, about three meter long. First part is a lot like the jejunum, further down the folds are almost completely gone. It mainly absorbs important products like vitamine B12 and bile acids, as well as other remaining nutrients.

The jejunum and ileum are suspended in the abdominal cavity by the mesentery. The mesentery contains the intestines arteries, veins, lymph vessels and nerves. Its purpose is to prevent *gastric volvulus*, which is a rotation of the stomach of more than 180^o, creating a closed-loop obstruction that can result in incarceration and strangulation [7]. This is done by keeping the organs loosely in place, as well as reduce friction when the intestines move during digestion.

The gastric chyme is moved by *peristalsis*, a wavelike series of pendular contractions and relaxtions. A typical wave only lasts for a few seconds, travelling only a few centimeters per second. Its primary purpose is to mix the chyme, rather than move it. Through this process of mixing, the intestines absorbs nutrients.

In contrast to these muscular contractions, there is *segmentation contractions*. Instead of peristalsis one-way motion in the caudal direction, segmentation move gastric chyme in both directions. This allows greater mixing with the secretions of the intestines. It also makes use of the circular muscles in the digestive tract, but slows down the motion of the chyme, rather than speeding it up.

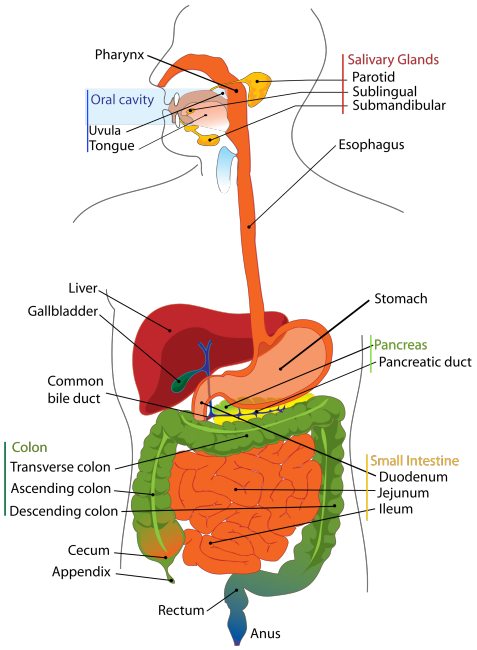


Figure 2.1: Digestive system [8]

As in the rest of the human body, tumors can occure in the digestive system. Cancer (malignant tumor or malignant neoplasm) is a group of diseases involving abnormal cell growth with the potential to invade or spread to other parts of the body. Not all tumors are cancerous. Benign tumors do not spread to other body parts. Since the intestines are such a big part of our body and closely connected with other organs, there is a danger of cancer spreading to other vital organs through bile ducts, blood vessels etc. This includes the liver, the lungs, and most other organs.

2.2 Examination methods for the intestines

Intestinal cancer, and in particular, colorectal cancer is a relatively frequent cancer form, in which it is important to diagnose at an early stage. There are many procedures for examining the intestines to detect and diagnose cancer/diseases [9].

Physical exams

This procedure consists of a professional checking the body for signs of disease and general signs of health. The patient's medical history is also used. The doctor can check the colon directly and insert a finger into the pasient's rectum, checking for lumps or other abnormalities. One can also do a fecal test. Stool is then checked for blood or other signs of something wrong. Most of these signs can only be seen with a microscope.

X-rays

Sometimes you want to look inside the body without physically penetrate it. This can be done by x-rays. The two most common ways are:

- Barium enema: A liquid containing barium is put into the rectum, and coats the lower gastrointestinal tract and x-rays are taken. This special form of x-ray is called *fluoroscopy*. Fluoroscopy makes it possible to see internal organs in motion. When the lower gastrointestinal tract is filled with barium, the radiologist is able to view and assess the anatomy and function of the rectum, colon and sometimes part of the lower small intestine.
- CT colonography (virtual colonoscopy): A procedure that uses a series of x-rays called computed tomography to make a series of pictures of the colon. This procedure uses a low dose radiation CT scanning to obtain an interior view of the the large intestine [10]. CT colonoscopy includes possible segmentation of the colon to virtually go through the intestine and look for polyps and other abnormalities that can be precancerous. CT colonoscopy uses X-rays and radiocontrast agents, so that it is both costly and also a certain radiation dose involved.

Endoscopy

Endoscopy is a nonsurgical procedure that examines the digestive tract, using an endoscope (a flexible tube with light and camera).

- Colonoscopy
  A procedure to look inside the rectum and colon for polyps, abnormal areas, or cancer. The colonoscope is inserted through the rectum into the colon. The colonoscope is a thin tube-like instrument with a light and a lens for viewing. It may also have a tool to remove polyps or tissue

samples, which are checked under a microscope for signs of cancer. This is a slightly uncomfortable examination and also resource intensive.

- Sigmoidoscopy
  Same procedure as conventional colonoscopy, but has fewer side effects, requires less bowel preparation, and poses a lower risk of bowel perforation (an uncommon event, when the screening instrument pokes a hole in the intestine) than colonoscopy [11]. Sigmoidoscopy also uses a similarly flexible, but shorter, tube to view the lower colon.

- Gastroscopy
  An examination of the upper digestive tract (the oesophagus, stomach and duodenum) [12]. It is performed with an endoscope, as colonoscopy, but from the mouth instead of the anus.

- Capsule Endoscopy
  Most tests and procedures only examine the colon and rectum. While capsule endoscopy is an appropriate procedure to examine the entire digestive system. It was first developed in the mid-1990s, but received FDA approval for use in 2001, and was FDA approved as a first line small intestine imaging device in 2003 [13]. The first capsule endoscopy that received FDA approval for use was developed by Given Imaging[1].

  Capsule endoscopy cameras, which is a capsule like device that you swallow, will pass through the gastrointestinal tract transmitting images with a certain frequency wirelessly to a storage device. These images can then be reviewed by a gastroenterologist in hindsight. The advantage, compared to colonoscopy, is that this method can also provide images of the small intestine. Capsule endoscopy is less uncomfortable for the patient and requires less educated personnel to conduct the test.

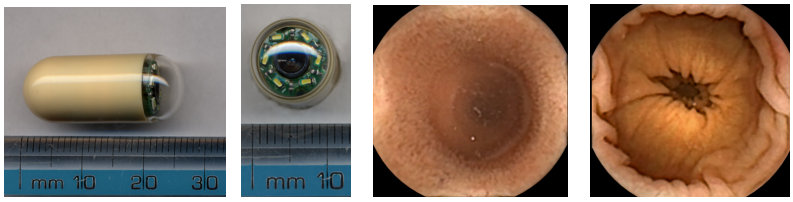


Figure 2.2: Capsule Endoscope [14]

[1] http://www.givenimaging.com/

Capsule endoscopy is a passive form of testing. This means you will not be able to interact or do anything directly whilst conducting the test. You will only be able to get images. If we want the examination to be unambiguous, we often need to take a biopsy or look closer at the problem area.

- Double Balloon Enteroscopy (DBE) [15]
  DBE, also known as "push-pull enteroscopy" or the "double-bubble", is a endoscopic procedure that allows pan-enteric (complete) examination of the small intestines. It often complement capsule endoscopy. If abnormalities are found, DBE is used to take biopsies or perform treatment which capsule endoscopy can not do. This therefore offer an alternative to surgery for some patients. These two procedures are one of the most powerfull ways to investigate the small intestine. They both causes minimal discomfort and has a very low complication rate.

  DBE consists of an endoscope and an overtube. There are one or two balloons attached to the scope. By inflating and deflating the balloon(s), it can advance through the intestines like a curtain over a rod. Accessories such as biopsy forceps, dilating devices, and cautery probes can be used in order to treat abnormal findings in the small intestine [13].

Today, screening for cancer is resource consuming and expensive. The effects of an aging population results in a high demand of healthcare facilities. To be able to offer the necessary healthcare facilities to an entire population, we must find less resource consuming procedures to diagnose diseases. Intestinal cancer has a high mortality rate, so it is important to diagnose it at an early stage. If the procedure to diagnose intestinal cancer was less resource consuming, we could offer this to the entire population.

Biopsy or looking closer at an abnormal area will not be possible with today's capsule endoscopy. After we have confirmed that something is wrong, often by finding polyps or other abnormalities that can be precancerous, we want to handle the problem.

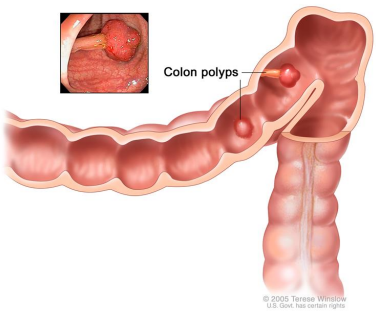


Figure 2.3: Colon Polyps [9]

Removal of polyps is one of the most common procedures done to prevent intestinal cancer, but this can not be done by capsule endoscopy directly. Finding the given problem area after an capsule endoscopy is also a difficult task. This is one of the reasons active capsule endoscopy is a very important research field.

We want to achieve active capsule endoscopy that can handle many of these problems. But to be able handle any of these problems, the capsule must be able to move freely in the intestines. If this could be done, we could take biopsies, get better picture of problem areas, and maybe even remove polyps directly.

2.3 In vivo robotics for GI tract

To achieve a robust and reliable propulsion system, one will need to look at multiple types of designs and actuators, and what are the constraints for the application area. The main issues with active capsule endoscopy is space utilization and power managment. An important feature of the capsule endoscope is, of course, the size. It must be easily swallowable to prevent discomfort for the patient. This gives us some constraints for the design. The pill must be power efficient because of a small power source, and the mechanical solution must prevent excessive usage of actuators.

Power utilization

Choosing the correct power source will be an important part of the design. The question comes down to using an internal or external power source. An internal

power source will typically mean a battery package. An external power source will be a wireless power system, typically wireless inductive power transfer.

It is a possibility that the endoscopic capsule requires more power than conventional batteries can provide. Advances that have been done to solve this problem is many. Some of these advances are reviewed in the paper "PillCam COLON capsule endoscopy: recent advances and new insights" [16]. It has been added batteries (three in total), and decreased energy consumption by implementing a sleep mode. This sleep mode ceases the transmission of images until the capsule reaches the stomach. The recorder receiving the transmission signal was also revolutionized. This new recorder is endowed with *artificial intelligence*. This 'thinking' recorder also communicates with the capsule. First it recognizes that the capsule is in the stomach. At this time the capsule is maintained at a low transmission rate of six images per minute in order to save energy. It then detects when the capsule leaves the stomach and enters the small intestine. At this point the recorder instructs the capsule to raise its transmission rate to four images per second. It will also turn up the transmission rate to about 35 images per second if the capsule is in motion. If the capsule never leaves the stomach, the patient will be notified and asked to ingest a prokinetic agent such as domperidone. Prokinetic agents are medications that help control acid reflux. Prokinetics help strengthen the lower esophageal sphincter (LES) and cause the contents of the stomach to empty faster [17].

When creating an active capsule endoscope, we need even more power. We now need to power a propulsion system as well. We have less room for batteries and need more power. That is why *wireless inductive power transfer* is a feasible alternative. (Wireless) Inductive Power Transfer, or IPT, involves the transmission of energy from a power source to an electrical load, without connectors, across an air gap [18]. It is based on electromagnetic coupling. As in every wireless system, we need a transmission system and a receiving system. In this system this is two coils – a transmitter and receiver coil. The transmitting coil is energized by an uniform, alternating current to generate a magnetic field. This will in turn induce energy in the receiving coil.

IPT systems is confronted by many constraints that may influence its performance in terms of energy-transfer efficiency. These include the size of the receiving coil and safety. Because of the space limitations, the size of the receiving coil is limited. The size of the coils, the distance distance between them and the fact that the human body is between them, lower its

ability to transfer energy. One must also consider that there can be some heat generation, and this can damage the tissue surrounding the device [1].

One abnormality that also needs to be considered is pacemakers (PM). It is important to ensure that it can handle the electromagnetic field from the IPT system. The function of pacing systems may be confronted with some specific problems regarding the various types of electromagnetic interference (EMI). To avoid these unwanted EMI effects one must be aware of this potential problems and need to take some precautions. Although PM are very sophisticated and technically challenging devices, patients with pacemakers need to be regularly and carefully evaluated. Current PM are relatively immune to EMI because it is shielded in a hermetically sealed titanium or stainless steel case with additional insulative coating. The increased usage of bipolar leads also decreases the sensitivity towards EMI [19].

Another alternative is turning body heat into electricity with thermoelectric generators. The concept builds on the *Seebeck effect*, a phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances. When heat is applied to one of the two conductors or semiconductors, heated electrons flow toward the cooler one. If the pair is connected through an electrical circuit, direct current (DC) flows through that circuit [20].

The problem with this technology is that only very small voltages get produced, and it relies on temperature differences. Inside you body the temperature is fairly stable, and will result in even less power production. Only after improving the efficiency of thermoelectric generators, would this be a realistic source of energy.

Space utilization

To achieve the best possible space utilization, it is important to model the design in a precise manner, before choosing a final design. The propulsion system needs to be as compact as possible. A compact and simple propulsion system must include simple mechanics and few parts. Even though the limited size of the system, it must be reliable and powerfull enough to propel the pill forward.

Actuators are one of the most space consuming parts of the system, so it is important to use small and as few actuators as possible.

Actuators

An actuator is the part of the propulsion system that is responsible for moving and controlling the system. Different kinds of actuators are electrical, hydraulic, pneumatic, thermal, magnetic and mechanical. Many of these types are used in the quest for a fitting propulsion system for an active capsule endoscope. Every actuator has its own strenghts and weaknesses.

Actuators	Features
Electrical	Clean actuators found in many variations. Due to the versatile design, they can be made in many sizes. Needs a power source to operate.
Hydraulic	Very strong actuators, because fluids are difficult to compress. The fluids' thickness means limited acceleration, and they require tubes to lead the fluid from the compressor to the actuator.
Pneumatic	Very fast actuators, because air is easily compressed. This also results in weaker actuators. Pneumatics also requires tubes to lead the preassure from the compressor to the actuator.
Thermal/Magnetic	Compact and lightweight actuators. They are economical with a high power density.
Mechanical	Converts movement's direction, e.g. rotary motion to linear motion.

2.3.1 Existing concepts

Previously researched designs for active capsule endoscopy are many and with different application areas. This is because different parts of the gastrointestinal tract needs different types of propulsion systems. The commercial pills are not equipped with active locomotion systems. While this may be sufficient for the analysis of the small intestine, it is crucial to have the possibility to steer the capsule to enable accurate investigation of some critical parts of the GI tract, especially in the stomach. The stomach is filled with fluid and has less restrictions. It has a bigger area to be examined, this creates a need for a more

freely moving robot pill.

In the paper "Wireless powering for a self-propelled and steerable endoscopic capsule for stomach inspection" [21] researchers have tried to cope with this problem. The paper describes the integration of active locomotion in an endoscopic capsule. Their device is designed to operate in a fluid environment, a liquiddistended stomach. It works as a submarine and is used to analyze the inside of the stomach. The propulsion system uses propellers to navigate.

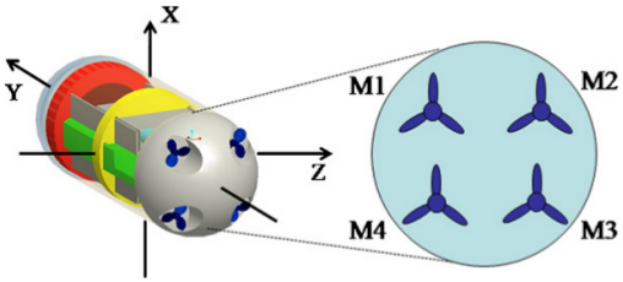


Figure 2.4: Schematic of the locomotion system and actuation diagram of the propellers [21]

But as discussed earlier, the area of the gatrointestinal tract that is most inaccessible, is the small intestine. This thesis will mainly focus on mobility in this area. The ideal ACE would include a accurate robotic steering and noninvasive localization of the robot pill.

