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Diploma Thesis

Development and Testing of Biomimetic Macroscale Models for Novel Endoscopes

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Abstract

The aim of this thesis is to improve current endoscopes by inspiration from living nature. Conventional current endoscopes have been widely used for more than 50 years and were hardly altered. The medical flexible endoscope is usually advanced manually by the examining doctor; the novel endoscopes shall be motorized. This makes the examination less stressful and tiring for the medical doctor and less risky and uncomfortable for the patients, especially for those with sensitive tissue. A self-propelling endoscopic system will reduce problems due to mechanical stress of the tissue, diminish mental pressure and save time. By identifying best practice examples in living nature and abstracting the basic physical principles relevant for endoscopes, macroscopic interlocking brick-based models with, e.g., implemented sensors, were conceptualized, built and tested. These tests determined the maneuverability of the models in macroscopic maze-based colon models via touch sensors, key forces regarding the interaction with the wall via spring balances and the pressure distribution of the actively moving models on pressure sensitive foil (Prescale Ultra Extreme Low (5LW), FUJIFILM). The macroscale endoscope models are based on the movement specifics of snakes (snake scales), moles (shovel hands) and tetrapod vertebrates (legs). The results will inspire endoscope developers towards more gentle locomotion systems regarding the contact with the sensitive gastrointestinal tract, with additional benefits from miniaturization (that is yet to be established).

Kurzfassung

Ziel dieser Arbeit ist die Verbesserung aktueller Endoskope durch Inspiration aus der belebten Natur. Konventionelle Endoskope werden seit mehr als 50 Jahren vielseitig eingesetzt und wurden dabei kaum verändert. Das medizinische flexible Endoskop wird im Regelfall manuell vom untersuchenden Arzt in den Magen-Darm-Trakt geführt und weitergeschoben; die neuen Endoskope sollen motorisiert werden. Dies soll dabei helfen, die Untersuchung weniger stressig und ermüdend für den untersuchenden Arzt und weniger riskant und unangenehm für den Patienten zu gestalten, mit besonderem Augenmerk auf Patienten mit empfindlichem Gewebe. Ein endoskopisches System, das sich selbst fortbewegen kann, kann dazu beitragen, Probleme durch mechanische Belastung auf das Gewebe zu verringern, psychischen Druck zu vermindern und Zeit zu sparen. Durch die Identifizierung von Best-Practice-Beispielen in der belebten Natur und die Abstraktion der für Endoskope relevanten physikalischen Grundprinzipien wurden makroskopische Modelle auf Klemmbaustein-Basis - unter anderem mit eingebauten Sensoren - konzipiert, gebaut und getestet. Diese Tests beinhalteten Untersuchungen der Maneuvrierbarkeit der Modelle in makroskopischen Labyrinth-artigen Dickdarmmodellen mittels Berührungssensoren, der wirkenden Kräfte bei Interaktion mit der beweglichen Wand mittels Federwaagen und der Druckverteilung der aktiven Modelle auf einer drucksensitiven Folie (Prescale Ultra Extreme Low (5LW), FUJIFILM). Die makroskopischen endoskopischen Modelle basieren auf den spezifischen Bewegungsabläufen und -mechanismen von Schlangen (Schuppen), Maulwürfen (Schaufelhände) und tetrapoden Wirbeltieren (Beine). Die Ergebnisse sollen Endoskopentwickler dazu inspirieren schonendere Fortbewegungssysteme hinsichtlich des Kontakts mit dem empfindlichen Magen-Darm-Trakt zu wählen, mit zusätzlichen Vorteilen durch die (noch durchzuführende) Miniaturisierung.

Contents

1 Introduction

The medical field is always searching for improvement. Support for the medical staff by computers, comfort for the patients as well as trustworthy diagnosis and treatment with highly evolved medical products and machines are some of the goals in the medical field. An important method which needs improvement is the endoscopy. This thesis aims at making a first move towards the development of improved endoscopic devices. What better way to begin this journey in designing a medical tube moving through the gastrointestinal tract than by observing the living nature and being inspired by the ways an animal without legs can move or an animal living in an underground tunnel system? Their locomotion was investigated and rebuilt in its fundamental points representing basic principles with the help of interlocking bricks. Due to cost and equipment availability reasons and because of the possibility of fast implementation of design changes all prototypes were built in a larger dimension than its intended future medical product.

All references in this chapter are located at the end of the respective paragraphs. Each paragraph contains one subject, which is presented in all references at the end of the paragraph.

All sketches in this thesis were designed by the author with the Inkscape vector graphics editor. [Inkscape Project, 2020]

1.1 Biomimetics

Biomimetics and bionics are generally viewed as recent fields of research. However, they have been around for some time. Even though the term itself did not exist, the idea of biomimetics was already in existence at the time of Leonardo da Vinci (1452-1519), who took inspiration from birds to concept and build a flying machine acting like feathers on a wing. The first biomimetic patent was the ”new sprinkler” inspired by the poppy seed capsule by Raoul Francé in 1920. [Gebeshuber et al., 2009a] [Walter et al., 2011] [Nachtigall and Wisser, 2013] [Nachtigall and Pohl, 2013]

The definition of biomimetics was formed and adapted over time, a recent one from Werner Nachtigall, the big old man of biomimetics in Germany: Biomimetics is

> *"Lernen von den Konstruktions-, Verfahrens- und Entwicklungsprinzipien der Natur für eine positive Vernetzung von Mensch, Umwelt und Technik."* [Nachtigall and Pohl, 2013]
> [translated to English]
> *"Learning from the design, process and development principles of Nature for a positive networking of people, environment and technology."*

The biomimetics concept can be separated in two different concepts: "real" biomimetics and biological technology. Whereupon biological technology can be seen as the first step in the process of biomimetics and both concepts work best hand in hand. Biological technology is the fundamental research of physical principles and fundamentals in flora and fauna, where movements, materials, surface structures, developments, fabrication processes etc. are investigated and described. Biomimetics builds on this research and its results and implements the abstract concepts in technology. An important term is "functional principle", due to the fact that biomimetics does not have the objective to imitate and copy nature, but use it as a model and implement its concepts in an appropriate, useful and improving fashion in new or existing technologies. Mere imitation or copying of form is known as bio-inspiration. [Nachtigall and Wisser, 2013] [Nachtigall and Pohl, 2013]

The modus operandi of biomimetics in its shortest and simplest form is: **Research** → **Abstraction** → **Implementation**. [Nachtigall and Wisser, 2013] [Nachtigall and Pohl, 2013] A slightly extended version of this procedure, specific to academic research, can be seen in Figure 1 which was adapted from © Brose by Stegerer and Hollermann.