The paper "Magnetically Controllable Gastrointestinal Steering of Video Capsules" [22], discuss an approach who solves exactly this. Their robot pill is not driven by peristalsis and gravity, but magnetic maneuvring. They demonstrate an accurate steering and noninvasive 3D localization of a magnetically enabled sample of the previous discussed capsule, PillCam from Given Imaging. The pill is successfully maneuvered through the main regions of the GI tract (esophagus, stomach, small intestine, and colon) in vivo, in a domestic pig model.

Steering is done with a robotic magnetic navigation system (Niobe, Stereotaxis, Inc, USA) already used for cardiovascular clinical procedures. The capsule was freely and safely moved with omnidirectional steering accuracy of 1.0 degree. Localization is also done in real time through *fluoroscopic imaging*, which also allows for 3-D localization with an error of 1.0 mm.

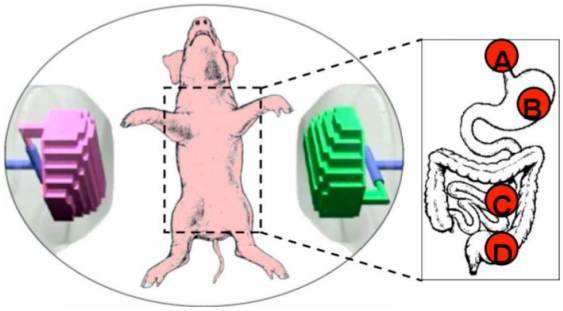


Figure 2.5: Magnetically guided capsule endoscope (MGCE) [22]

The MGCE system can only examine the GI tract in a clinic and need to be operated by a professional through the entire examination process. Since the main advantages of active capsule endoscopy, from a societal view, is efficiency, the lack of mobility of this system makes it a non-optimal solution.

More mobile designs will need to have the propulsion system internal in its body (*in vivo robotics*). These types of robot pills, mainly consists of two types: expanding and non-expanding.

Expanding robot design

This type of system expands a part of their body to touch the intestinal walls. This increases the friction, and holds the pill in the same position throughout the entire movement. These designs are often inspired by nature. To be more specific the movements of small crawling insects and worms.

Legged robot design have been thoroughly researched for many years, mainly because its ability to traverse through obstacles, and it is the most familiar form of movement for human beings. Legged robot design is, however, more costly and slower than e.g. wheeled locomotion. A legged robot will have to keep its balance when wandering freely. But when used in the intestines it has full radial support, and one can ignore the balance problem. "A New Mechanism for Mesoscale Legged Locomotion in Compliant Tubular Environments" [23] is a paper trying to utilize the use of a legged robot design.

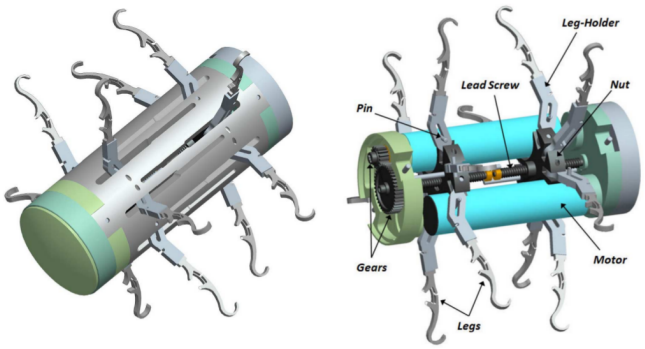


Figure 2.6: Legged locomotion [23]

The legged pill robot use legs with radial tips to move in the intestines. The radial leg tip is used for optimal locomotion, and makes them less harmfull to the intestinal walls.

Another approach are wormlike propulsion systems. They generally work like in figure 2.7. It can also anchor itself in one position with its expanding parts.

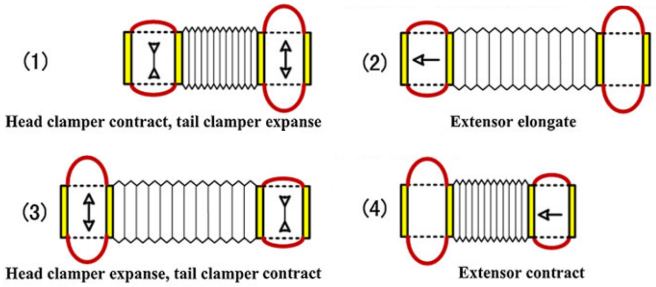


Figure 2.7: Wormlike locomotion [1]

Two essential part of this architecture is extension and expansion. There are muliple ways of doing this, but the main difference is the actuators.

- Electrical motors are one popular alternative. The robot design illustrated in figure 2.8 shows the resulting design from the article "A wireless capsule robot with spiral legs for human intestine" [1]. This design requires two motors for expansion and one for extension. Energy consumption will be the same as for one motor, considering only one motor is running at once. Space utilization is an issue in this design. Three electric motors require more space, leaving very little space for

other components.

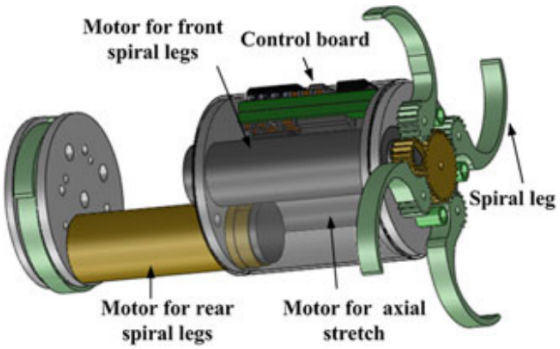


Figure 2.8: Mechanical model [1]

This is a mechanical demanding design and is not very space efficient. The expanding feature is the biggest part of the architectures. It gives the robot pill great grip in the intestinal wall, but the cost is the more advanced mechanics.

- In 2013 the paper "Wireless powered capsule endoscopy for colon diagnosis and treatment" [24] explained a prototype using a peristaltic pump with a micro valve. The air preassure is used to expand balloons and to extend the bodys length. The balloon anchor reduces the risk of pucturing the intestinal wall. This construction also includes a module for biopsy. The space is well utilized, and all modules have room. Its weakness is the valve used for air intake. If the valve becomes clogged by foreign objects, the entire propulsion system fails.

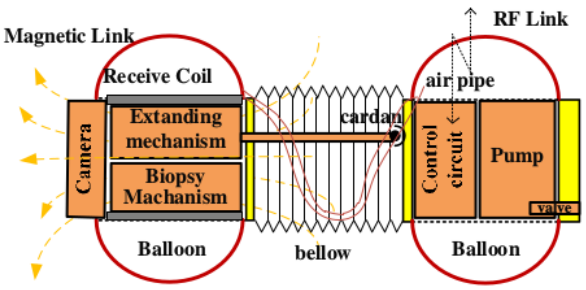


Figure 2.9: The modules in the capsule [24]

These expanding designs are very advanced, and the more advanced a robot design is, the more parts can malfunction. Construction without expanding parts may be the solution to make a more robust design.

Non-expanding robot design

This type must be able to obtain enough friction and momentum without full contact with the intestinal walls.

It is tried to do this with a fully internal propulsion system, by using an onboard vibratory motor [25]. This system involves a vibratory motor with a rotating mass. Since this circular trajectory is along the xy-plane, the rotation of the eccentric mass generates a centripetal force constrained to the x-axis (see figure 2.10), due to the intestinal walls.

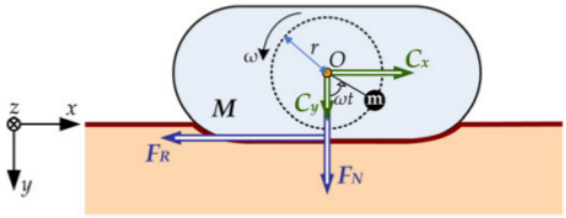


Figure 2.10: The mechanical model of vibratory actuation [25]

This type of construction will not have any form of anchoring, and while moving, the pill will vibrate, so recording will suffer bad quality. This means that all recording will work best after propulsion. Another issue is if one want to expand the design to include biopsy and smaller gastrointesinal surgeries.

Instead of creating a propulsion system, there has been research on using the bodies own propulsion, the muscles surrounding the intestine [26]. By using *electrical muscle stimulation* (EMS) one can control the muscles. The idea is elicitation of muscle contraction by using electric impulses. If this can be applied to reverse the involuntary wavelike movements that push the content of the intestine forward (peristalsis), there will be no need for an internal propulsion system in the capsule. A problem with this approach is testing.

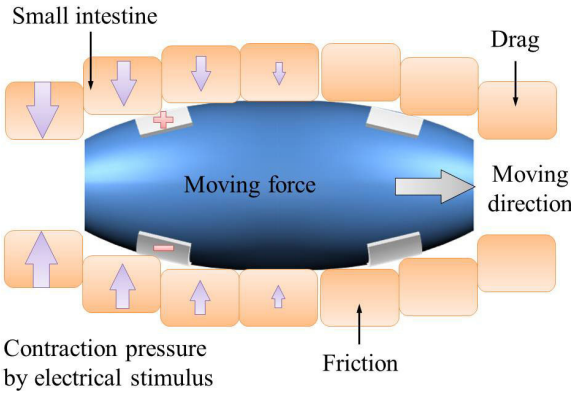


Figure 2.11: Model of electrically propelled pill [26]

Woo et al. [26] used porcine small intestines for testing. The intestines were inserted into a solution called Krebs' solution, to maintain the intestine's tissue. The small intestines can then be activated by electrical stimuli. After activiation they naturally performs peristalsis.

The general problem with non-expanding designs are less friction and guidability. But the less advanced architectures will give more robust solutions. An optimal result would include robust design, well-working propulsion system, low power consumption, and a compact construction.

Part II

Implementation and Testing

Chapter 3

Tools and Engineering Processes

This chapter introduces some alternative tools that can be used throughout this study, and focuses on the physical work done. This includes 3D design of the robot pill, realization from model to physical prototype, choice of parts, and the testing methods used.

Tool	Name	Version
Geared motor	ZWPD006006 [27]	136
FDM 3D printer	Ultimaker[1]	2+
FDM 3D printer	Stratasys Fortus[2]	250mc
Photopolymer 3D printer	Stratasys Objet[2]	Connex500
Laser Engraving / Cutting	Epilog Zing[3]	16

Software	Name	Version
CAD software	Solidworks[4]	2013 Educational version
Slicing software, Ultimaker	Cura[1]	15.04.2
Slicing software, Fortus	Insight[2]	10.2
Slicing software, Objet	Objet Studio[2]	9.2.8.3

[1] www.ultimaker.com
[2] http://www.stratasys.com
[3] www.epiloglaser.com
[4] www.solidworks.com

3.1 3D design

All 3D modelling is done in Solidworks, a powerfull tool for mechanical CAD (computer-aided design), including simulation and rendering toolboxes. Solidworks are one of the most popular CAD softwares, and has many possibilities. These types of software lets the user create, analyze and optimize their designs by simple parametric modelling, meaning that everything is based on parameters and constraints. This opens a world where one can use simple variables to easily change your design. By using equations one can have global variables that easily change certain features of one's design.

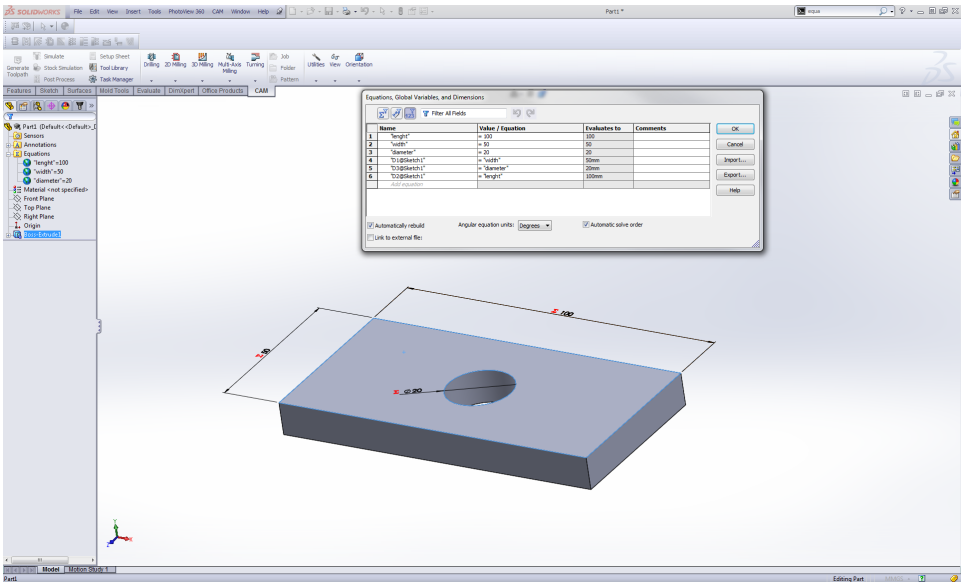


Figure 3.1: Parametric modelling in Solidworks

3.2 Realization of the 3D model

The realization of the 3D design made in a CAD software can be done by additive manufacturing (AM) or subtractive manufacturing (SM). Which ever approach one uses, these machines need to know what to do. In 3D environments this is usually done with g-code, a set of instructions on how to move along the various axis (position and orientation), and other configurations. The software used to go from a model to g-code is called a slicer, or a slicing software. In 2D environments one would use vectorized drawings.

3.2.1 Additive manufacturing

AM is typically 3D printing, a process where you fuse material on material to build a predesigned structure. There are many kinds of 3D printers, and printer technologies available. They vary in quality, price, material and durability. Some of the processes also needs afterwork to strengthen the model.

Powder bed technology uses an inkjet-like printing head that deposits a liquid binding material in each layer. Before next layer can be printed, it spreads a new layer of powder. The printing head can deposit binding material in different colors, like a normal paper printer. After print is done, one can soake in different resins to strengthen the model.

Another technology that uses a inkjet-like print head is *PolyJet*. It uses a print head that jets and instantly UV-cures tiny droplets of liquid photopolymer. If support is needed, because of overhang or complex shapes, the 3D printer jets a removable gel-like support material that can easily be washed off [28].

Photoploymer is used in AM because it changes its properties when exposed to light. One of these structurally changes is hardening. This makes it a perfect material to be used to build 3D objects. Instead of UV-light, *Stereolithography* (SLA/SL) uses a laser.

SLA hardens a liquid photopolymer with the laser. On each layer, of the solid 3D object, the liquid reacts with the laser and cure to form a very precise hardened layer. Often post processing is needed to clean and cure the 3D printed object. Curing involves subjecting the part to intense light in an oven-like machine to fully harden the resin. Stereolithography is a very accurate 3D printing process with excellent surface finish. However the post-processing steps required and the stability of the materials over time, which can become more brittle, is a drawback [29].

Lasers can also be used in *sintering*. This is the process of forming a solid mass from heating and/or pressure [30]. Particles from a material is fused together without melting and creates one solid piece.

- *SLS* (selective laser sintering) uses a laser to form solid 3D objects from powder. This powder can be of many sorts of materials. It is similar to powder bed printing, but instead uses a laser to bind the powder by local sintering. Has the advantage of being able to use many kind of different powders.

- *DMLS* (direct metal laser sintering) uses a high power laser or Electron Beam (EBM) to directly sinter metal powder.

Extrusion is a process used to create objects by extruding a material and fuse it with material from the previous layer. It is also called FDM (fused deposition modelling), a trade name registrer by Stratsys. Other printers utilize a simliar process, generally reffered to as *Freeform Fabrication* (FFF). They are often more basic, due to patents still held by Stratasys [29].

These kinds of printers build all parts layer-by-layer by fusing material, e.g. melting a plastic wire. It can have multiple nozzles with different functions. One nozzle can feed plastic for desired component, and the other can feed support material. The support can also be of the same material as the building material, then you only need one nozzle [31].

Material

Extrusion-based printers are used to realize most of the 3D models in this thesis. The two most dominant plastics used are PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene). Both are known as thermoplastics, meaning they harden after melting.

ABS is strong, flexible and has high temperature resistance. It can warp without a heated bed. ABS is petruleum based and easy to recycle. It is soluale in acetone, allowing welding parts.

PLA is environmentally friendly since it is derived from renewable resources, typically sugarcane, and it is biodegradable. It emits very few fumes and it's not necessary with extra ventilation. It has a more liquid form than ABS, which causes less wrapping and the possibility for sharper details with active cooling. PLA has less risk for cracking and warping when actively colled than ABS. It will in general have a more glossy feel [32].

Type	Storage	Fumes
PLA	Dry	No ventilation needed
ABS	Dry	Needs proper ventilation

3.2.2 Subtractive manufacturing

SM is a process where 3D models are constructed by cutting material away from a bigger block. Normally done with a CNC (computer numerical control) milling machine, but can also be done by e.g. laser cutting.

CNC machines uses rotating cutter to remove material. They often work in three axis (x, y, and z-axis), so the operator doesn't need to flip the solid block too much.

Laser cutters cuts through material with a laser beam. This approach is used if the design can be illustrated in a 2D drawing.

3.3 Actuators

This study only focus on the propulsion system of a robot pill. This means that the components usually needed to create a robot pill, power source, camera, RF link, control circuit, is not necessary. The only components used in this thesis are the actuators for the propulsion systems.

3.3.1 DC motor

The main motor used are ZWPD006006-136 from ZHAO WEI ENTERPRISE[5]. It is a coreless DC motor with plastic planetary gearing with transmission reduction 136/1. The motors voltage range is 0.2 $\sim$ 6 VDC, but is rated for 3 VDC.

No Load		At Rated Load					At Stall		
rpm	mA	rpm	mA	gf/cm	mN/m	W	mA	gf/cm	mN/m
240	25	200	40	120	12.24	0.1	190	280	28.57

[5]http://zhaowei.manufacturer.globalsources.com

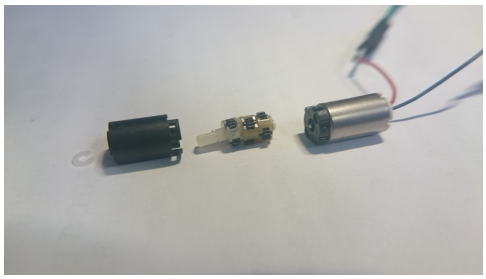


Figure 3.2: ZWPD006006-136

From their website [33], one can read about many of the tests done on this motor.

- Life test:
  The motor is used continuously over a long period of time. After motor is stopped they repeat the previously step.
- Noise test:
  The motor is put at a distance of one meter, and the they test that the noise is below required decibel levels.
- Waterproof testing:
  The motor works for two weeks when submerged 10 mm. below the surface, and 12 hours when submerged 100 meter below the surface.
- Salt spray test:
  They use salt spray to test the motors resistance to corrosion.
- Impact testing:
  It is important two test that the motor can withstand some impact. This is tested by dropping or striking the motor with a relativaly high speed.
- Storage test:
  The motor is tested after being stored under normal temperatures for up to two years.

3.3.2 DC vibration motor

Figure 3.3: Coreless DC vibrator motor

This actuator has no manufacturer part number, because it was bought from Ebay[6]. This coreless DC vibration motor is only used for experimenting on the propulsion system used by Carta et al. [25].

No load speed (rpm)	Rated DC (V)	Size body (mm)	Size oscillator (mm)
9600	1.5-4.5	8x4	4x2

3.4 Testing methodology

Testing has to be done in a realistic model of the human intestines. Two approaches are discussed in this thesis; using pig intestines, and creating a realistic model from silicone.

Pig intestines are slightly larger than humans, and will give room for a somewhat upscaled robot pill. The research team working on the robot design with spiral legs [1], as discussed earlier, tests their propulsion system in porcine intestines. The pill robot meassures 16 mm. in diameter and 45 mm. in length. This is approximately 1.6-1.8 times the size of PillCam developed by Given Imaging. The problem with this size in 3D printing is fragile and inaccurate models. Very small errors will have major effects on the performance of the robot pill. Upscaling is therefore a good alternative. But if this is done, one will need to create a realistic model from some other material. Human intestines

[6] www.ebay.com

are thin, flexible and covered with muscles. To create a realistic model, one needs to simulate many of the features included in real intestines.

By creating a realistic silicone model of the intestines, one have the advantage of being able to scale according to the pill robot. This means that it is easier to realize a pill robot.

Type of silicone has to be chosen so that the model correctly represent the intestinal flexibility. The hardness of silicone is meassured in Shore Hardness. There are many different scales used for rubber compounds, but the most common is Shore A and Shore D. To elaberate; Shore A is used for measuring the hardness of flexible mold rubbers, while Shore D is used for hard rubbers. Since the study needs a flexible silicone, its natural to choose from the Shore A scale. Rubber bands is about Shore A 20 [34], and is very flexible. A thicker model will be more durable, but will result in a less flexible modell. So in this thesis it is used a silicone with Shore A 12.

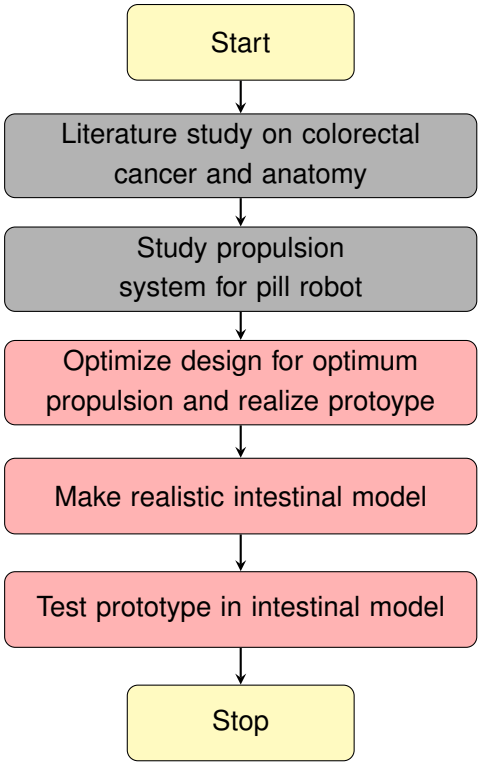
The model has to mimic the texture of the intestines. As discussed earlier the small intestines are covered with folds (*plicae circulares*). The intestines are also compressed by being folded inside your body, and by the radial muscles surounding it. So the diameter of 2.5-3 cm. is unrealistic in a model. So by shrinking the diameter and including folds on the inside, one can achieve a realistic model.

Realization of the model is done by creating molds. These molds are filled with silicone and a hardener. The hardener is what makes the silicone solid.

When testing the model, it is important to remember the muscle movements. This can be done by assuming the muscles are always contracted and adapt the diameter accordingly, or by physically simulate the contractions.

Chapter 4

The Development Process



After studying different propulsion systems for active capsule endoscopy, one can see that the two main types are expanding and non-expanding designs. The expanding model by Chen et al. [1] clearly shows that expanding designs need advanced mechanics. The robot need to be simple and robust for reliability and durability. Some of the most used and simplest robotic designs use wheeled locomotion. This therefore makes an interesting approach to create a robust, yet simple, propulsion system.

A **wheeled design** can have different types of wheels. The most common is ordinary wheels and belts. Since there are liquids and chyme in the intestine, the design must be completely sealed. Belts have the disatvantage of having lots of void between the sprockets. If this void gets filled with foreign matter from the intestines, the locomotion will stop. Although the ordinary wheels has less void, they can also become clogged.

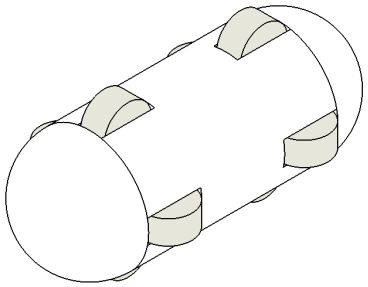


Figure 4.1: Wheeled design

Another wheeled design is a **drill-like propulsion**. A drill writhes through matter with a skewed circular movement. The problem with the drill-like locomotion is that one part of the design must lock the pill in place, while the other drills it forward. This can be solved by having two drills rotating the opposite way, but working in the same direction. This is done by making one helix screwing clockwise and the other counterclockwise (right handed and left handed helices).

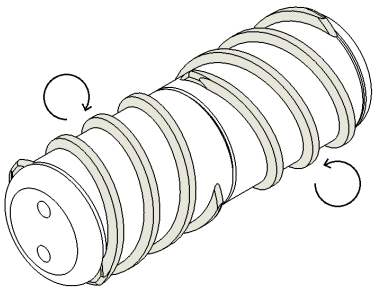


Figure 4.2: Drill-like locomotion

If compared, the wheeled design has more moving parts, a small void that can be clogged, and the space utilization is worse. A drill-like propulsion only has two wheels, and the possibility to change the geometrical parameters of the helical grousers. Properties that can be studied are the profile of the wheels, number of revolutions in the helix (grouser pitch), and the design of the grousers, meaning depth and width. The design of the wheel can also be studied. The wheel can have a straight shape (like figure 4.2), or coned with different steepness. The mechanics also needs fewer actuators because it only has two wheels. This gives a more afforable power consumption.

There are other scientists that have tested similar methods in other fields, e.g. *laparoscopic surgery*, a *minimal invasive surgery* (MIS) performed in the abdominal cavity. Laparoscopic surgery is also known as *keyhole surgery*, which perfectly illustrates the procedure. The surgery is done through one or more small incisions, instead of one big incision. In laparoscopic surgery, the abdomen is inflated with carbon dioxide gas so the surgeon can maneuvre more freely [35]. Rentschler et al. [36] used a design comparable to the drill-like system discussed.

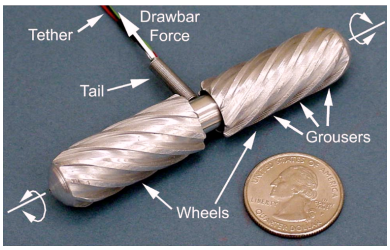


Figure 4.3: Robot for laparoscopic surgery [36]

Their robot is meant to be slit into one of these "keyholes", and help

the surgeons with different tasks. They have other restrictions regarding workspace, and their robot is designed to move perpendicular to what is needed for this thesis. But the consept of using helical grousers to improve the wheel-surface interaction inside the human body still stands. If the wheeled mobility can be achieved in one direction, this means the grip accomplished in MIS can be translated to movement in other directions by having the right restrictions.

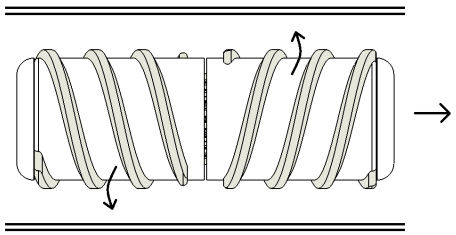
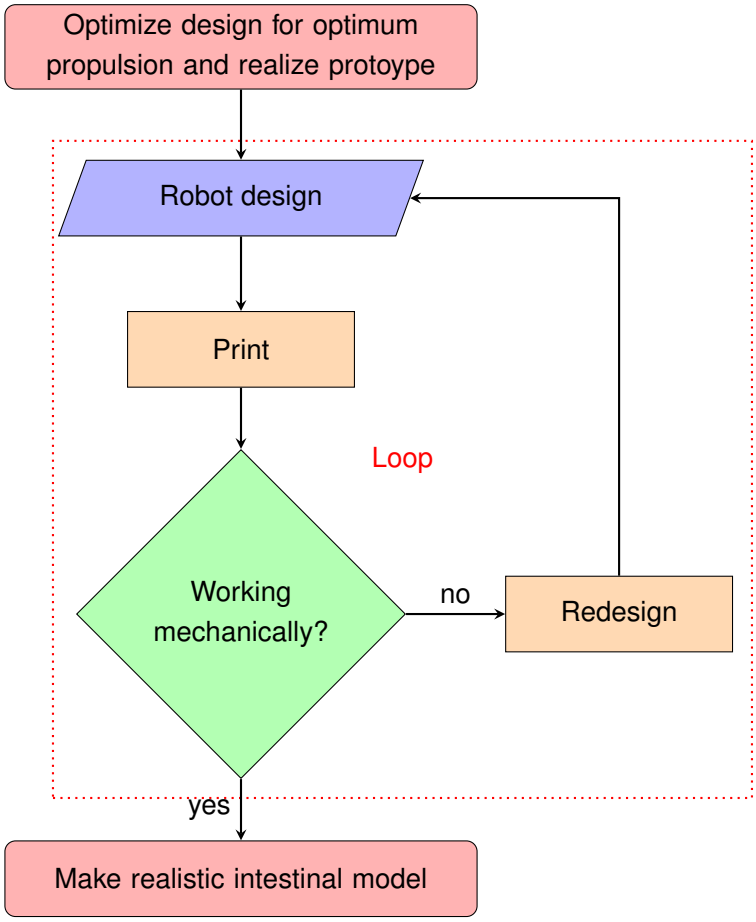


Figure 4.4: Drill-like design limited to one axis

A pill moving in the intestines are limited to movement in one axis, because of the intestinal walls surrounding it. In theory the drill-like design, where the wheels go each its way, will rotate in place. If rotation is restricted due to the intestinal walls, the direction of the helical grousers should decide the direction of the pill through the digestive system. The biggest problem with this design is the hindrance of the inner body rotating instead of creating locomotion.

4.1 Prototyping the robot pill



The prototyping of a robot pill is done in an iterative process, where each iteration will depend on previous design, to realize a pill with optimum propulsion.

By recreating some other designs, one will be able to get a more fundamental understanding on designing propulsion systems for a robot pill. So before embarking on the wheeled design, both the robot with spiral legs by Chen et al. [1] and the robot with vibratory locomotion by Carta et al. [25] where recreated.

4.1.1 Robot with spiral legs

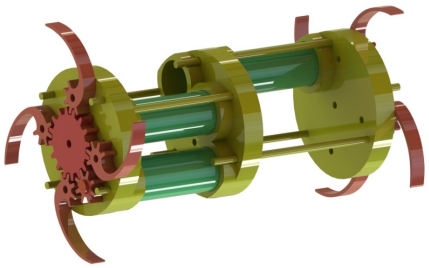


Figure 4.5: 3D model

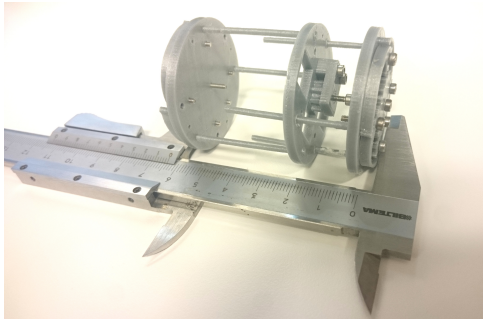


Figure 4.6: 3D print

The first prototype of this robot was designed without holders for the motors. Just the physical mechanics for the propulsion system (see figure 4.6). Some changes were done to the solution for extending the robot pill, but else equal, as seen on the second prototype (figure 4.5). The design consists of many gears, is weak against lateral forces, and has little spare room due to usage of three motors. Second prototype were never printed, due to data already aquired from the first prototype and the paper "A wireless capsule robot with spiral legs for human intestine" [1].

4.1.2 Robot with vibratory locomotion

Figure 4.7: 3D model

Figure 4.8: 3D print

As the robot pill in "A multi-coil inductive powering system for an endoscopic capsule with vibratory actuation" [25], this prototype uses a vibratory motor for locomotion. This type of locomotion depends on the intestinal walls to limit the possible directions to one axis.