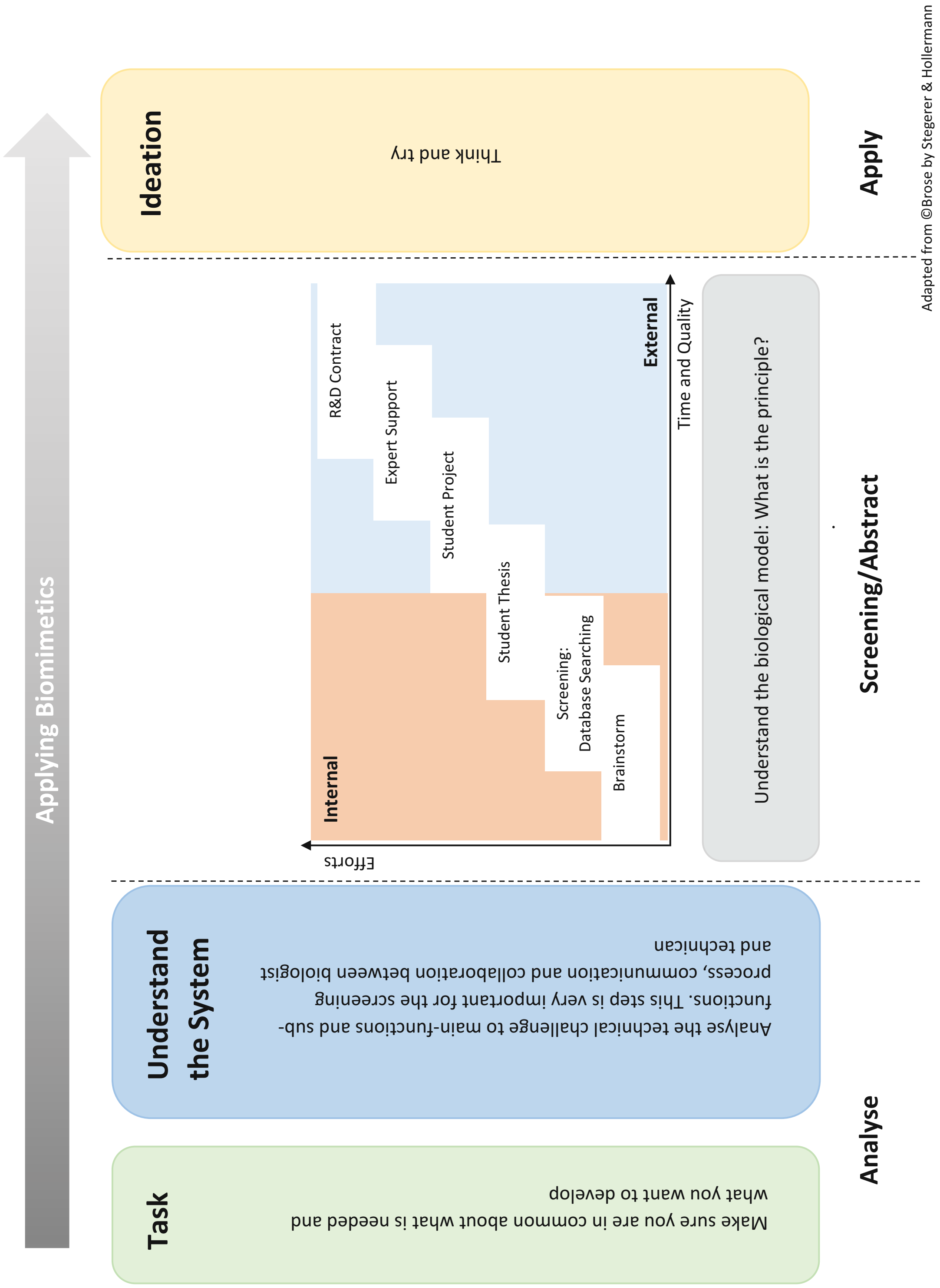


Figure 1: Applying biomimetics adapted from © Brose by Stegerer and Hollermann

Due to the interdisciplinary nature of biomimetics - combining multiple large fields of research, the most prominent ones biology and engineering - a shared language and clear terms and definitions have to be found. [Gebeshuber and Drack, 2008] [Gebeshuber et al., 2020]

Two prominent examples, which are usually mentioned, when introducing the field of biomimetics, are the hook-and-loop fastener, known as Velcro®, which is based on the burdock and the water-repellent house paint Lotusan® by the company STO®, which is based on the surface of the lotus leaf. The functionality of different biomimetic concepts is often based on structures, quite often in the range of nanometers and not on materials. One example for these concepts are the structural colors, which can be found on the scales of butterfly wings. Periodic nanostructures in the size of the wavelength of light on these scales result in non-fading colors, while being independent of the material. [Gebeshuber and Drack, 2008] [Nachtigall and Wisser, 2013] [Nachtigall and Pohl, 2013] [Gebeshuber et al., 2020]

Further information concerning the fascinating field of biomimetics is found in the extensive standard literature by Ingo Rechenberg, Wilhelm Barthlott and Werner Nachtigall as well as in more recent research by Ille C. Gebeshuber. [Gebeshuber et al., 2008] [Gebeshuber et al., 2009a] [Gebeshuber et al., 2009b]

1.2 The Human Gastrointestinal Tract

In an endoscopic examination an endoscope is used to examine parts of the human body which are difficult to access without operations.

The area of interest for endoscopic examinations is the gastrointestinal tract, which can be divided into four different parts: the esophagus, the stomach, the small and the large intestines. At the moment there are three different procedures at the disposal of a medical doctor who needs to examine all components: the gastroscopy for the first two organs, the capsule endoscope for the small intestine and the colonoscopy (a.k.a. coloscopy) for the colon. Since this is not a biological thesis, but a thesis related to a new design of endoscopes, only the surface and important parts for the endoscopy of the gastrointestinal tract should be covered in this introduction to gain an understanding of physics-related challenges and requirements. [Liu et al., 2015] [Zhong et al., 2015]

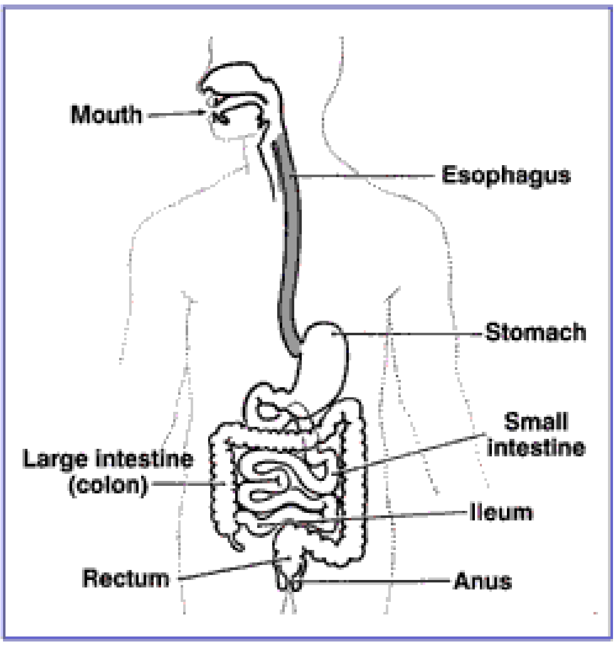


Figure 2: The human digestive tract (PD)

Figure 3: Capsule Endoscope (PD)

Figure 4: Flexible Endoscope, Rama, Wikimedia Commons, licensed under the Creative Commons Attribution-Share Alike 2.0 France license, URL:https://creativecommons.org/licenses/by-sa/2.0/fr/deed.en

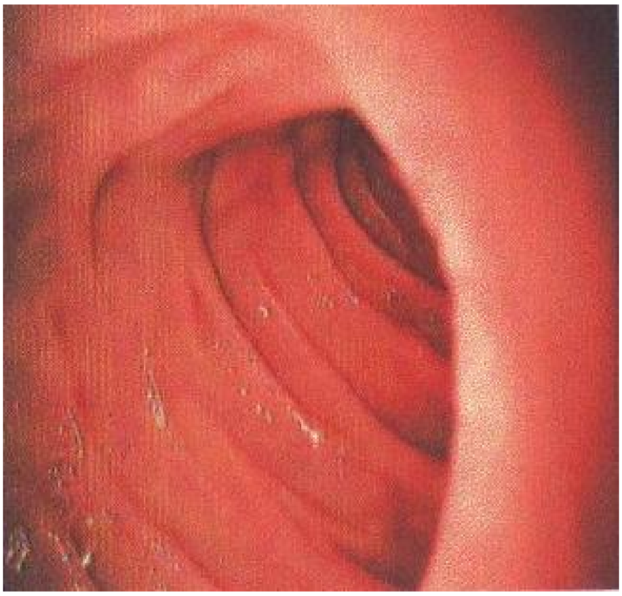


Figure 5: Human duodenum, picture taken with an flexible endoscope (PD)

Both small and large intestines can be divided into different parts of different diameters, which also are individual for each human. The colon has a diameter of around 6 cm and at the narrowest part of around 2.9 cm, the small intestine is even smaller with a diameter of around 3 cm and at the narrowest segment of around 1.5 cm. These limitations have to be taken into account when designing an endoscope, which has a diameter of around 1 cm, depending on the area, where the endoscope is used for diagnosis. The composition of colon and small intestine is similar, with the exception that the small intestine has villi to absorb chyme. Both have a lumen surrounded by mucus, which has to be taken into account when designing a locomotion system for an endoscope. Circular and longitudinal muscles are the origin of the motility of the intestines, which divides into two different motions: segmentation and peristalsis. For the passive capsule endoscope the peristalsis, which moves the food, is the predominant way of locomotion, while the segmentation, where the intestine compresses the food and reduces it to smaller pieces, is a simple task to withstand for the endoscope and to be considered when identifying suitable materials. [Phee et al., 1997] [Liu et al., 2015]

The journey of the capsule endoscope as it is today is simple: it is swallowed and the natural journey begins. In the small intestine the capsule endoscope starts taking time-controlled pictures in an optimum frequency and either saves them or sends them to a device outside of the patient. The optimum frequency in which the pictures are to be taken is important and difficult to determine due to the individual daily condition. On the one hand, if the peristalsis is slow and the frequency too high, there are multiple pictures of the same area and the battery might not last for the whole journey. On the other hand, if the peristalsis is quick and the frequency too little, there are gaps concerning the mapping of the small intestine. Another problem is the tracking of the location in the small intestine. Therefore, it would be desirable to design an active capsule endoscope, which can stop and traverse forward and backwards through the small intestine. So far the capsule endoscope is not usable for the colon, due to its natural collapsed state. [Kassim et al., 2006] [Liu et al., 2015] [Zhong et al., 2015]

The conventional colonoscopy is a long (around 30 minutes) and difficult procedure. The long insertion tube with manually steerable tip has to be inserted by the surgeon, while examining the patient. To help insertion and for better visibility the colon is inflated with air or CO_2 and has to be empty. [Phee et al., 1997] [Kassim et al., 2006]

1.3 State of the Art of Endoscopy

In the science of gastroendoscopy there are different approaches for the movement in the intestines. The four leading companies for endoscopy in Austria are Olympus, Storz, Fujinon and Pentax. Commercial endoscopes are in most cases moved manually by the medical doctor. Olympus has a special electromagnetic system to track the exact position of the endoscope to avoid complications during the examination. Fuji and Pentax further use a different method: They use one or two balloons on the endoscope to navigate and move through the intestines. Olympus has a special attachment for their commercial endoscope, which flattens colonic folds. [Bhattacharyya et al., 2016] [Kishioka, 2013] [Keuchel et al., 2015] [Ciuti et al., 2016]

In a review paper from 1997 by Phee et al. the future is painted in a brighter picture concerning the improvement of the endoscope:

> *"Within the next decade, it is probable that colonoscopy will utilize a miniature endoscopic "robot" that walks or glides up the colon, blasting polyps with a laser cannon while supplying spectroscopic tissue information for instant analysis, and marking the site of lesions on a holographic image of the patient's colon."* [Phee et al., 1997]

Regarding the fact that the flexible endoscope, first commercially available in 1969, is still the most widely used endoscope in medicine today, it feels a bit like the future has let Phee and his colleges down. In recent reviews by the team around Phee in 2003 and 2006 this part was dropped. [Phee et al., 1997] [Kassim et al., 2003] [Kassim et al., 2006]

Various attempts were made to replace or upgrade the currently used endoscope with all its flaws and advantages. Researchers often took inspiration from the locomotion of animals. These and other designs will be described in this introduction.