Prototype	Length (mm.)	Diameter (mm.)
1	50	20
2	40	16

4.1.3 Robot with wheeled locomotion

The principal for the wheeled locomotion, as explained earlier, needs a mechanical design that is robust and simple, but also easy to print on a 3D printer. Each prototype is scaled to the PillCam developed by Given Imaging. Which has the approximately size is 10 mm. in diameter and 25 mm. long.

Version numbers are organized as following:

Prototype *propulsion type* - *prototype number* - *scale*

Prototype 0-1-2

Propulsion Type	Prototype	Scale	Printer
0	1	2	Ultimaker 2+

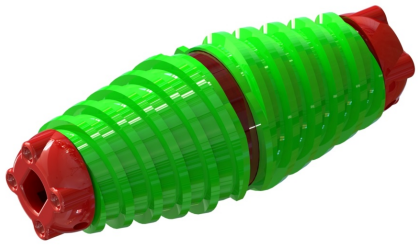


Figure 4.9: 3D model

Figure 4.10: 3D print

The first prototype was made completely without any mechanical solution for rotation of the drills. This model was used to show that the concept of two drills working in opposite direction, with respectively right and left handed helices, would create a movement in the same direction.

Prototype 1-2-2

Propulsion Type	Prototype	Scale	Printer
1	2	2	Ultimaker 2+

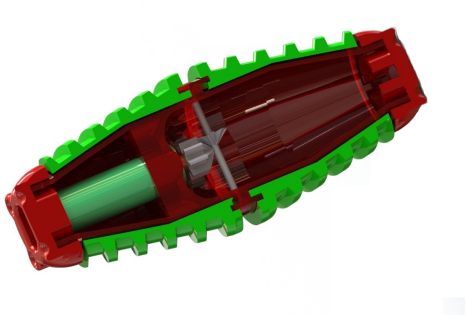


Figure 4.11: 3D model

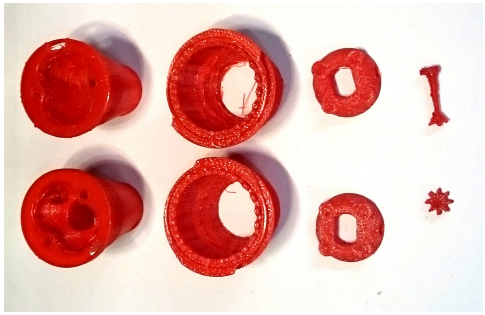


Figure 4.12: 3D print

This prototype uses a bewel gear to transfer power to the drive shaft. Bewel gears are gears where the axes of two shafts intersect, in this scenario, the motor and the drive shaft. The shafts are mounted 90 degrees apart, and the gears are conically shaped. The transmission is simple, but the drive shaft is so small that 3D printing will create a very weak structure. The shaft is thin and long, so without any casing protecting it from lateral forces, it will be the weakest part of this design.

This propulsion type is very compact and utilizes the small amount of space very well. There are also few transmissions, which wears less on the motor. The only power takeoff (PTO) between the outside and the inside of the robot pill is the single drive shaft. This in turn means that this architecture is easy to waterproof.

Because of the difficulties creating the bewel gear, this design was not sucessfully created.

Prototype 2-3-2

Propulsion Type	Prototype	Scale	Printer
2	3	2	Stratasys Fortus

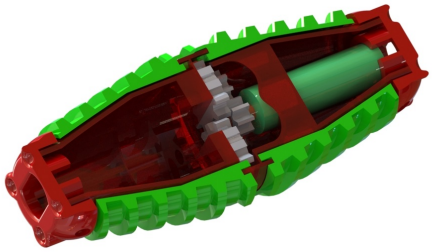


Figure 4.13: 3D model

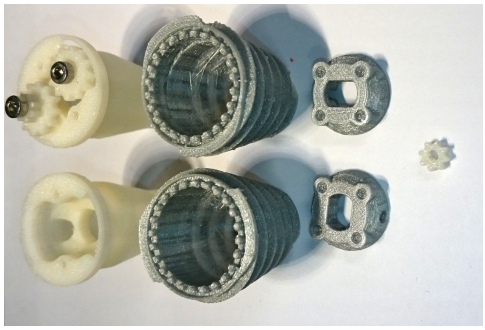


Figure 4.14: 3D print

The second propulsion system uses epicyclic gearing (aka. planetary gearing). An epicyclic gear train consists of two gears mounted so one revolves around the other. In this case the wheels revolves around an inner gear driven by the motor. This opens a bigger gap between the inside and outside of the body, but since this propulsion type only consists of regular circular gears, it will be easier to 3D print. The design itself is also more robust due to the strength of regular gears. Since the size of this prototype is very small, the tiniest imperfections in the design will create much friction on the large surface of the gears.

By using a FDM printer, it was shown that with this scale and propulsion type, it was too large unevenness in the surface of the printed prototype to drive the wheels. The motor did not manage to drive the gears with this force of friction.

Prototype 1-4-4.5

Propulsion Type	Prototype	Scale	Printer
1	4	4.5	Ultimaker 2+

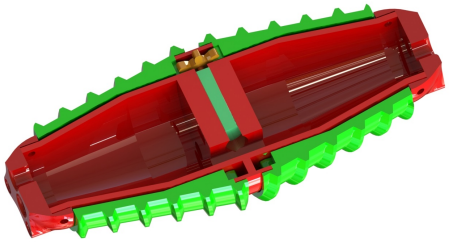


Figure 4.15: 3D model

Figure 4.16: 3D print

To solve the problem with imperfections, the design was scaled to approximately 4.5 times the size of the original PillCam. Leaving it with 46.6 mm. in diameter and 110 mm. long. With this size and propulsion type 1, the drive shaft can be replaced with the motor itself. This leaves only one power transmission. From the motor directly to the wheel. This prototype prooves that propulsion type 1 is well-working, and has plenty of room for other components. But if created in a usable size, one would need a smaller motor. The weakest part of this prototype is the gear itself. To strengthen the gears, they were made from polymethyl methacrylate (PMMA), also known as acrylic, and cut out with a laser cutter.

Prototype 1-4-4.5 works great, but because of the size, it will have to be tested in synthetic intestines. It is important to create a realitic intestinal model to perform complete and accurate testing. The motor looses less power due to fewer transmissiosn, but it also has more mass to move, so it is conceivable to believe that this prototype is weaker than the smaller ones.

Different wheels are made to test the effects the different properties of the grousers result in.

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	MAX (mm.)	MIN (mm.)
1	2	24.0	2.0	2.0	4.3	2.0
2	2	16.0	3.0	2.0	3.3	1.0
3	3	24.0	2.0	2.0	3.3	1.0
4	2	12.0	4.0	2.0	3.3	1.0

Figure 4.17: Prototype 1-4-4.5 wheels

Prototype 2-5-1.7

Propulsion Type	Prototype	Scale	Printer
2	5	1.7	Stratasys Objet

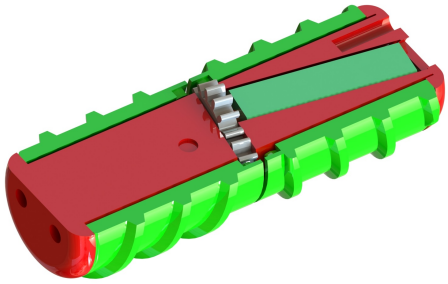


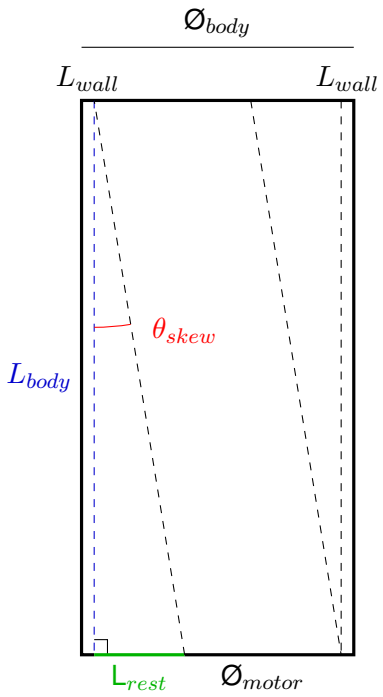
Figure 4.18: 3D model

Figure 4.19: 3D print

The most realistic way of testing a pill robot, would be in pig intestines. To achieve this, one would need to scale the model to a suitable size. Since pig intestines is somewhat bigger than humans, the original design can be upscaled. The size used by Chen et al. [1] for testing in pig intestines is 1.6-1.8 times bigger than PillCam from Given Imaging. The scale chosen for this prototype is therefore approximately 1.7.

The formerly occurring problem with uneven surfaces will recur. So by switching from a FDM printer to the the PolyJet technology, the surfaces will be somewhat smoother. The material used are a mix of Veroclear and Tango+. The ratio used for mixing these plastics are RGD8625-DM. Meaning that the material is mostly Veroclear. This creates a solid model, with some flexibility to prevent cracking.

To make enough room for the DC coreless motor, and to cope with such a small size, this prototype uses propulsion type 2. The planetary gears and the motor are skewed to use as little room as possible. The coned form of the wheels are also replaced with a straight design to create more room.



The angle θ_{skew} is the angle to skew the motor.

The known constraints are (in mm.):
$Ø_{body} = 10.8$
$L_{body} = 22.0$
$L_{wall} = 0.5$
$Ø_{motor} = 6.2$
$L_{rest} = Ø_{body} - 2 \times L_{wall} - Ø_{motor} = 3.6$

The right-angled triangle gives:

$$\theta_{skew} = tan^{-1}\left(\frac{L_{rest}}{L_{body}}\right)$$

Calculations:

$$\theta_{skew} = tan^{-1}\left(\frac{L_{rest}}{L_{body}}\right) = tan^{-1}\left(\frac{3.6}{22}\right) = 9.293^{\circ} \quad (1)$$

When fully assembled, the total size of the prototype is:

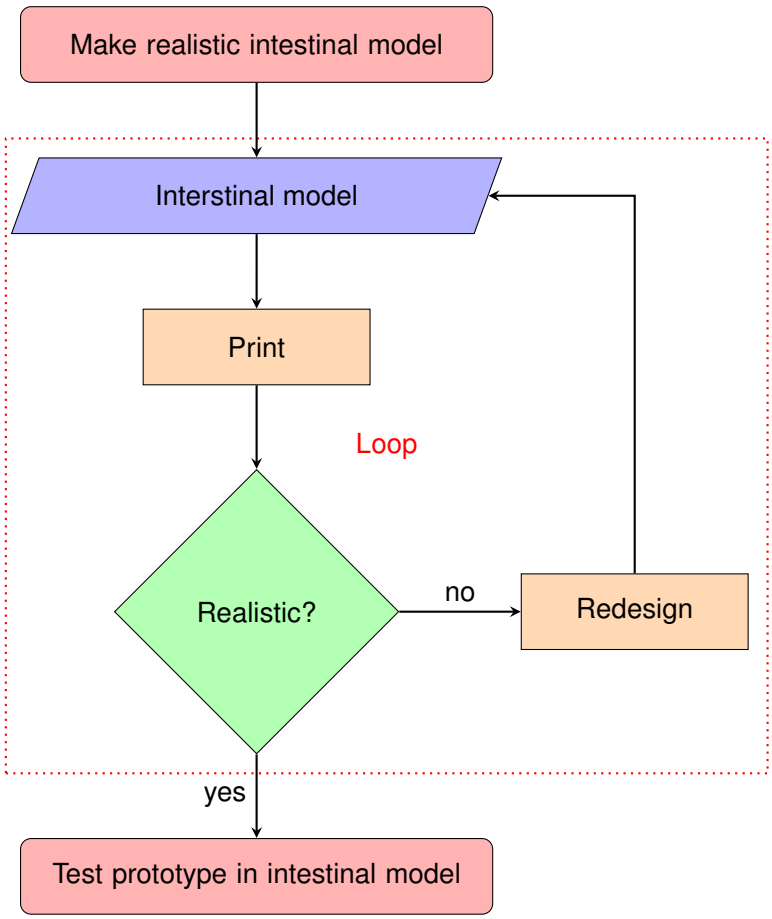
Diameter	Length
16.5 mm.	45.0 mm.

Prototype 2-5-1.7 is small enough to be tested in pig intestines. It is therefore important to throughtly test how different wheels affect the intestinal walls, and which properties that gives the best propulsion. Properties that can be changed on the wheels are the grouser pitch, width, depth, and quantity. This will give a good idea of what is the best design for the wheels. Not just for propulsion, but also which configuration that is the most gentle to the intestinal walls.

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	MAX (mm.)	MIN (mm.)
1	2	11.25	2.0	1.0	2.0	1.0
2	2	11.25	2.0	1.0	3.0	1.5
3	4	22.50	1.0	1.0	2.0	1.0
4	4	22.50	1.0	1.0	3.0	1.5
5	6	45.00	0.5	1.0	2.0	1.0
6	6	45.00	0.5	1.0	3.0	1.5
7	2	11.25	2.0	1.2	1.5	0.75
8	2	9.00	2.5	1.2	1.5	0.75
9	2	7.50	3.0	1.2	1.5	0.75

Figure 4.20: Prototype 2-5-1.7 wheels

4.2 Synthetic intestinal model



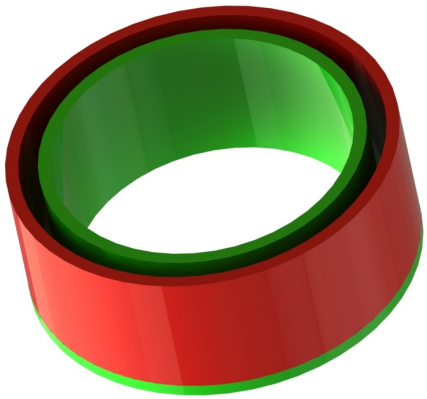


Figure 4.21: 3D model of mold

The same iterative process used for prototyping the robot pill is used for creating the synthetic intestinal model.

A synthetic model from silicone has to be flexible enough to act as realistic human intestines. This is done by using flexible silicone and thin intestinal walls. By creating a parameter-based mold, one can easily test different diameters and wall thicknesses.

The human intestines are approximately 2.5-3 cm. in diameter, and the PillCam from Given Imaging is 1.0 cm. in diameter and 2.5. cm long. So this is the basis for calculating what the ratio between the intestinal model and the robot pill.

The ratio between human intestines and the PillCam:

$$\frac{[25 \ldots 30]}{10} = [2.5 \ldots 3.0] \tag{2}$$

This gives a realistic ratio for fully inflated intestines without plicae circulares (folds). But since the intestines include these folds, a more realistic ratio should be calculated from a smaller diameter. The largest folds are 8.0 mm. (mainly smaller) and covers from half to the whole intestinal circumference. New ratio is calculated with a diameter of 20-25 mm.

$$\frac{[20 \ldots 25]}{10} = [2.0 \ldots 2.5] \tag{3}$$

The small intestines is also squeezed by a wavelike series of pendular muscle contractions and relaxtions (peristalsis). To realistically simulate this behaviour, a person will physically compress the intestinal model while testing.

To calculate a realistic scaling factor, it is important to take into account that the intestines is not fully inflated inside the human body. By comparing how big difference there are between inflated and not inflated pig intestines (see figure 4.22), and considering that the intestinal walls are radially attached to muscles (which will expand the diameter some), the scaling factor is set to 1.5.

Figure 4.22: Comparison of inflated and non-inflated intestines

The correct scaling of the diameter is then given by:

$$f(s) = s * 1.5 \begin{cases} s & = \text{scale of prototype} \\ 1.5 & = \text{scaling factor} \end{cases} \quad (4)$$

This will not give the pill full radial contact with the intestinal walls, but by physically applying muscle contractions, it works as an realistic representation of the human intestines.

1. and 2. prototype

Thickness	Height	Diameter	Printer
5 mm.	20 mm.	80 mm.	Ultimaker
3 mm.	20 mm.	50 mm.	Ultimaker

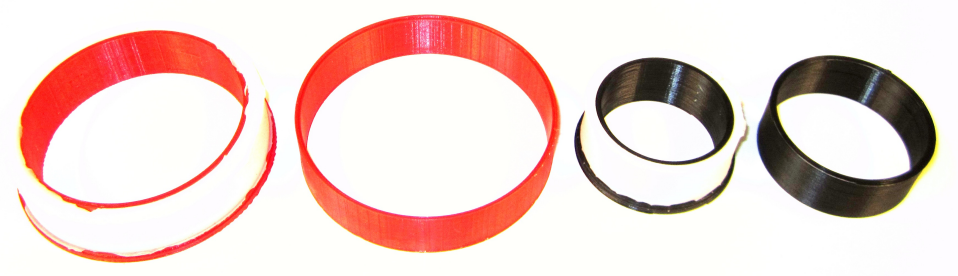


Figure 4.23: Prototype 1 and 2: mold, silicone

These two first intestinal models were made just to test the durability and flexibility of the silicone.

Prototype 1 was made with 5.0 mm. intestinal walls. It was very durable, but the force needed to stretch the material was too high.

Prototype 2 had 3.0 mm. intestinal walls, and gave a more natural feeling. Compared to the intestines of a pig, it was still too thick.

3. prototype

Thickness	Height	Diameter	Printer
2 mm.	50 mm.	25 mm.	Ultimaker

Figure 4.24: Mold and silicone

Figure 4.25: Model of mold

To create a realistic model, but maintain the strength and durability, this prototype had 2.0 mm. intestinal walls. The first attempt failed due to the difficulties pooring liquid silicone in such a small crack. In next attempt a funnel was added to the outer walls of the mold (as in figure 4.25).

This model is created with the human intestine as inspiration. By the ratio calculated earlier, the calculation for testing prototype 2-5-1.7 gives the diameter:

$$16.5 * 1.5 = 24.75 \approx 25 \text{ mm.} \tag{5}$$

4. prototype

Thickness	Height	Diameter	Printer
2 mm.	100 mm.	25 mm.	Ultimaker

Figure 4.26: Mold and silicone

Figure 4.27: Model of mold

This mold was made with the same calculations as in third prototype, but with the length extended to get a longer intestinal model for testing.

One problem encountered when using a mold with this length, was that the outer walls of the mold was very hard to remove.

5. prototype

Thickness	Height	Diameter	Printer
2 mm.	100 mm.	70 mm.	Ultimaker

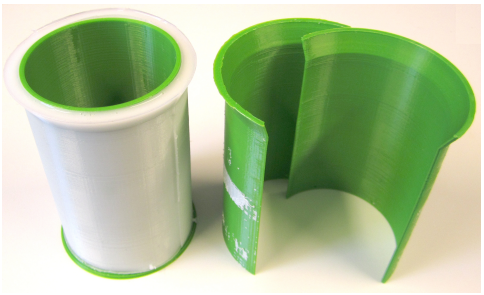


Figure 4.28: Mold and silicone

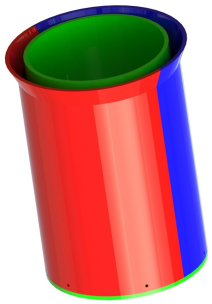


Figure 4.29: Model of mold

This mold used a split outer wall, due to the problems in previous prototype.

An intestinal model for prototype 1-4-4.5 must be scaled accordingly to previous calculated ratio. New diameter will be:

$$46.6 * 1.5 = 69.9 \approx 70 \text{ mm.} \tag{6}$$

4.3 Pig intestine

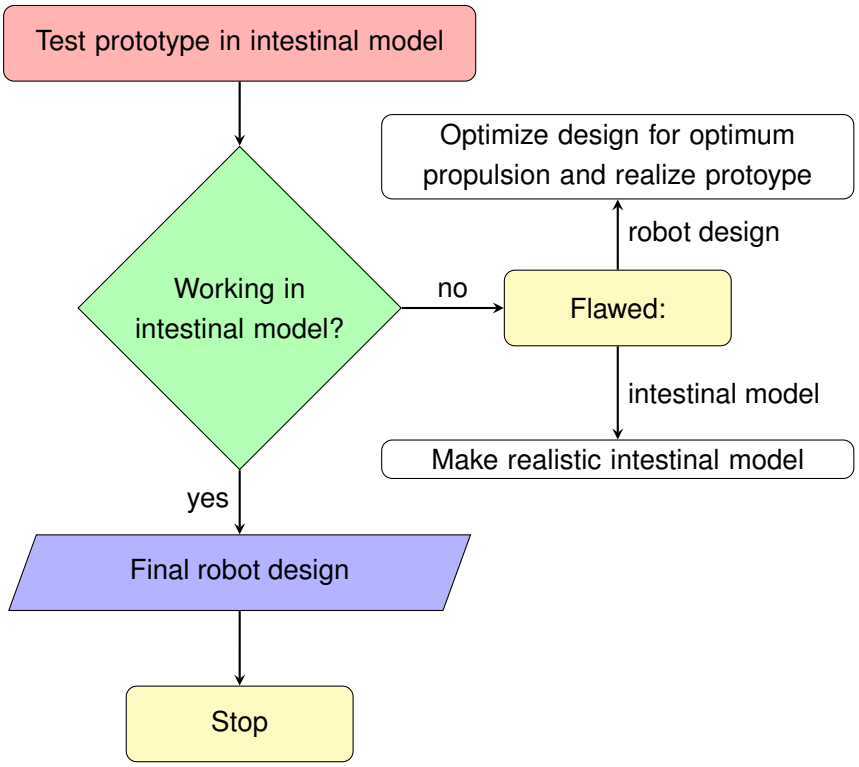
Pig intestines were obtained from one of the local butcher shops, the intestinal sections had an average diameter of 2.5-3.0 cm. This is the same diameter as human intestines, which makes it a bit tighter than orginally assumed. But since the intestines usually are crammed inside the human body and held in place by the mesentery, the pig intestine specimen are stretched over two mounting points. The intestines are not attached on its entire surface, but since this is difficult to manage, there are only small parts of the intestine simultaneously tested. This will give some room inside the intestines and a more realistic diameter compared to the size of robot pills.

Figure 4.30: Mounting points for pig intestines

The in vitro testing has to be done in flexible and moist intestines. When exposed to air, the intestines will dry up and loose its flexibility. So all tests have to be done rapidly after exposure to air. To prolong the time it takes to dry up, they are soaked in olive oil. This also gives the inside of the intestinal walls a bit more slippery surface, instead of dry and sticky. Because of the risk of injuring the intestines from the wheel-surface interaction, there will be a examination of the surface of the intestinal walls after each test.

Chapter 5

Testing the Prototypes



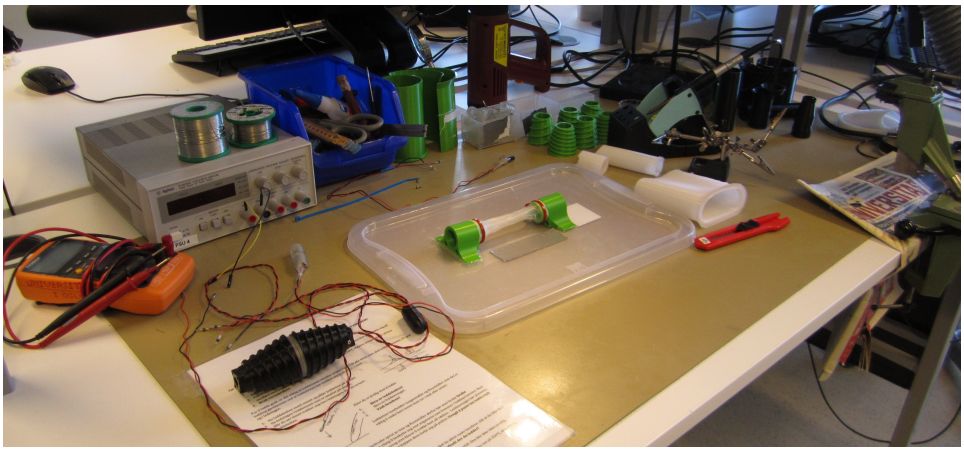


Figure 5.1: Workspace for testing

Testing without intestinal environment

This procedure is done by simply testing the prototype on a flat surface, with and without lateral walls. The surface is covered with a rubber mat.

Testing in synthetic intestinal model

The intestinal model are held by the researcher, and muscle simulation is done by physically compressing the intestinal walls of the model. The prototype is judged on speed and mobility.

In vitro studies in pig intestines

Pig intestines are stretched over two mounting points, and the prototype is judged on speed, mobility, and how sensitive it is to the intestinal walls. After each experiment, the intestinal walls are checked for damage.

5.1 Robot with vibratory locomotion

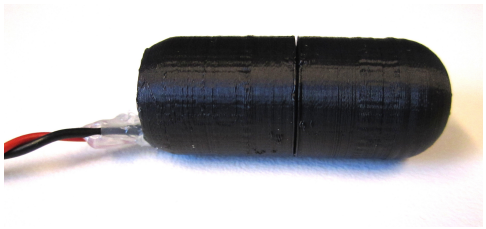


Figure 5.2: Robot with vibratory locomotion

5.1.1 Testing without intestinal environment

Propulsion is achieved on the flat surface of the rubber mat. This shows that the vibratory motor do accomplish to create a rotational force in the desired direction. When lateral walls are added, the robot pill is to weak in relation to the friction from the walls and the extra weight of the cord powering it.

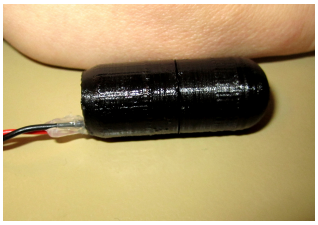


Figure 5.3: Testing

5.1.2 Testing in synthetic intestinal model

The testing in an environment without an intestinal model showed that the rotational force did in fact work in wanted direction. When limiting the force to one axis, it should create a propulsion. This experiment resulted in very little locomotion, even though different input voltages were tested.

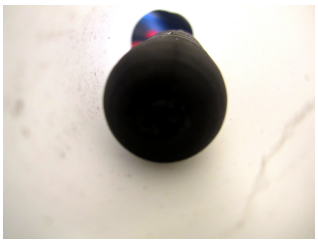


Figure 5.4: Testing

5.1.3 In vitro studies in pig intestines

The vibratory robot pill did not manage to get any propulsion in the pig intestines. Experiments were done with an input voltage in the range 2.0-6.0 V.

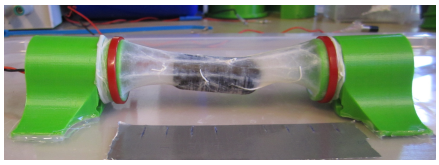


Figure 5.5: Testing

5.2 Prototype 1-4-4.5

Figure 5.6: Printed prototype

5.2.1 Testing without intestinal environment

Some propulsion is achieved on the flat rubber mat. But due to the coned form of the wheels, only a small part of the wheels touch the surface at the same time. This makes the contact with the surface alternate between the two wheels in a rocking movement.

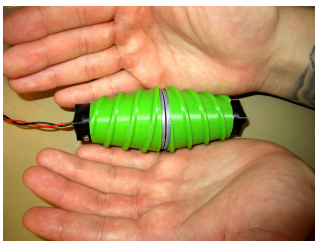


Figure 5.7: Testing

When adding lateral walls, and form them so as the robot pill get as much contact as possible, the propulsion is decent.

5.2.2 Testing in synthetic intestinal model

The same problem occures in this test. The intestinal walls in the synthetic model are straight and little surface contact results in the same rocking movement. This makes the body rotate more than desired.

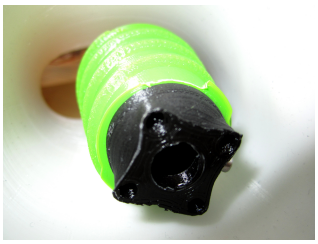


Figure 5.8: Testing

There were some differences when testing the different wheels, even though their surface contact was limited. Wheel number one and three did best. They both have a pitch of 24.0 mm. They only differ in number of grousers and the width of the grousers.

5.3 Prototype 2-5-1.7

Figure 5.9: Printed prototype

5.3.1 Testing without intestinal environment

All prototypes works decent, but they all lack some friction from the rubber mat. The rubber mat is too slippery, so the only thing creating locomotion is the contact with the lateral walls, in this case human hands.
Without the lateral walls, to limit possible axis, the robot pill had a side-to-side motion.

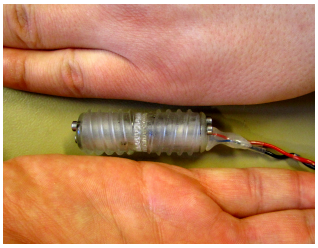


Figure 5.10: Testing

5.3.2 Testing in synthetic intestinal model

The simulated muscle compression was hard to do realistically because the silicone will bend, rather then compress. Real intestines are thinner and will create better surface coverage. All tests were done with an input voltage of approximately three volts.

Figure 5.11: Testing

The results show that most of the wheels manage to create some locomotion. The combination of the smooth surfaces of the intestinal walls and the grousers, produces a very slow propulsion.

In the following table the various wheels are ranked by how much propulsion they achieved.

worst			best
6	4, 5, 9	1, 2, 8	3, 7

5.3.3 In vitro studies in pig intestines

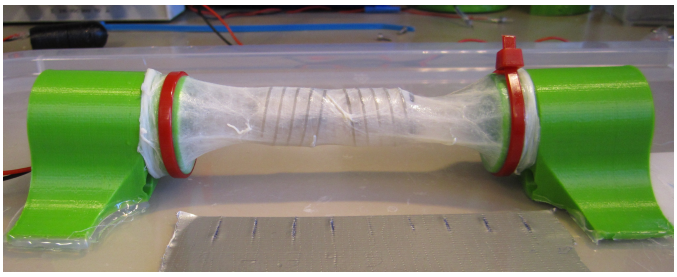


Figure 5.12: Testing

Testing of 1. wheel

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	bottom (mm.)	top (mm.)
1	2	11.25	2.0	1.0	2.0	1.0

test	speed	voltage
#	(mm/s)	(V)
1.1	1.3	5
1.2	2.0	4
1.3	2.5	5
1.4	2.5	4

Figure 5.13: 1. Wheel

The diameter of the intestines used in test 1.1 was small. This resulted in the need for increasing the input voltage. In test 1.4 the intestines were switched with fresh ones.

Testing of 2. wheel

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	bottom (mm.)	top (mm.)
2	2	11.25	2.0	1.0	3.0	1.5

test	speed	voltage
#	(mm/s)	(V)
2.1	-	-
2.2	2.0	4

Figure 5.14: 2. Wheel

The intestines used in test 1.1 was also used in 2.1. This resulted in no locomotion at all.

Testing of 3. wheel

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	bottom (mm.)	top (mm.)
3	4	22.50	1.0	1.0	2.0	1.0

test	speed	voltage
#	(mm/s)	(V)
3.1	-	-
3.2	2.5	4
3.3	2.0	4

Figure 5.15: 3. Wheel

The intestines used in test 1.1 was also used in 3.1. This resulted in no locomotion at all. Completely fresh intestines were used for test 3.2, while the intestines used for test 3.3 was a bit dry.

Testing of 4. wheel

id #	grousers #	pitch mm.	revolution #	depth mm.	grouser width bottom (mm.)	grouser width top (mm.)
4	4	22.50	1.0	1.0	3.0	1.5

test #	speed (mm/s)	voltage (V)
4.1	-	-
4.2	-	-

Figure 5.16: 4. Wheel

The intestines used in test 1.1 was also used in 4.1. This resulted in no locomotion at all. Test 4.2 was done in intestines with a greater diameter, but it still had too much friction. The robot pill had fast locomotion if the intestines were physically expanded.