One early used model is the snake. In 1988 a snake-like active endoscope was designed with shape memory alloy springs, which could bend the endoscope and move it around obstacles in experiments via Joystick. However the endoscope was still pushed forward manually. [Phee et al., 1997] [Kassim et al., 2003] [Kassim et al., 2006]

Another design was proposed several years later: a flexible bead chain on a string was advanced through the tip of the endoscope, found its way through the colon and imitated its shape. After maximum insertion the bead chain was stiffened via pulling the string and the endoscope followed the bead chain like a train on tracks. When the endoscope tip reached the end of the chain, it was loosened and the process started again. This design was also presented under the model of a snake, probably because of the slithering nature of this particular endoscope. [Phee et al., 1997] [Kassim et al., 2003]

The Neoguide by Intuitive Surgical has multiple bending sections to imitate the natural form of the colon, nevertheless the endoscope is still advanced manually. [Yeung and Chiu, 2016]

There is a device called iSnake by Shang and colleagues, which consists of multiple articulated joints, which is also advanced manually. [Shang et al., 2011] [Yeung and Chiu, 2016]

One of the first animals which probably comes to mind when thinking about creatures moving their legless bodies through tubes is the earthworm. Several endoscopic designs rely on the peristaltic wave movement of the earthworm. Another animal which is always named alongside the earthworm is the inchworm with its two clamps around the extending midsection. Their two movements are often combined. There were several proposals and realizations concerning this type of movement. To imitate the extending of the earthworm some researchers used balloon-like extensions. To imitate the clamps of the inchworm, suction onto the colon wall was used by introducing vacuum and by producing a vacuum in the colon, sucking in the colon wall (like snails) and pinching it with the body of the endoscope as well as a needle based mechanism, which are both proposed in a design for an active capsule endoscope. Problems concerning the movement inspired by earthworm and inchworm are the friction between the endoscope and the colon wall, which is often slippery as well as the challenges from bends of the colon due to the relatively stiff nature of the robots. [Phee et al., 1997] [Kassim et al., 2003] [Kassim et al., 2006] [Hosokawa et al., 2009] [Liu et al., 2015] [Ciuti et al., 2016] [Yeung and Chiu, 2016]

Figure 6: Caterpillar using the Inchworm method for motion (picture taken by the author)

Figure 7: Earthworm (PD)

Two different designs were developed on basis of the movement of a millipede, with its legs and their wavelike movement. One with three inflatable cuffs by Utsugi in 1979, where the two outer cuffs move the middle one back and forth and provide adhesion to the colon wall. The other design by Allred in 1994 has numerous sets, which move in unison, of five small legs, which move out of phase to slowly advance the endoscope. The development of a u-shaped piezoelectric motor by Avirovik and colleagues in 2014 may lead to an even more natural movement similar to that of a millipede, which could further be used for endoscopes. [Kassim et al., 2003] [Kassim et al., 2006] [Avirovik et al., 2014]

Figure 8: Millipede (PD)

One fascinating commonality of ants and lizards is their ability to run on walls. Some even run upside down on the ceiling. A research group fabricated an endoscope with four legs and a camera as an eye, which could walk along the colon, although it could not overcome its bends. A combination of a legged creature and a snake is represented by the endoscope EndoCrawler which has been developed by Ng et al., which consists of different segments with legs. [Ng et al., 2000] [Kassim et al., 2003] [Kassim et al., 2006]

An often neglected feature of the octopus is fleeing rapidly by squeezing water from its mantle. This behavior was the model for a further type of endoscope, which is advanced by a water jet, streaming out of a nozzle behind the tip. [Kassim et al., 2003] [Kassim et al., 2006]

Naturally there are many designs by mechanical means, which shall not be neglected here. There is the seemingly obvious use of wheels and tracks, similar to those used on military tanks. There was also the proposal in 1976 of Masuda for a telescopic approach, with an everted tube, which pulls the endoscope forward, while unrolling under pressure. The last suggestion of locomotion is through the impact of a moving permanent magnet against two electrically magnetized stationary magnets. [Kassim et al., 2003] [Kassim et al., 2006]

The Aeroscope by GI View Ltd in Israel is comparable with the double balloon system, where a balloon at the front seals the colon and another balloon with pressure gradient propels the endoscope forward. [Yeung and Chiu, 2016]

One different relatively new commercial endoscope is the capsule endoscope. It is used for mapping and examination of the small intestine by simply letting the patient swallow it. It is moved passively through natural peristalsis and takes pictures throughout its journey. It is not usable in the colon, because the colon is collapsed in its normal state and little can be seen. There are various approaches to make the capsule endoscope controllable and active. This is discussed below. [Kassim et al., 2003] [Liu et al., 2015]

The main difficulties are the limited space of the capsule and the even without locomotion short living battery. The capsule should only have a maximum of 1.5 cm in diameter and 3 cm in length to allow the patient to swallow the capsule without pain or discomfort. [Liu et al., 2015]

The locomotion of inchworm and earthworm were not only used in the flexible endoscope design, but also for the capsule endoscopes. One interesting stopping and adhering method uses a microfibrillar adhesive inspired by beetles, which combines van der Waals forces and liquid adhesive forces. This special adhesive coats the end of legs, which adhere to the intestine wall. [Liu et al., 2015]

Another locomotion idea for capsule endoscopes which was covered by multiple research teams is by integrating paddles or legs. By either moving the paddles and legs or using the paddles to adhere to the intestine wall the whole capsule is moving forward by pulling on the platform where the paddles are mounted. One design by Li and colleagues in 2015 was inspired by ciliated cells, where the cilia act like legs. [Li et al., 2006] [Buselli et al., 2008] [Liu et al., 2015] [Ciuti et al., 2016]

Similar to the flexible endoscope locomotion of wheels, there is a design by Sliker and colleagues with six wheels for a capsule endoscope. While this capsule endoscope can move faster and is less power consuming it cannot stop or drive backwards. There also exists a capsule endoscope moved by treads. [Liu et al., 2015] [Ciuti et al., 2016]

There are different design ideas for swimming capsule endoscopes. One with a spiral form pushing back mucus by Chen and colleagues, one with a tip similar to a screwdriver by Liang and colleagues and the last one similar to a submarine with four propellers on the back to swim in a stomach filled with water by Tortora and colleagues. Similar to the last one there is an endoscope with a locomotion inspired by the flagellum of a cell or a tadpole by Zhong and colleagues, a flap-based capsule endoscope by two different research teams and a capsule endoscope with external water supply powered and oriented by water jets by Caprara and colleagues. [Liu et al., 2015] [Zhong et al., 2015] [Ciuti et al., 2016]

Another possibility for motion is via vibration, which easily overcomes the friction force and the gravity, while being less invasive and gentler than other already mentioned methods. It always needs to be kept in mind that patients that need endoscopy examinations might have extra sensitive intestines due to various diseases. [Liu et al., 2015] [Ciuti et al., 2016]

A seemingly violent approach was researched by Swain and Colleagues. By stimulating the intestine via electrical stimuli, which leads to contraction of the intestines, the capsule endoscope can be driven forward or backwards. [Swain et al., 2005] [Liu et al., 2015] [Ciuti et al., 2016]

A completely different approach was taken by Yoo and colleagues. To overcome size restrictions they used the model of molecules. They made four different capsule endoscopes, which assemble with magnets after being ingested. The three capsule endoscopes combined by the fourth one, each have a joint and can move. One problem concerning this design is the possibility of pinching the intestine when assembling the capsule endoscopes. [Yoo et al., 2014]

Opposed to the active internal movement treated above there is the possibility to move a passive capsule endoscope forward with the help of an external magnetic field. There are also attempts to combine an internal method with the external method by integrating legs into the capsule endoscope. [Liu et al., 2015] [Ciuti et al., 2016]

Not only for the locomotion of the endoscope animals are used as models, but also for the instruments at the end of the endoscope. These instruments are used for minimal invasive surgery. There exist instruments shaped like the claws of a scorpion and others imitating a stag beetle's leg. [Owaki et al., 2011] [Yeung and Chiu, 2016]

1.4 Macroscopic Models and Related Scaling Issues

All prototypes in this thesis are at a macroscopic scale, one or two orders larger in size than the final endoscope. This allows for fast and easy prototyping with the given equipment, but presents us with scaling issues. The developed prototypes are therefore not usable in any actual field tests and examinations involving intestines. The design and ideas need to be transferred and there is need to address scaling issues. Scaling issues always appear when working with Micro-Electro-Mechanical-Systems (MEMS), which is the case in this thesis about microrobots, like the tips of flexible endoscopes and capsule endoscopes. This subject will be discussed here.