Testing of 5. wheel

id #	grousers #	pitch mm.	revolution #	depth mm.	grouser width bottom (mm.)	grouser width top (mm.)
5	6	45.00	0.5	1.0	2.0	1.0

test #	speed (mm/s)	voltage (V)
5.1	-	-
5.2	-	-

Figure 5.17: 5. Wheel

Same result as in the testing of the fourth wheel.

Testing of 6. wheel

id #	grousers #	pitch mm.	revolution #	depth mm.	grouser width bottom (mm.)	grouser width top (mm.)
6	6	45.00	0.5	1.0	3.0	1.5

test #	speed (mm/s)	voltage (V)
6.1	-	-
6.2	-	-

Figure 5.18: 6. Wheel

Same result as in the testing of the fourth and fifth wheel.

Testing of 7. wheel

id #	grousers #	pitch mm.	revolution #	depth mm.	grouser width bottom (mm.)	grouser width top (mm.)
7	2	11.25	2.0	1.2	1.5	0.75

test #	speed (mm/s)	voltage (V)
7.1	5.0	4
7.2	3.3	4

Figure 5.19: 7. Wheel

This wheel performed very well. It has the same pitch as the first wheel, but with deeper and thinner grousers, the surface is smaller. The pill had enough grip in the intestinal walls to propell itself, but not so much that it got stuck or damaged the intestines.

The intestines in test 7.2 was more loosely attached, than in test 7.1.

Testing of 8. wheel

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	bottom (mm.)	top (mm.)
8	2	9.00	2.5	1.2	1.5	0.75

test	speed	voltage
#	(mm/s)	(V)
8.1	6.7	5
8.2	5.0	4
8.3	5.0	4

Figure 5.20: 8. Wheel

Wheel eight performed as well as the previous wheel. The only difference is a lower pitch. Even though a higher pitch would normally mean increased speed, this is not the case in this test. This could be the result of different dryness and diameter in the pig intestines.

Testing of 9. wheel

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	bottom (mm.)	top (mm.)
9	2	7.50	3.0	1.2	1.5	0.75

test	speed	voltage
#	(mm/s)	(V)
9.1	5.0	6
9.2	-	5
9.3	-	4

Figure 5.21: 9. Wheel

The high density of the grousers create a greater surface. This results in too much friction, and no propulsion. In test 9.1 the intestines were more tightly attached, which hinder the intestines to twist, and propulsion can be achieved with a higher resistance. When the input voltage is set to max (6.0 V.), some propulsion is aquired, but the grousers may then damage the intestinal walls.

Part III

Results and Conclusion

Chapter 6

Results and Analysis

An analysis of the different results will give an overview of the main trend of the findings. This will give a deeper understanding of which features that give the best outcome.

6.1 Robot with vibratory locomotion

The robot with vibratory locomotion tried to recreate the propulsion system used by Carta et al. [25]. The idea was to use centrifugal force limited to one axis. The experiments done without an intestinal environment proves that the theory is plausible. But when tested in pig intestines the force created was not strong enough to get any real propulsion. The reasons can be multiple, but the most probable is that the DC vibration motor has a very small oscillator. As a result of this, the force created is equally small.

6.2 Prototype 1-4-4.5

Table 6.1: Prototype 1-4-4.5, parameters

Propulsion Type	Prototype	Scale	Printer
1	4	4.5	Ultimaker 2+

The size of this prototype led to some limitations. It can not be tested in pig intestines. But by analyzing the experiments in the non-intestinal environment and in the synthetic intestinal model, it is clear that the momentum is limited because of its coned design. The conical shape results in a very small wheel-surface interaction.

Table 6.2: Prototype 1-4-4.5, wheels

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	MAX (mm.)	MIN (mm.)
1	2	24.0	2.0	2.0	4.3	2.0
2	2	16.0	3.0	2.0	3.3	1.0
3	3	24.0	2.0	2.0	3.3	1.0
4	2	12.0	4.0	2.0	3.3	1.0

Because of the small wheel-surface interaction, it was very little difference in performence for the various wheels. But if used in a setting where the front is tighter than current position, as in the intestines (see figure 6.1), it may perform better.

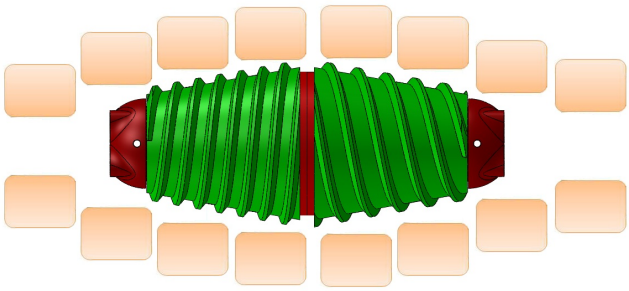


Figure 6.1: Conically shaped robot pill

6.3 Prototype 2-5-1.7

Table 6.3: Prototype 2-5-1.7, parameters

Propulsion Type	Prototype	Scale	Printer
2	5	1.7	Stratasys Objet

Prototype 2-5-1.7, the smallest prototype, managed to get the best results. Its propulsion was superior to the other prototypes. The design's wheel-surface interaction was very good, and the straight shape was optimal for flat surfaces. It was clear that the different properties of the grousers had great influence on the results.

Table 6.4: Prototype 2-5-1.7, wheels

id	grousers	pitch	revolution	depth	grouser width	
#	#	mm.	#	mm.	MAX (mm.)	MIN (mm.)
1	2	11.25	2.0	1.0	2.0	1.0
2	2	11.25	2.0	1.0	3.0	1.5
3	4	22.50	1.0	1.0	2.0	1.0
4	4	22.50	1.0	1.0	3.0	1.5
5	6	45.00	0.5	1.0	2.0	1.0
6	6	45.00	0.5	1.0	3.0	1.5
7	2	11.25	2.0	1.2	1.5	0.75
8	2	9.00	2.5	1.2	1.5	0.75
9	2	7.50	3.0	1.2	1.5	0.75

The biggest issue was large contact surface. This made the pill robot to get stuck. Things that made a big surface was too low grouser pitch, too many grousers, and too thick grousers. Another problem occured when the grousers were to shallow. The intestinal walls, since they are flexible, also got contact with the surface between the grousers. This also created too much friction. When the grouser had a too high pitch, the problem with wheel-surface interaction between the grouser recured. Also, the high pitch demands more force because it wants to move more than the ones with smaller pitch.

The tests without intestinal environment did not give any indication on which wheel performed the best. But when tested in the synthetic intestinal model, the various wheels showed some difference in propulsion. In the following table (6.5) the various wheels are ranked by how much propulsion they achieved.

Table 6.5: Prototype 2-5-1.7, results from testing in synthetical model

worst			best
6	4, 5, 9	1, 2, 8	3, 7

It is important to take account for human error. The intestinal model simulate muscle contractions (peristalsis and segmentation contractions) by physically compressing the model. It is possible that different forces are applied between tests.

When tested in pig intestines, the best performing designs was wheel seven and eight (see table 6.6). Which fit well with the results from the experiments in the synthetic model. Both wheels had thin and deep grousers. The pitch gave 2.0 and 2.5 revolutions, respectively, for each wheel. As expected, does these wheels have small contact surface.

Table 6.6: Prototype 2-5-1.7, results from testing in pig intestines

wheel #	test #	speed (mm/s)	voltage (V)	comment
1	1	1.3	5	Very small diameter on intestines
	2	2.0	4	–
	3	2.5	5	–
	4	2.5	4	Fresh intestines
2	1	–	–	Very small diameter on intestines
	2	2.0	4	–
3	1	–	–	Very small diameter on intestines
	2	2.5	4	Fresh intestines
	3	2.0	4	–
4	1	–	–	Very small diameter on intestines
	2	–	–	Fresh intestines
5	1	–	–	Very small diameter on intestines
	2	–	–	Fresh intestines
6	1	–	–	Very small diameter on intestines
	2	–	–	Fresh intestines
7	1	5.0	4	–
	2	3.3	4	Loosely mounted intestines
8	1	6.7	5	–
	2	5.0	4	Tightly mounted intestines
	3	5.0	4	Loosely mounted intestines
9	1	5.0	6	Very tightly mounted intestines
	2	–	5	–
	3	–	4	–

Chapter 7

Discussion

The synthetic intestinal model could not provide the same realistic properties as the real intestines. If made so tight that the pill had full radial contact, the force was to strong. It is not realistic that the pill is held in place with that amount of force, so therefore it was room around the pill robot and the muscle contractions (peristalsis and segmentation contractions) were physically simulated. The problem with this, is that the silicone bends, rather than compress. The surface of the intestinal walls is also very slippery in comparison to the real intestines.

The pig intestines aquired had an average diameter of 25-30 mm. This is the same as human intestines, and gives an upper diameter smaller than expected. In the human body the intestines are also suspended in the abdominal cavity by the mesentery. This keeps the intestinal walls loosely in place. The intestinal walls are also surrounded by muscles. In order to make up for this, only small parts of the intestines are tested simultaneously. The outer walls of the intestines are not suspended to anything, but will be more or less kept in place, due to the short samples tested. Although the intestine specimen was fixed at both ends, this diameter may result in a somewhat unrealistic environment for the upscaled prototype.

The mesentery and the muscles surrounding the intestines, will prevent the intestines from rotating too much. Since the design uses a rotating propulsion system, it is important to prevent this. This is done as mentioned above by stretching the intestines between two mounting points. How tightly this is done, affects the propulsion of the robot pill and the realism of the intestinal environment. If mounted too tight, the intestinal walls will squeeze around the pill. While in the opposite case, the intestines rotate instead and squeeze the

pill too hard.

The results of the experiments differ because of the diameter, and how tight the intestines are stretched between the mounting points, but it also differ because of the flexibility of the intestinal walls. The specimen will dry up when exposed to air. So it is important to keep them as fresh as possible, and exchange them when necessary.

The results are also affected by the fact that the prototypes are 3D printed. The surface will allways be somewhat uneven, due to the printing procedure. This might cause the wheel-surface interaction to be rougher than what initially wanted.

machining parts/injection molding vs 3D printing

In all the experiments there was used an external power source. This results in the robot pill pulling the wire behind itself. This adds extra weight and more power is needed to get propulsion.

There is a risk of injuring the intestines when propelling through them. To prevent this it is important that the grouser-organ impact forces is so small that they do not tear the intestinal walls. Internal organs can be highly deformable and very slick, but since the diameter of the prototypes tested was a bit big for the intestine specimen and the surface is rough from being printed, there are even a greater chance of injuries. After each test there was a physical examination of the pig intestines. Non of the experiments showed any visible injuries on the intestinal walls.

7.1 Compared to earlier research

Earlier research shows many different types of propulsion systems. As this study aims for a fully *in vivo* robotic design, the two main groups are; expanding and non-expanding designs. Comparing to other designs, eg. legged design, the wheeled design is a design with need for few actuators and simple mechanical solutions. The robot pill with spiral legs by Chen et al. [1] is a well tested idea, using an expanding design, and is good candidate for comparison of results.

The spiral legged design also used pig intestines for testing their robot pill. The pig intestines they obtained had an average diameter of 35 mm. and their design had a diameter of 16 mm. Which gives them an average intestine-pill

ratio of:

$$\frac{35}{16} = 2.19 \tag{7}$$

The intestine-pill ratio for PillCam from Given Imaging[1], granted the average diameter of human intestines being 27.5 is:

$$\frac{27.5}{10} = 2.75 \tag{8}$$

When comparing these to ratios, one can clearly see that Chen et al. [1] also took into consideration that a smaller intestine-pill ratio is realistic, due to the earlier mentioned reasons. Since this thesis bases its results from pig intestines with an average diameter equal to human intestines, its ratio might be too small too be realistic;

$$\frac{27.5}{16.5} = 1.67 \tag{9}$$

This explains the need for a more tightly stretched intestine than used for the robot pill with spiral legs (see figs. 7.1 and 7.2).

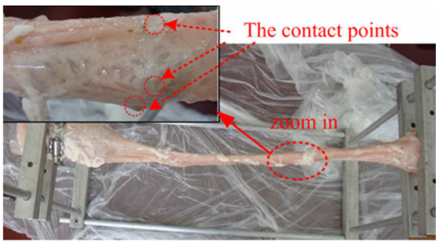


Figure 7.1: Test bed: Chen et al. [1]

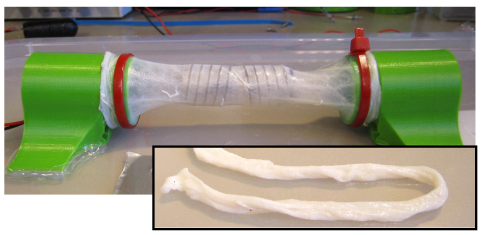


Figure 7.2: Test bed: this thesis

As one can also see from the figure, the intestine specimen used in this thesis is preprocessed and thinner. This can also have some impact on the results from the experiment.

The two propulsion systems are completely different. Compared to the wheeled

[1] http://www.givenimaging.com/

locomotion used in this thesis, the robot pill with spiral legs [1] uses a slow walking pattern. It moves with a wormlike locomotion (see figure 7.3). This kind of locomotion takes time because of the multiple steps needed to propel the pill forward. While the wheeled locomotion only needs to rotate the wheels.

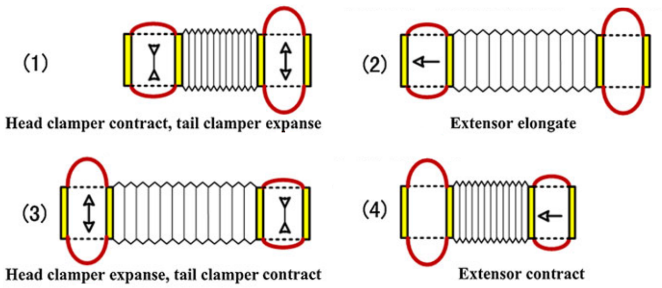


Figure 7.3: Wormlike locomotion [1]

The locomotion test done by Chen et al. [1] shows that they get an average speed of 2.3 cm/min. on a straight path. Compared to the wheeled locomotion tests done in this study, these results are extremely slow. All results in this thesis was so fast that meassure used was mm/s. Taking the average of the two best wheels (seven and eight), gives:

$$\frac{5.0 + 3.3 + 6.7 + 5.0 + 5.0}{5} = 5.0 \text{ mm/s} \tag{10}$$

By converting their average speed of 2.3 cm/min to mm/s,

$$2.3 \text{ cm/min} = 0.38 \text{ mm/s} \tag{11}$$

, one can see that this study's results are 13.2 times faster. This is due to a way faster propulsions system, but can also be partly a result of the difference in intestine specimen. Chen et al. [1] writes that their robot pill was more likely to slip when the diameter was more than 39.0 mm. The designs used in this thesis rely on the pendular muscle contractions to optimize the wheel/surface interaction. But as tested on a flat surface with lateral walls, the prototype will still move without complete pendular surface contact.

By reducing the speed of the wheels, the risk of injuring the intestinal wall will also decrease.

Chapter 8

Conclusion

mindre diskusjon

The need for active capsule endoscopy is clear after researching the different tests and procedures used to examine the GI tract. Most procedures do not reach the small intestines, and the only real alternative without surgery, is capsule endoscopy followed by the time-consuming procedure enteroscopy. The benefits of a robot pill is that it can navigate in the intestines, do biposies, and do smaller gastrointestinal surgeries. There is still a long way to go before any of these functions is a fact. But even the propulsion system alone saves resources by being able to provide better images. This in turn provides the gastroenterologists a better idea if enteroscopy is necessary.

So, the most basic building block to make acitive capsule endoscopy a reality is a well-working and robust propulsion system. If one want the portability of today's capsule endoscopy, one will need a fully *in vivo* robotic design. As mentioned earlier the two main groups are expanding and non-expanding designs. Where the expanding type expands parts of its body to increase the pill-surface interaction, while the non-expanding type rely on the pendular muscle contracions in the intestines. The benefits with the by expanding design is its ability to anchor itself in one position. The problem is slow and advanced mechanics. This results in many moving parts, and is therefore more fragile. Because of the size and power restrictions of a robot pill, few actuators with compact mechanics are preferred. This is were non-expanding designs exceeds the capabilities of the expanding designs.

After comparing this study's experiments with the expanding design of the robot

pill with spiral legs, one can see that the propulsion system has some promising results. It consists of few parts and is robust. The planetary gearing provides a reliable and durable power transimission. The robot pill navigates easily forward and backward in the intestines. Some questions are still unanswered, due to the testing in a not fully realistic intestinal environment. The pill-intestine diameter ratio is smaller than realistically wanted, the mesentery do not stabilize the intestinal walls, and the lack of pendular muscle contractions makes the testing semi-optimal.

But given the current conditions, the wheeled design works as expected. The drill-like wheels rotates in opposite directions, with respectively right and left handed helices, and creates a combined propulsion in the same direction (see figure 8.1).

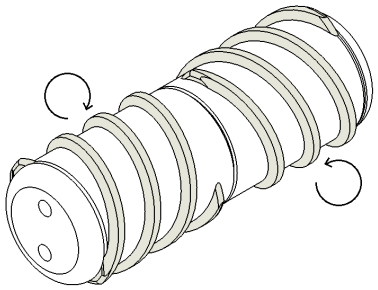


Figure 8.1: Drill design

When both wheels has approximately the same surface interaction, the body of the pill will be kept stable while the robot pill achieves propulsion. The only problem encountered while testing, was when the capsule got stuck as a result of too much friction. One reason for this was that the pig intestines obtained had a smaller diameter than expected. The other reason was that the wheel's surface got too much contact. While conducting the testing, it was clear that the wheels with the largest surface and the biggest grouser pitch, did the worst. Wheels with short or widely spaced grousers performed poorly because it was too big contact between the wheel and the intestinal walls. The same goes for wheels with too small grouser pitch.

Resulting in the optimized wheels having thin, tall grousers with small grouser pitch. The best performing wheel had the following properties:

grousers	pitch	revolution	depth	grouser width	
#	mm.	#	mm.	bottom (mm.)	top (mm.)
2	9.00	2.5	1.2	1.5	0.75

From a societal context, the use of active capsule endoscopy is revolutionary. As mentioned earlier, it is desired to screen complete populations for intestinal cancer. Meaning that when a person reaches a certain age, that person is to be checked for intestinal cancer. It is then essential to have an efficient and inexpensive procedure for doing this. A reasonable conclusion is that this can be solved with active capsule endoscopy. This kind of completely *in vivo* system is less resource consuming, because less equipment and supervision is needed. After the pill robot is swallowed and the data storage is mounted with a belt, the patient can leave the premises. This is a procedure that can be done by fewer and less educated staff members, and saves resources compared to today's procedures. For this to be completely automatic some image processing must be implemented, so the pill knows where to take more images, biopsy, etc. This procedure has the possibility of saving many lives. Especially where there is a shortage of resources, due to its efficiency and inexpensivity.

COMPARE

- physician has to examine the stored images i ettertid
- automatical detection of obstacles, . . . area (use tools auto or hust mark images)

compare

It can be argued that this study can have a big impact on how propulsion systems is designed in this field. This thesis shows that the wheeled locomotion is a reliable alternative to a propulsion system for active capsule endoscopy. With some further testing, it may indicate that the non-expanding designs are the future for active capsule endoscopy. The usage of a single actuated design, keeps mechanics within the size and power constraints. Which in turn may indicate that this propulsion system can be used to achieve an actual active endoscopic capsule.

Chapter 9

Future work

This propulsion system can further be developed by solving some of the issues encountered in this study. The most important would be to test the system in a more realistic intestinal environment, with a more suitable pill/intestine diameter ratio. Next step would be to test the endoscopic capsule with a smoother surface. This can be achieved by realizing the prototype with injection moulding, instead of 3D printing. This will also give more freedom concerning the design; thinner walls, stronger parts, and less friction. By testing different configurations for the wheels with these new conditions, one would get a better impression of the resulting design.

A partly coned shape of the wheels migth improve the mobility of the capsule. This and the bewel geared propulsion system was never tested in real intestines. By doing this, one could expect a even better propulsion.

Other features that are wanted from a future endoscopic capsule would be:

- **Tools** for taking biopsies and perform smaller gastrointestinal surgeries where needed.
- A **smart capsule** that can operate the tools implemented and use image processing to automatically navigate the capsule.
- Implementing a **power source**, wireless or internal.
- Better **camera** for better output images.

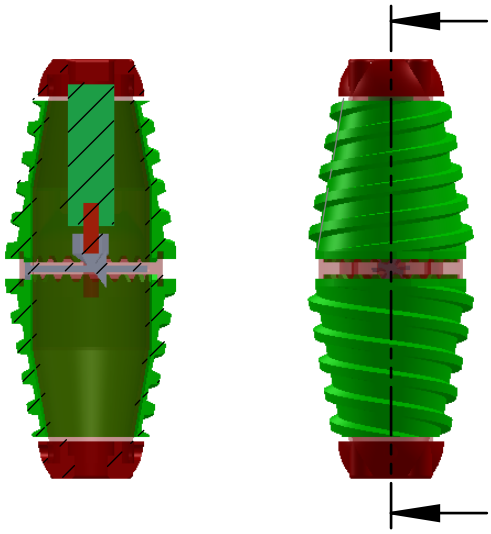
Mention anchoring, pga. biposy, etc.

Appendix A

Technical drawings

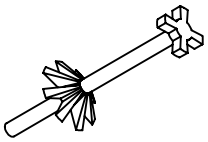
Parts:	Quantity:
Wheels	2
Bodies	2
End pieces	2
Gears	2

Prototype 1-2-2



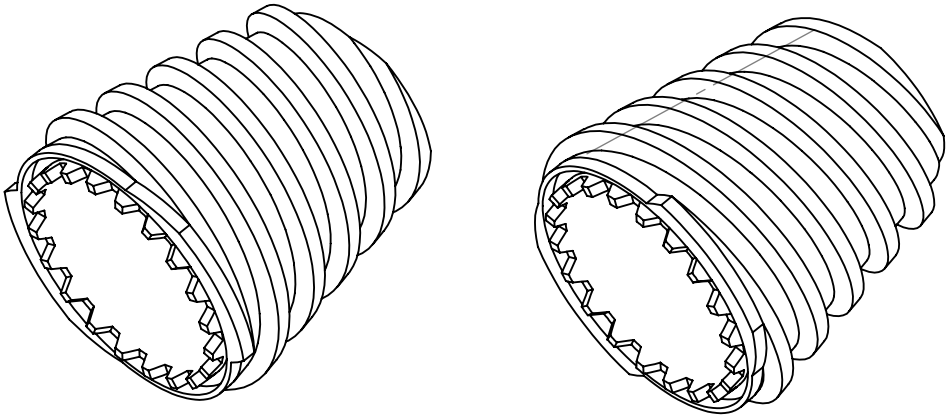
scale 1:1

Gears



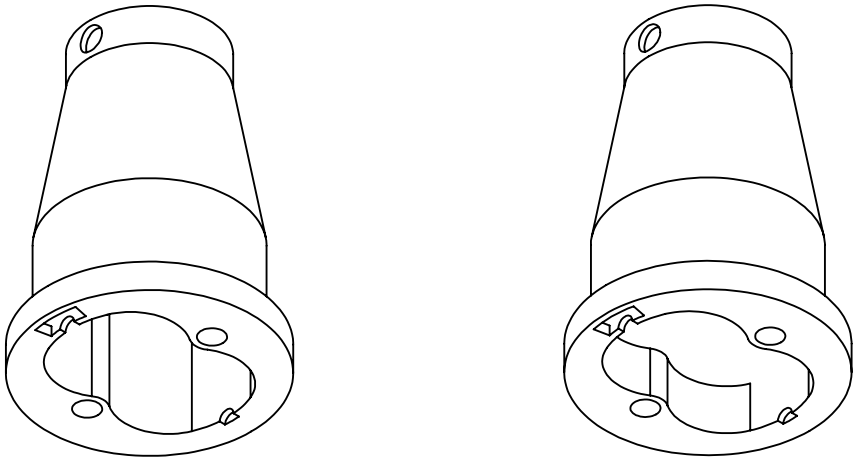
scale 2:1

Wheels



scale 2:1

Bodies



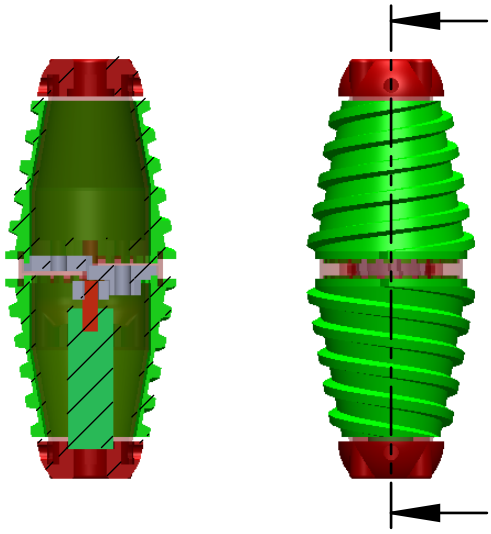
scale 2:1

End pieces

scale 2:1

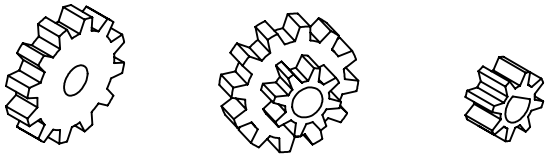
Parts:	Quantity:
Wheels	2
Bodies	2
End pieces	2
Gears	3

Prototype 2-3-2



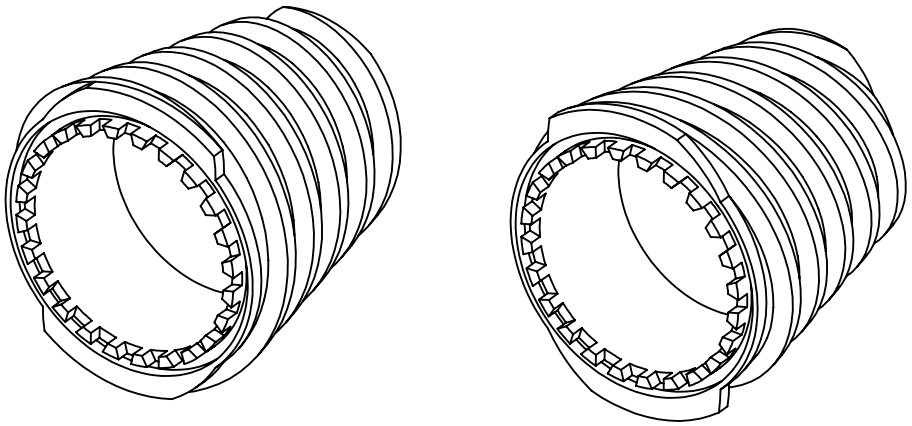
scale 1:1

Gears



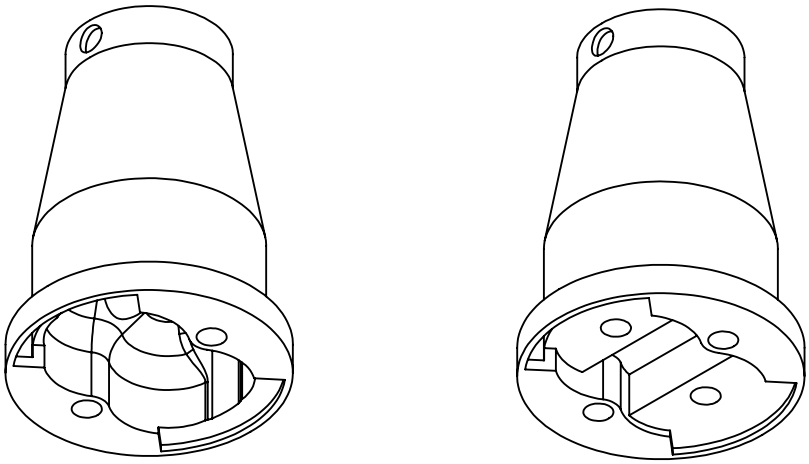
scale 2:1

Wheels



scale 2:1

Bodies



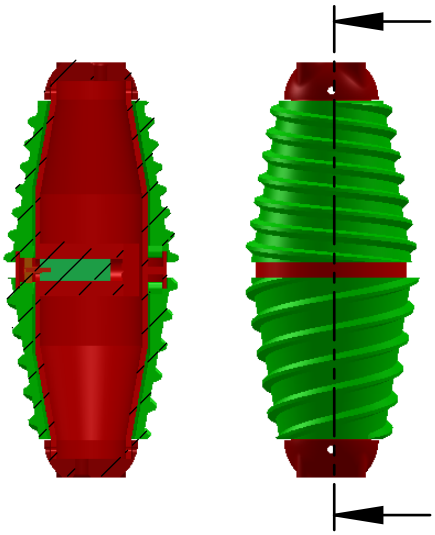
scale 2:1

End pieces

scale 2:1

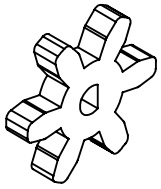
Parts:	Quantity:
Wheels	2
Bodies	2
End pieces	2
Gears	1

Prototype 1-4-4.5



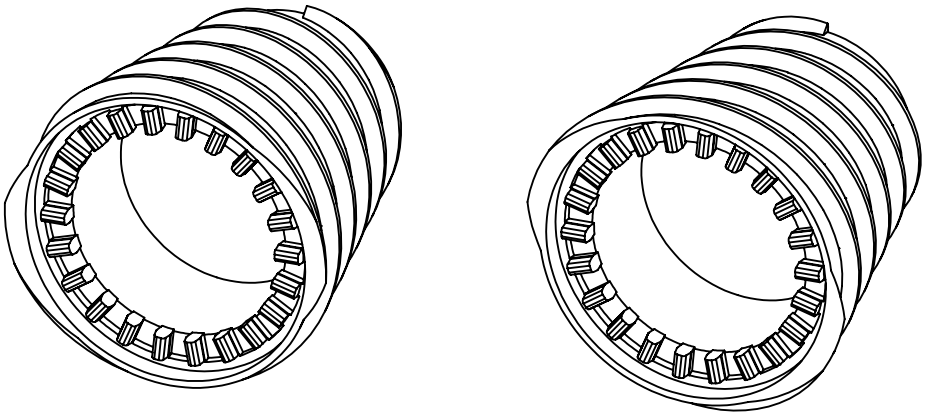
scale 1:2

Gears



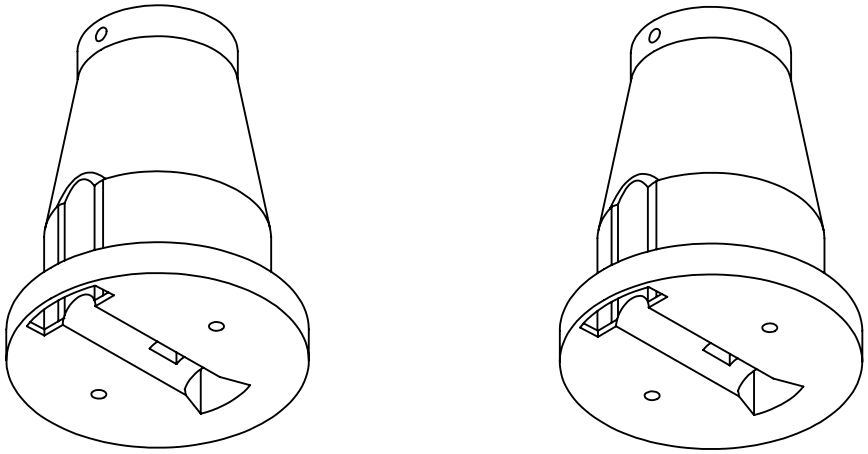
scale 2:1

Wheels



scale 1:1

Bodies



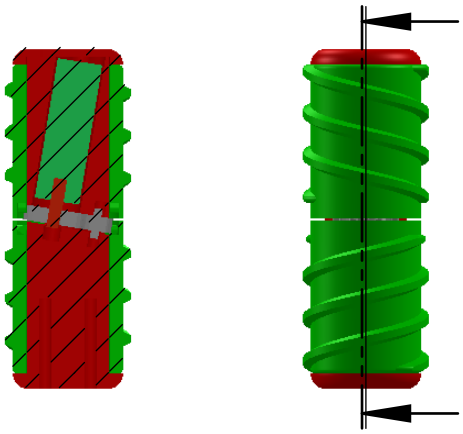
scale 1:1

End pieces

scale 1:1

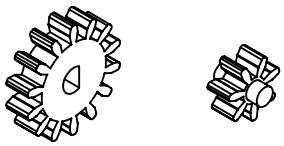
Parts:	Quantity:
Wheels	2
Bodies	2
End pieces	2
Gears	2