"Scaling is intended as the set of effects which arise and/or change in their intensity when the dimensional scale changes by one or more orders of magnitude." [Baglio et al., 2008]

Each microrobot consists of three different parts: energy providers, microactuators, so the system can move and execute the task it was built for, and microsensors for internal and external information of the system. For the capsule endoscope (remember the restricted dimensions mentioned above of around 1.5 cm in diameter and 3 cm in length) all scaling issues of the parts of the microrobot are crucial. Whereas the energy source scaling issue can be neglected for a flexible endoscope, because it is normally connected to the medical doctor and the outside world by a cable. Therefore the energy source can be outside of the patient and use the available space of the doctor's office. [Baglio et al., 2008]

An important effect of scaling systems is the surface area to volume ratio. Considering a cube, which sides are scaled down by a factor of 10, the surface area of the cube reduces by 10^2, while the volume even reduces by 10^3. This has the very interesting effect of a mass reduction naturally proportional to the volume, while the friction of the cube is only $^1/_{100}$ compared to the original cube. [Baglio et al., 2008]

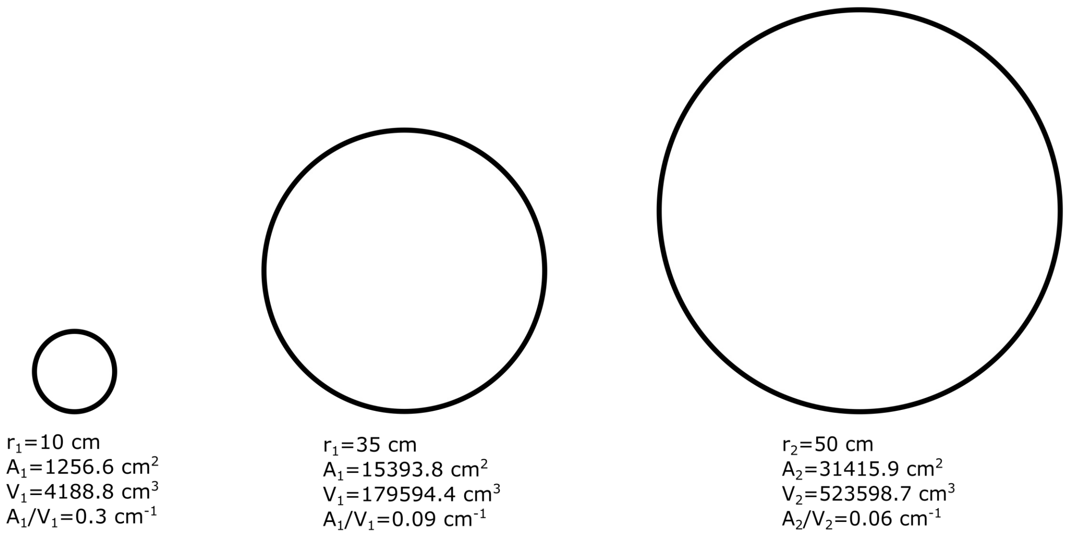


Figure 9: Sketch to illustrate the change of the surface area to volume ratio of spheres

To address once again the biomimetic aspect of this thesis, the surface area to volume ratio is an important factor in the growth of penguins. The colder the habitat of the penguins, the bigger the penguins, due to the smaller surface area to volume ratio and the therefore relative smaller area, where the penguin can lose body heat. This explains that the Emperor Penguins in Antarctica are taller than the Galapagos Penguins near the equator. [Gales, 1987] [Schlichting and Rodewald, 1988]

There is a phylum of animals, which is restricted in its growth by the surface area to volume ratio: the Arthropoda, with the most prominent members insects and spiders. Firstly, since Arthropoda have instead of a skeleton a chitinous exoskeleton which covers the surface area of the animal, the volume and hence mass increase quicker compared to the surface area and can no longer be supported by the exoskeleton. This would be deadly for the animal, especially in the skinning phase. Secondly, insects and spiders have tracheae instead of lungs, where the surface area of the tracheae is crucial for the oxygen intake. For an increased volume the surface area of the tracheae would not suffice for the insects cells needed oxygen intake and it would therefore suffocate. In the prehistoric times, when the oxygen content was higher, giant dragonflies and millipedes roamed the earth and their fossilized remains and their models can still be seen in museums. [Schlichting and Rodewald, 1988] [Lloyd, 2007] [Than, 2011]

Different materials behave differently at different scales, and can even gain from being scaled down. For example: a cantilever beam made of a uniform and isotropic material can achieve improved mechanical robustness by being linearly scaled down by a factor of 10. While the weight ($\propto l^3$) of the cantilever reduces by a factor of 1000, its elastic constant ($\propto l$) only reduces by 10, which means the new cantilever is only 10 times less stiff. [Baglio et al., 2008]

This in addition to other typical material specifications, such as elastic modules, fracture stress etc. has to be taken into account, when scaling down mechanical sensors, which are used to measure mechanical properties. Thin-film materials are used in micromechanical sensors which behave differently than the bulk materials in their macroscale counterparts. For micromechanical sensors the surface area to volume ratio is an important factor. Since the ratio increases compared to the macromechanical sensors, the surface area has to be taken into consideration more thoroughly. Therefore, for instance gravity and inertial forces, which can be troublesome in macroscale mechanical sensors or have to be carefully attended to at least, can be neglected in the microscale. This is naturally an advantage, unless you want to measure exactly these effects, which then can be very challenging. [Baglio et al., 2008]

Microactuators convert energy from the energy source into movement. In the case of this thesis, magnetic microactuators might be used in motors to propel the future endoscopes forward, which are based on the prototypes developed in this thesis. Magnetic actuators on the macroscale behave differently than on the microscale. This affects the assumptions typically made for the magnetic actuators on the macroscale: they can no longer be successfully realized on the microscale. This is very important for this thesis, since the prototypes are built in amplified size and it has to be considered, when the prototypes are implemented in their actual desired size. Magnetic actuators include a gap in the magnetic circuit between the movable part of the actuator and the magnetic core. While the reluctance of the core can be neglected in comparison to the reluctance of the gap, this is no longer the case when the actuator gets transformed into the microscale. In the design of magnetic microactuators the maximum generated force is achieved when the reluctance of the gap and the core are equal. [Nami et al., 1996] [Baglio et al., 2008]

Electric energy providers should be of no concern in this thesis, due to the ongoing promising research.The electric energy providers of the prototypes will be not included in the descriptions and dimensions. Energy consumption and efficiency will not be taken into account in this thesis.

The next chapter will deal with the Materials and Methods used in this thesis.

2 Materials and Methods

2.1 Testing Tube

In order to determine the variation of the dimensions of the animal or plant and subsequently the endoscope, a method will be needed that does not stress or hurt the animal. The solution for this is an elastic hose with a fine-meshed net. The net is photographgraphed in the event of a penetration and the resulting pictures will be analyzed with GIMP 2.10.18 (GNU image manipulation program). [The GIMP Development Team, 2020] The hose is darkened in the different pictures and five progressing pictures are overlaid for direct visibility.

2.2 Testing the Testing Tube Method

To test if the method was feasible, a woolen sphere with a diameter of 5 cm connected with a wooden half sphere with a diameter of 2 cm was pulled through two different insect nets. The first insect net (Insect-Stop Fliegengitter, Windhager HandelsgesmbH, Thalgau, Austria) has quadratic holes with a length of around 1 mm and the second insect net (Insect Stop, Emil Lux GmbH & Co., Wermelskirchen, Germany) has hexagonal holes with a length of around 1 mm. It should be noted that both nets only stretch in one direction, the other direction has to be inflexible for integrity. This anisotropy has to be taken into account, when rolling the hose into a tube.

2.3 Movable Wall

In order to reduce the strain on the sensitive colon walls, the force which the prototypes apply on the colon walls is important to cover in this thesis. The experiment to measure this force is realized with a movable wall (Figure 10). The movable wall (b) is a small wall on wheels (a) on rails (d) built with interlocking bricks on fleece (c), which is mimicking the rough and soft colon walls. This wall is connected to a spring balance (Figure 11) (b) with a measure range of 1 N with a thin wire. The spring balance is fixed on a specifically with MATADOR® built stand (a), which allows it to be in its required position. The wire gets redirected by a wheel (c), from horizontal, which is needed for the movable wall to vertical, which is needed to measure with the spring balance. The wire is strained so it does not touch the ground (red arrows).

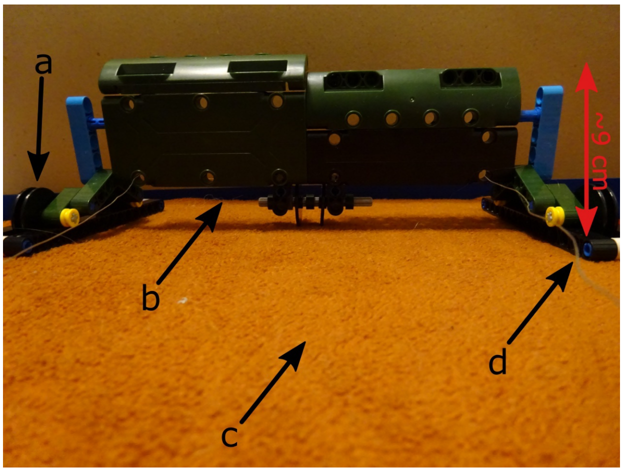


Figure 10: Movable wall: (a) wheels (b) wall built with interlocking bricks (c) fleece mimicking the rough colon walls (d) rails

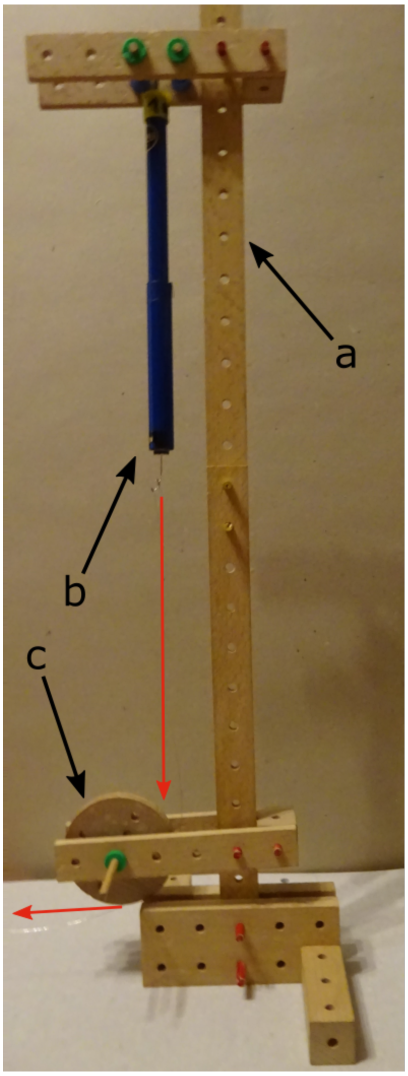


Figure 11: The spring balance on its stand: (a) stand (b) spring balance (c) wheel redirecting the wire (the red arrows indicate the course of the wire)

There were three different experiments executed with the movable wall. Firstly, the initial force of the locomotion system on the movable wall was measured with the spring balance. Secondly, the maximum force of the locomotion system was measured with the spring balance by applying force on the movable wall by the prototypes until the wall no longer moved or the locomotion system started to turn itself. Finally, the maximum weight on the movable wall the locomotion system can move was determined by fixing a bag to the back of the movable wall and filling it with sand until the prototype was no longer able to move the wall. This sand weight was then measured with a scale. The movable wall and the prototypes were moving on fleece to mimic the soft and rough surface of the intestines and therefore provide a good comparison.

2.4 Pressure Measurement Foils

Special foils named Prescale (FUJIFILM Corporation, Tokyo, Japan) were used in this thesis. Prescale Foils can display a range of pressures in shades of pink and are mainly used in quality control of industrial products. These foils can show the area and intensity of the pressure applied by animals or endoscopes (and their models), when traversing over the foil or through a hose formed by the foil.

There are different types of foils for different pressures. The foil type used in this thesis is the Ultra Extreme Low (5LW) type. It displays pressure impacts ranging from 0.006 MPa to 0.05 MPa. Due to the fact that the foils are only sensitive in a specific pressure range, the pressure of the particular implementation has to be calculated in advance to choose the right foil. In this thesis the following foil types were available: Ultra Extreme Low (5LW), Extreme Low (4LW) and Ultra Super Low (LLLW).

There are two versions of foils: the two sheet type (W) and the Mono-sheet type (S). For low pressures up to 10 MPa the two sheet type is necessary, which means the foil is stored and transported in its two components to prevent the foil from being triggered accidentally before usage and has to be combined with caution by hand before application. For higher pressures over 50 MPa the mono-sheet type is standard. For the pressure between 10 MPa and 50 MPa the Prescale foil exists in both executions. All foil types mentioned above have the "W" as their last character in their abbreviation and are therefore executed with two sheets.

The foils were used as a screen for the pressure markings of the moving prototypes and to analyze the parts in contact with the ground. In this thesis there is no need for a detailed analysis of the different pressures of different parts of the prototypes. If the concepts of the prototypes are used and improved in further projects, there may be the necessity of a special scanner and a special software to analyze the foils and their results of these improved prototypes more thoroughly.

An interesting question was the operating mode of the foils. In the documentation the setup of the foils (Figure 12) and the technology of the foils (Figure 13) is described in detail. However there was nothing found concerning the functionality and implementation of the software nor the explanation how the intensity of the color, which indicates the pressure, comes about. Examined under a microscope (Inskam 316 WiFi digital microscope; Inskam, Shenzhen, China) the differentiation between two different pressure markings (Figures 14 and 15) seems to be a difference in density and size of dots. Without technological assistance there cannot be distinguished a difference in color intensity. Supposedly the software analyzes the density and size of the dots and generates a coherent picture with different shades of pink to indicate the different pressures. It is entirely possible that the intensity can be distinguished for a different application with larger contact surfaces without the software, but the contact surfaces of the prototypes are small and the foils were therefore only used to screen their pressure markings. These results can be used in further research to improve the prototypes, which is indicated in Chapter 3.4.

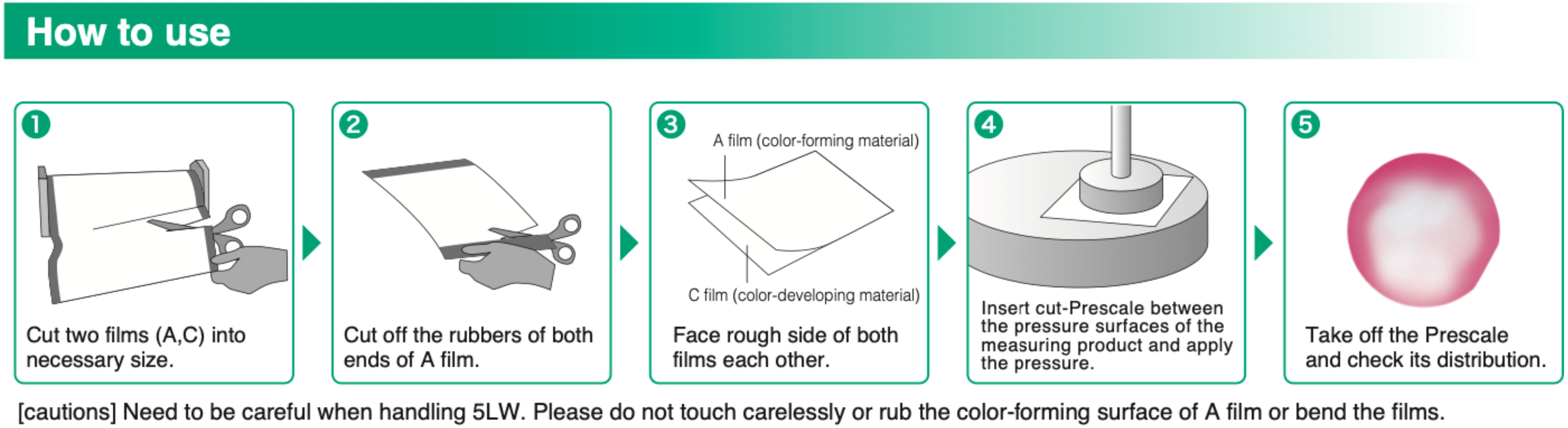
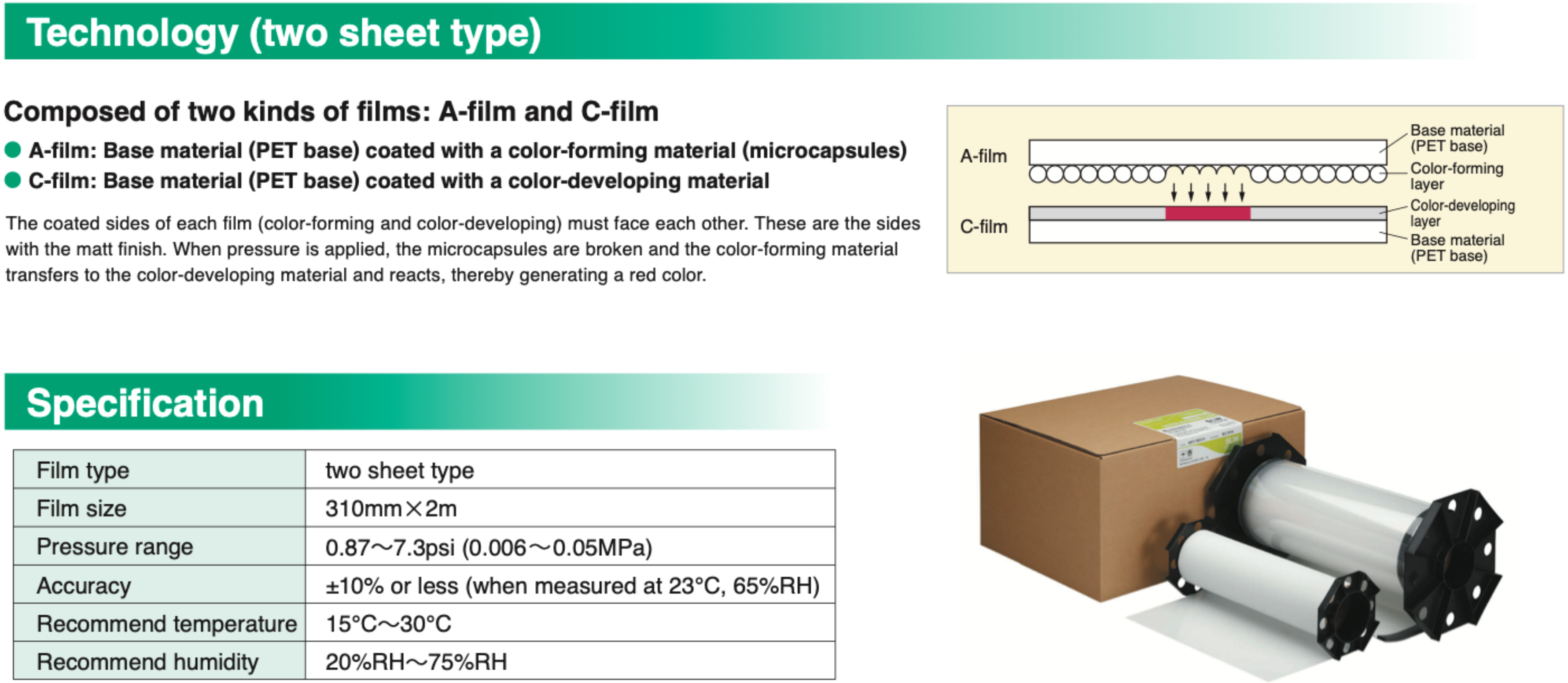