Prototype 2-5-1.7



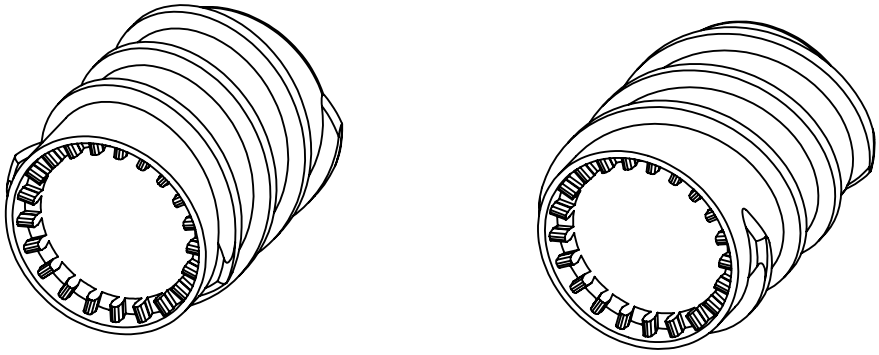
scale 1:1

Gears



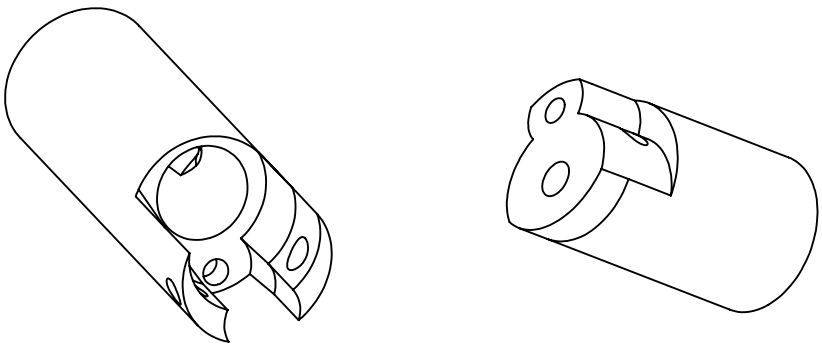
scale 2:1

Wheels



scale 2:1

Bodies



scale 2:1

End pieces

scale 2:1

Appendix B

Data sheets

ZHAOWEI 兆威

ZHAO WEI ENTERPRISE (H.K.) COMPANY LIMITED
SHENZHEN ZHAOWEI MACHINERY & ELECTRONICS CO., LTD.

ZWPD006006

Standard Plastic Geared Motor

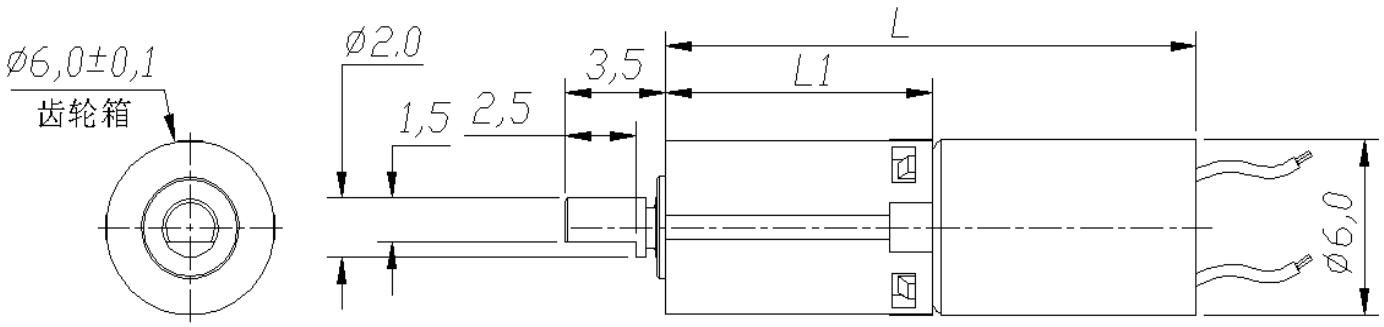
典型应用：智能手机、照相机、机械手、电子开关（锁）、机器人、遥控装置等
Typical Application: Mobile phone、Camera, Robotic hand, Electronic switch(lock), robot, Remote control device, and etc.

输出功率：约0.07W～0.2W
Output Power: 0.07W~0.2W

塑胶输出轴
Plastic output shaft **

Model	Voltage		No Load		At Rated Load					At Stall			Transmission Reduction		Overall Length L	Gear Box Length L1
	Range	Rated	Speed	Current	Speed	Current	Torque		Power	Stall Torque		Stall Current				
	VDC	VDC	rpm	mA(MAX)	rpm	mA(MAX)	gf.cm	mN.m	W	gf.cm	mN.m	mA	Ratio	Stage	mm	mm
ZWPD006006-26	0.2～6	3	1200	25	1000	40	25.0	2.55	0.1	55.0	5.61	190	26/1	2	16.35	7.05
ZWPD006006-136	0.2～6	3	240	25	200	40	120.0	12.24	0.1	280.0	28.57	190	136/1	3	18.7	9.4
ZWPD006006-700	0.2～6	3	47	25	40	40	200.0	20.41	0.1	452.0	46.12	190	700/1	4	21.05	11.75

* above specifications are subject to change without notice, just for reference and customizable according to requirements
** plastic output shaft is better to be used in those conditions need small torque, or of no radial load, or via coupling joint



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ELASTOSIL® M 4511

RTV-2 SILICONE RUBBER / MOLD MAKING

Product description

Pourable, condensation-curing, two-component silicone rubber that vulcanizes at room temperature.

Special features

- very good flowability and self-deaeration
- very low Shore A hardness (approx. 12)
- high tear strength
- extremely high elongation and flexibility
- outstanding chemical resistance to attack by polyester and polyurethane resins, mold life is significantly extended

Application

ELASTOSIL® M 4511 is a high-performance moldmaking compound, which is particularly suitable for the reproduction of models with extensive undercuts. ELASTOSIL® M 4511 is especially suitable for the processing of polyester and polyurethane resins.

Due to its very high extensibility and low flexural modulus, ELASTOSIL® M 4511 is best suited for the reproduction of fine or fragile models, where the piece may be damaged by more rigid molding materials on demolding.

ELASTOSIL® M 4511 exhibits low hardness and high strength, plus excellent ink transfer characteristics. These make it a perfect base material for the production of printing pads.

Processing

If molds for processing epoxy or polyurethane resins are to be made,ELASTOSIL® M 4511 is cured by adding 5 wt % Catalyst T 21.

For molds used to process other reproduction materials such as polyester resins, plaster, concrete, synthetic stone, wax or low-melting alloys, 5 wt % Catalyst T 51 should be used.

Pot lifes and curing times of both catalysts may be accelerated, and thus adjusted to suit the individual application by blending with Catalyst T 47.

The pot life is the period of time at 23 °C / 50 % rel. humidity during which the catalyzed mix to attain a viscosity of 100,000 mPa s and still be just pourable

For faster curing either catalyst may be blended with Catalyst T 47. E.g. at a ratio of 95 : 5 (T51 : T47) the pot life decreases to about 30 min, and the mold needs only about 4 h to cure.

Further instructions on blending any catalyst with Catalyst T 47 may be found in our data-sheet: "WACKER® T-series catalysts".

Comprehensive instructions are given in our leaflet "ELASTOSIL® - PROCESSING RTV-2 SILICONE RUBBERS".

Detailed information on other mold-making compounds in the ELASTOSIL® M range is contained in our brochure "ELASTOSIL® M. Mold-Making Compounds For Maximum Precision".

Catalyst	Pot life, [min]	Curing time (tack-free), [h]
5 % T 21	60-90	8-10
5 % T 51	60-90	8-10

Storage

The 'Best use before end' date of each batch is shown on the product label.

Storage beyond the date specified on the label does not necessarily mean that the product is no longer usable. In this case however, the properties required for the intended use must be checked for quality assurance reasons.

Additional information

Please visit our website www.wacker.com.

Safety notes

Being a condensation-curing silicone rubber,

ELASTOSIL® M 4511 contains only constituents that over many years have proved to be neither toxic nor aggressive. Special handling precautions are therefore not required, i.e., only the general industrial hygiene regulations apply.

Catalysts T 21, T 51 and T 47 contain organotin compounds, are flammable (flash points 50 °C) and may cause irritation in contact with eyes and skin. Adequate protective measures are required.

Comprehensive instructions are given in the corresponding Material Safety Data Sheets. They are available on request from WACKER subsidiaries or may be printed via WACKER web site http://www.wacker.com.

Product data

Typical general characteristics	Inspection Method	Value
Product data (uncured)		
Color		white
Density at 23 °C		1,22 g/cm³
Viscosity, dynamic at 23 °C , after stirring	DIN EN ISO 3219	25000 mPa.s
Product data (catalyzed with 5 wt % Catalyst T 51)		
Viscosity at 23 °C	ISO 3219	20000 mPa*s
Product data (cured)		
Density at 23 °C in water	ISO 2781	1,22 g/cm³
Hardness Shore A	ISO 868	12
Tensile strength	ISO 37	3,50 N/mm^2
Elongation at break	ISO 37	600 %
Tear strength	ASTM D 624 B	> 18 N/mm
Linear shrinkage		< 0,4 %

With 5 wt % Catalyst T 51, after 4 days at 23 °C / 50 % rel. humidity.
These figures are only intended as a guide and should not be used in preparing specifications.

For technical, quality, or product safety questions, please contact:

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WACKER SILICONES

WACKER® T-Series Catalysts

RTV-2 Silicone Rubber / Mold Making and Pad Printing

Characteristics

Crosslinker systems for room-temperature condensation-curing two-part silicone rubber grades

Special Features

- Low viscosity
- Curing rates can be adjusted within a wide range
- Specific systems (Catalysts T 21 and T 51) guarantee large numbers of polyester and polyurethane resin castings
  Only Catalyst T is suitable for BfR-compliant applications.

Use and Processing

Production of flexible molds and printing pads with condensation-curing ELASTOSIL® M silicone rubber grades.

Pot Lives and Curing Times
The curing rates and pot lives of ELASTOSIL® M products can be adjusted within a wide range, either by varying the amount of T-series catalyst used or by blending it with Catalyst T 47.

Pot lives can be adjusted to between five and 120 minutes in this way, with curing times ranging from one to 24 hours.

Example:
100 g of Catalyst T 51 are needed for a mold made from 2 kg ELASTOSIL® M 4514. The pot life is about 75 minutes, and the product can be demolded after 10 h.

For faster curing, mix the required amount of catalyst in a ratio of, for example, 9.5 : 0.5 (T51 : T47), i.e. 95 g T 51 + 5 g T 47. The pot life decreases to 30 minutes, and the mold needs only about 4 h to cure.

The figures contained in the tables overleaf are a guide to reactive rubber blends that cure rapidly but still have an adequately long processing window.

It is possible to increase the proportion of T 47, but pot lives become extremely short. The rubber blend may flow less easily as a result, reducing the fidelity of reproduction.

The blending ratios given in the tables for individual catalysts and Catalyst T 47 are based on parts by weight.

Blends of the individual catalysts with Catalyst T 47 have a long shelf life, making it possible to prepare larger quantities that can be used over a lengthy period.

Molds for Use with Casting Resins
To manufacture molds intended for use with epoxy and polyurethane resins, condensation-curing ELASTOSIL® M silicone rubber grades are processed with 5 wt. % Catalyst T 21.

Molds intended for use with polyester resins, by contrast, are made using 5 wt. % Catalyst T 51.

The reactivity of these catalysts, too, can be varied by blending them with Catalyst T 47. The resistance of the silicone molds to the respective casting resins is not affected.

General Information
Please follow the general information provided in our leaflet "Wacker RTV-2 Silicone Rubber – Processing"

You will find detailed information on our ELASTOSIL® M product range in our brochure "ELASTOSIL® M Mold-Making Compounds for Maximum Precision."

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Pot Lives and Curing Times

ELASTOSIL® M 3502 / M 4511 / M 4512 / M 4514 / M 4541

CATALYST	BLENDED WITH CATALYST T 47 (T 21 or T 51 : T 47)	AMOUNT	POT LIFE [min]	CURING TIME [h]
T 21	-	5 %	60 – 90	8 – 12
	95 : 5	5 %	20 – 40	4 – 6
	90 : 10	5 %	10 – 20	2 – 4
T 51	-	5 %	40 – 80	6 – 10
	95 : 5	5 %	15 – 30	2 – 5
	90 : 10	5 %	5 – 15	1 – 2
T 47	-	1.5 %	3 – 10	1 – 2

ELASTOSIL® M 4503

CATALYST	BLENDED WITH CATALYST T 47 (T 35 : T 47)	AMOUNT	POT LIFE [min]	CURING TIME [h]
T 35	-	5 %	90 – 120	15 – 20
	90 : 10	5 %	20 – 40	6 – 8
	40 : 10	5 %	10 – 20	2 – 4
T 47	-	2 %	3 – 10	1 – 2

ELASTOSIL® M 4400 / M 4440 / M 4470

CATALYST	AMOUNT	POT LIFE [min]	CURING TIME [h]
T 37	3 %	80 – 100	10 – 12
T 37	4 %	50 – 70	8 – 10
T 40	2 %	30 – 50	6 – 7
T 47	2 %	3 – 8	0.5 – 1

ELASTOSIL® M – BfR-compliant food applications; rubber-grade recommendation on request

CATALYST	AMOUNT	POT LIFE [min]	CURING TIME [h]
T	1 – 3 %	20 – 60 min	4 – 12 h

The pot lives listed indicate how long it takes at 23 °C/50 % relative humidity for the catalyzed mix to reach a viscosity of 100,000 mPa s and still just be pourable.

The curing times listed indicate how long it takes at 23 °C/50 % relative humidity until the rubber can be demolded tack-free.

All figures are intended as a guide and should not be used in preparing specifications.

Storage

T-series catalysts should be stored between 5 °C und 25 °C in the tightly closed original container.

The "Best use before end" date of each batch is shown on the product label.

Storage beyond the date specified on the label does not necessarily mean that the product is no longer usable. However, the properties required for the intended use should be checked in this case for quality assurance reasons.

Safety Information

Our T-series catalysts contain tetraorganotin compounds, some of which are flammable (flashpoint < 61 °C), and may cause irritation in contact with eyes and skin. Adequate protective measures are required.

Comprehensive instructions are given in the appropriate material safety data sheets. These are available on request from WACKER sales offices.

Additional information

Please visit our website www.wacker.com

Management system certified to ISO 9001 and ISO 14001

Version 1.00 from 29-07-10

For technical, quality, or product-safety questions, please contact:

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