Figure 12: Description of the utilization and the setup of the Prescale Foils taken from the official documentation of the PRESCALE Pressure measurement film ultra extreme low two sheet type which can be found at the internet page https://www.fujifilm.com/products/measurement_film/en/prescale/pdf/PRESCALE_5LW_E_0726.pdf



Technology (two sheet type)

Composed of two kinds of films: A-film and C-film

- **A-film: Base material (PET base) coated with a color-forming material (microcapsules)**
- **C-film: Base material (PET base) coated with a color-developing material**

The coated sides of each film (color-forming and color-developing) must face each other. These are the sides with the matt finish. When pressure is applied, the microcapsules are broken and the color-forming material transfers to the color-developing material and reacts, thereby generating a red color.

Specification

Film type	two sheet type
Film size	310mm×2m
Pressure range	0.87～7.3psi (0.006～0.05MPa)
Accuracy	±10% or less (when measured at 23°C, 65%RH)
Recommend temperature	15°C～30°C
Recommend humidity	20%RH～75%RH

Figure 13: Description of the technology behind the Prescale Foils two sheet type and the specifications of the Prescale Ultra Extreme Low (5LW) taken from the official documentation of the PRESCALE Pressure measurement film ultra extreme low two sheet type which can be found at the internet page https://www.fujifilm.com/products/measurement_film/en/prescale/pdf/PRESCALE_5LW_E_0726.pdf

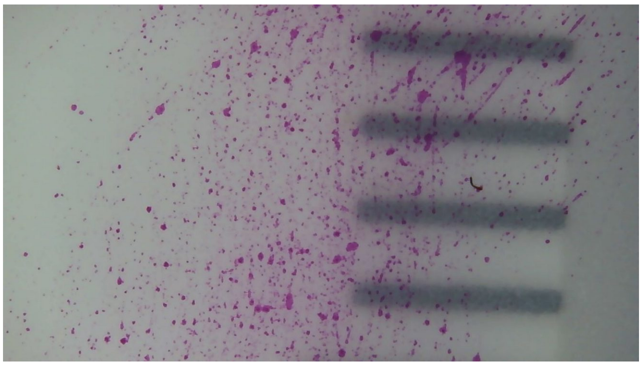


Figure 14: Pressure markings of a lower pressure under the microscope (space between two black lines: 1 mm) photograph taken with Inskam 316 WiFi digital microscope

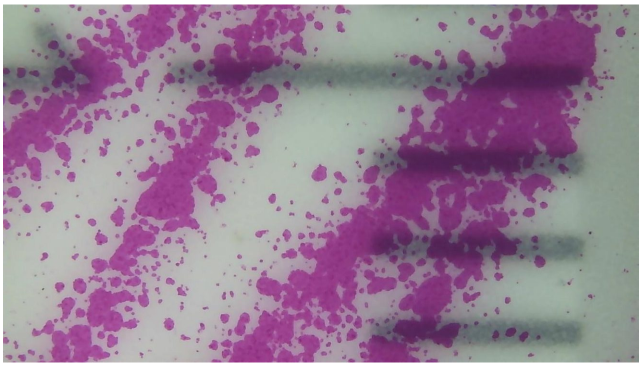


Figure 15: Pressure markings of a higher pressure under the microscope (space between two black lines: 1 mm) photograph taken with Inskam 316 WiFi digital microscope

2.5 Interlocking Bricks

Interlocking bricks were chosen as building material for the prototypes. The parts are finished and can be easily assembled and disassembled in a creative way, when errors occur or new ideas pop up. The most prominent corporation for interlocking bricks is the LEGO® corporation, but there are various companies offering interlocking bricks. Next to three different LEGO® sets (LEGO® Mindstorms® EV3 [31313], LEGO® TECHNIC Remote-Controlled Stunt Racer [42095], LEGO® Mindstorms® NXT [8527/8547]) a Qihui set (Qihui Panzer RC [8011]) was used in this thesis.

The strategy behind using interlocking bricks is that one is not tied to a complex and often expensive software and an extensive design process, without knowing for sure if the product will handle as planned. The quick design and building of prototypes with interlocking bricks is bound with less frustration compared to a process starting from scratch, if unforgiving misfits or errors occur after many hours of designing, fabricating and building the project. The sets can also be used for further projects and are therefore even cost-effective and long-lasting, since the parts are not uniquely fabricated for a specific project. The limited number of parts and their predetermined shape can pose a challenge of creating something completely new. Designing from scratch is more flexible and will be inevitable in the long run of the project, but the idea can be implemented in an easy and relatively quick way, with the satisfaction of quickly being able to identify promising approaches. Interlocking bricks can provide the foundation of the project, which can always be extended.

The LEGO® Sets Mindstorms® EV3 and its older equivalent Mindstorms® NXT contain different sensors and motors. In this work the infrared sensor and the touch sensor, which has the two states "pressed" or "not pressed", were used. All motors and sensors are powered and controlled by the EV3 Brick which is a programmable device contained in the Mindstorms® EV3 Set. In the table below the specifications of the different motors are compiled, taken from the official LEGO® website (LEGO.com), expanded with [Kmieć, 2013] and [Hurbain, 2020].

Table 1: Motor specifications taken from [Kmieć, 2013], [Hurbain, 2020] and LEGO.com

Motor	**rotational speed**	**running torque**	**stall torque**
NXT Large Servo Motor	82-117 RPM	16.7 Ncm	50 Ncm
EV3 Large Servo Motor	160-170 RPM	20 Ncm	40 Ncm
EV3 Medium Servo Motor	240-250 RPM	8 Ncm	12 Ncm
TECHNIC Power Functions L-Motor	380 RPM	6.48 Ncm	18 Ncm

2.6 Programming the LEGO® Mindstorms® EV3 Brick

The LEGO® Mindstorms® EV3 Brick powers the motors and receives and sends information from and to the sensors. The programming software used is the LEGO®

Mindstorms® EV3 Software which is powered by LabVIEW® by National Instruments®. It is an icon-based programming language that mimics the interlocking bricks nature of LEGO® even in the programming interface. The programming blocks used in this thesis shall be described in this chapter.

All used programming blocks are given in Figure 16. Every program starts with the **start** block (1). The next two blocks are the **large motor move tank** blocks (2 and 3) which power the two large motors. These blocks have different modes. They can be on (a) or on for a certain time (e) which can be defined in seconds (h). Each motor is regulated separately from -100% (backwards) to 100% (forward) (b, c, f and g). While the second block results in the system driving forward, block three results in a left turn for 1 second (h) with a brake after 1 second (i). The outputs (d), where the motors are connected to the EV3 Brick, can be selected in the top right of the large motor move tank blocks. The fourth block is a **loop** (4) which repeats any string of blocks inserted in this block. The number of passes (j) can be selected. This block is set to infinite loops in the example below. The last block is a **switch** (5) where the state of the touch sensor (l) is monitored (k). If the wished state (m) is registered the string of blocks within the true box (o) is executed, if the touch sensor is not in the wished state the string of blocks in the false box (p) is executed. The output (n) where the sensor is connected to the EV3 Brick can be selected in the middle of the block.

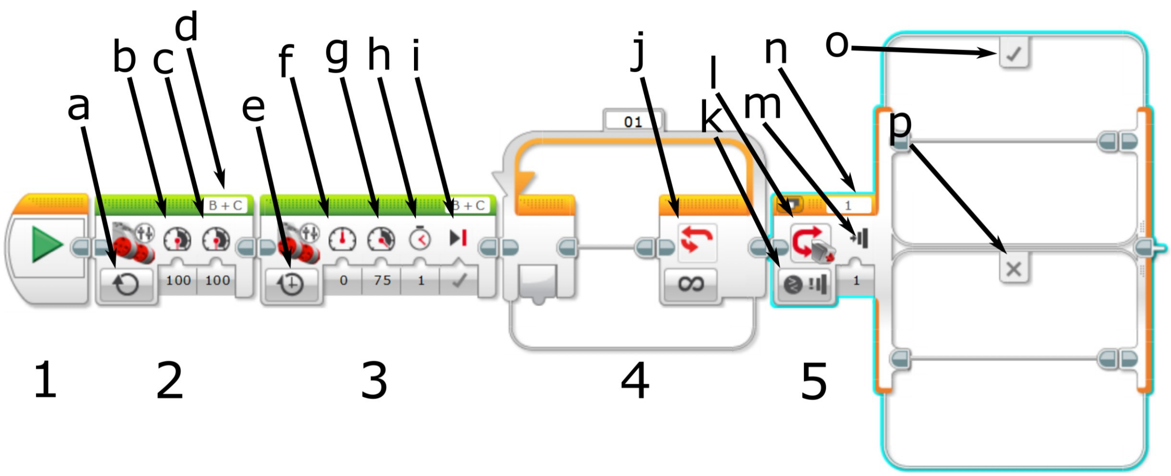


Figure 16: Used Programming Blocks of the LEGO® Mindstorms® EV3 Software

Below is a list of the programming blocks of the LEGO® Mindstorms® EV3 Software used in this thesis:

- start (1)
- large motor move tank (2 and 3)
- loop (4)
- switch (5)

3 Results and Discussion

3.1 Results of the Testing Tube Method

While testing the testing tube method with the sphere with the attached half sphere, multiple things became apparent. First and foremost, there is a significant difference between the two nets. The net with the quadratic holes is less flexible than the net with the hexagonal holes. It buckles behind the sphere and the bulge is hard to document on the pictures. The development of the movement through the net hose could be seen more clearly with the net with the hexagonal holes.

Another aspect, which has to be considered, is the restricted freedom regarding the fixation of the net to an inflexible board. The net has to be fixed to the ground to keep it from slipping and rolling. This results in the asymmetric nature of the nets. Would the net hose exist in zero gravity, the results of the sphere with the attached half sphere moving through the hose would be rotationally symmetric. Since the net has to be fixed to the ground, the half sphere facing down has not the same freedom as the half sphere facing up and the bulge of the half sphere cannot be seen, while the bulge of the sphere is more prominent. When the half sphere is pointing down, the sphere has to be balanced with two strings, since the sphere tries to rotate due to gravity. Balanced with the strings, this movement can be prevented. This problem is sketched in Figure 17.

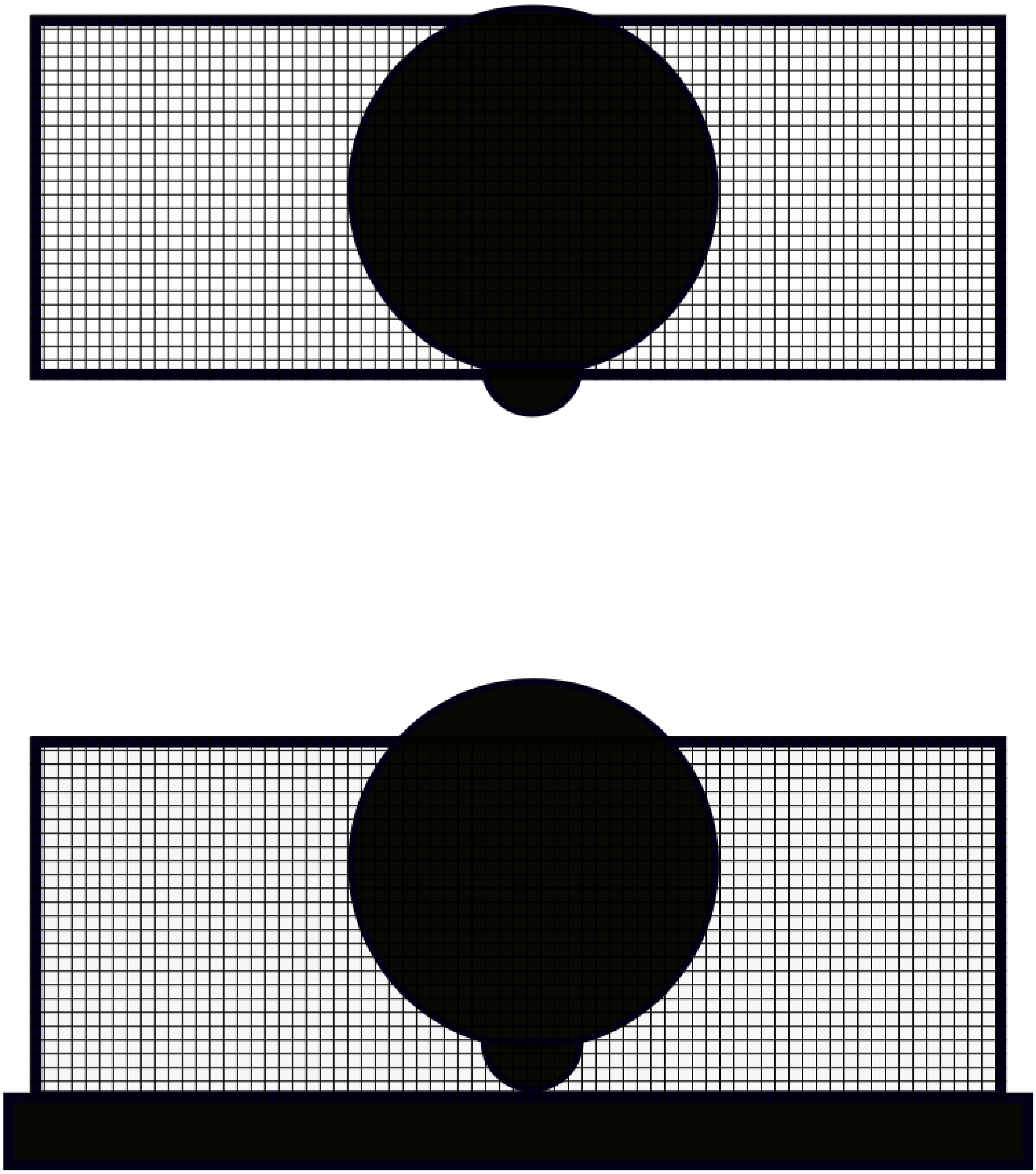


Figure 17: Sketch to illustrate the restricted freedom regarding the fixation of the net (top: net hose without fixation; bottom: net hose with fixation)

During the experiment pictures were taken for each net type (quadratic and hexagonal holes), each camera position (from above, front view, sketched in Figure 18) and each position of the half sphere (as seen from the front: up, down, front, back, sketched in Figure 19) at five different positions of the sphere in the net hose. The sphere with the attached half sphere was pulled through the net hose and stopped at five different positions to take the picture. This is sketched in Figure 20. To analyze the experiment the five pictures of each series were first edited so the net and its deformations were clearly visible in black and then these edited pictures were superimposed, which should theoretically show the bulge of the sphere with the attached half sphere as sketched in its ideal form in Figure 21. The different positions of the sphere with the attached half sphere can be distinguished by the different levels of gray.

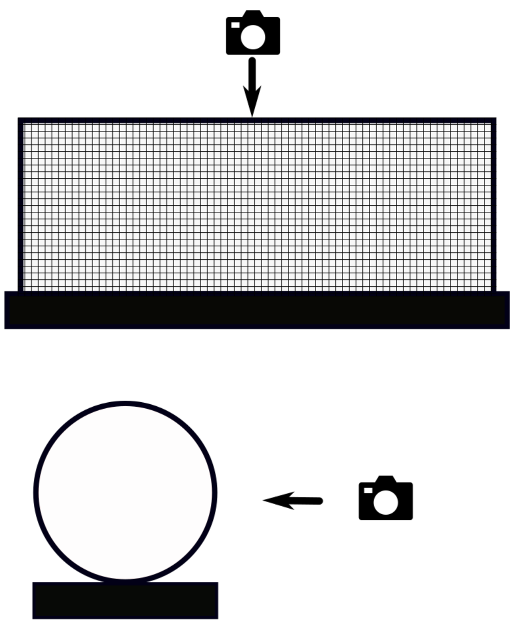


Figure 18: Sketch to illustrate the two positions of the camera

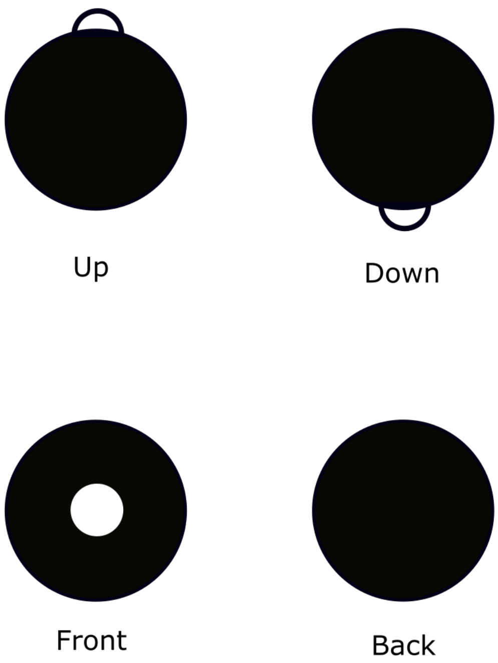


Figure 19: Sketch to illustrate the four positions of the half sphere as seen from the front

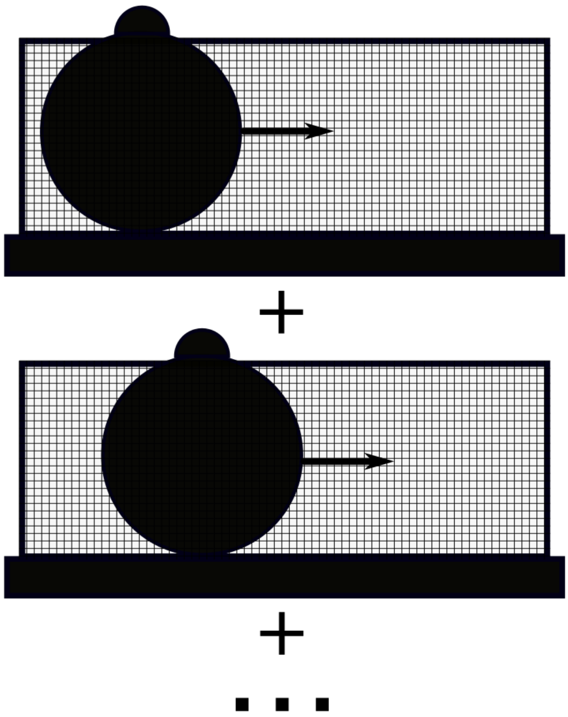


Figure 20: Sketch to illustrate the different pictures of the sphere in the net hose

Figure 21: Sketch to illustrate the ideal case of the superimposed picture

The experiment results in 16 different pictures by combining both net types and both camera positions with each position of the half sphere. Only four exemplary pictures of these pictures should be placed in this thesis to not go beyond the scope of this thesis. The following figures of this experiment appear blurred, since there are five pictures superimposed in one figure and it is nearly impossible to avoid movement of the camera between the shots and align the different shots perfectly.

All following figures have four icons in the lower left corner. They describe the type of net (hexagonal or quadratic holes), the position of the camera, the position of the sphere with the attached half sphere and the direction of movement. The icons of the position of the camera and the position of the half sphere are taken directly from Figures 18 and 19.

Figures 22 and 24 are from the sphere with the attached half sphere in the net hose with the hexagonal holes. Figures 23 and 25 are from the net hose with the quadratic holes. For better comparison the same position of the half sphere is observed in both net types. The chosen position for the pictures taken from the front is the half sphere facing up and the chosen position for the pictures taken from above is the half sphere facing the back. These positions were chosen to illustrate an approximated version of a problem similar to the one sketched in Figure 17.

In Figure 22 the half sphere faces up in the net with the hexagonal holes. The bulge can be beautifully followed, due to the unyielding nature of the fixation. Figure 22 approximates the ideal case sketched in Figure 21 with slightly smoothed bulges of the half sphere.

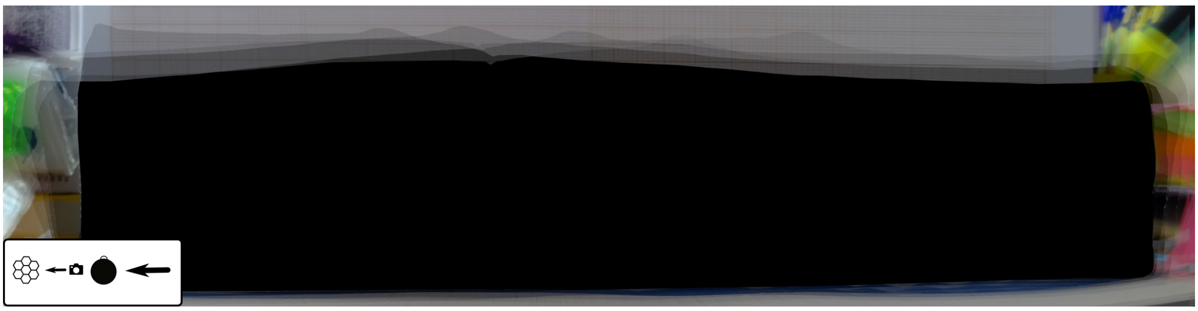


Figure 22: The superimposed picture of five positions of the sphere with the attached half sphere in the net with hexagonal holes where the half sphere faces up. The pictures were taken from the side. (direction of motion: right to left)

In Figure 23 the half sphere also faces up. In contrast to the net with the hexagonal holes, the buckling of the net with the quadratic holes can be seen directly behind the half sphere at each position, where the net has a sharp kink, while the bulge itself is hard to see, because the net is so inflexible. This is not ideal for the purpose of this method.

Figure 23: The superimposed picture of five positions of the sphere with the attached half sphere in the net with quadratic holes where the half sphere faces up. The pictures were taken from the side. (direction of motion: left to right)

In Figure 24 the half sphere faces the back of the net with the hexagonal holes. Nevertheless, bulges can be noticed in both directions in Figure 24. So not only the half sphere is deforming the net hose, but the sphere itself as well. The net adumbrates the nature of the half sphere, even though it is not as clear as sketched in the ideal case. The sharp transition of half sphere in sphere is slightly smoothed.

Figure 24: The superimposed picture of five positions of the sphere with the attached half sphere in the net with hexagonal holes where the half sphere faces the back. The pictures were taken from above. (direction of motion: right to left)

In Figure 25 the half sphere faces the back in the net with the quadratic holes. Extreme buckling can be seen at the opposite side of the attached half sphere, while the bulge of the half sphere itself is hard to see. The net deforms in front of the half sphere adequately, while it strains behind the half sphere. This means the sphere with the attached half sphere deforms not only the area of interest where the sphere with the attached half sphere is at one moment, but the whole net hose. This can be seen in the straining and buckling. This makes it hard to quantify the deformations which can be important in future applications of this method.

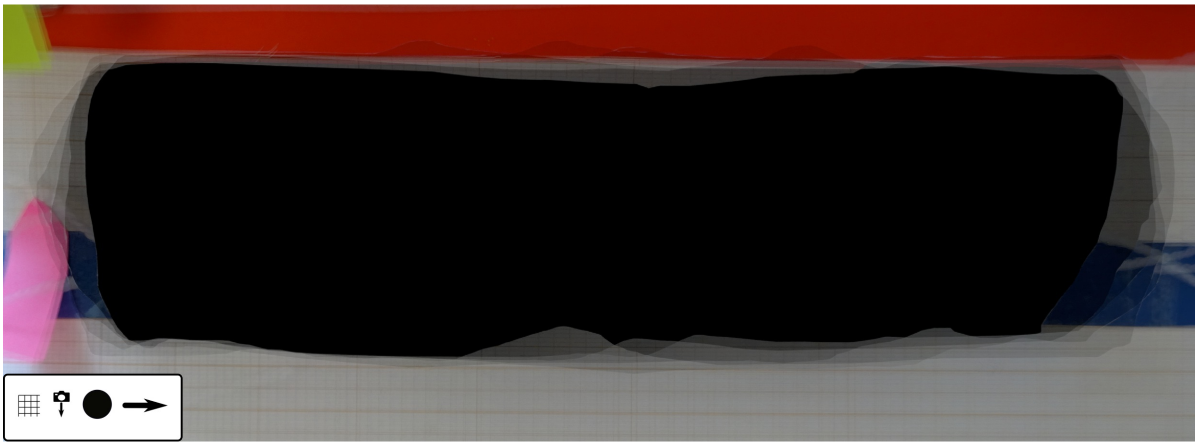


Figure 25: The superimposed picture of five positions of the sphere with the attached half sphere in the net with quadratic holes where the half sphere faces the back. The pictures were taken from above. (direction of motion: left to right)

Lastly the results from the pictures not analyzed and shown in this thesis shall be summarized: When the half sphere is parallel to the camera axis (front and back for the camera in front and up and down for the camera above), some bulge can be still seen in the net hose with the hexagonal holes, while the variations in the net hose with the quadratic holes resemble noise more than quantifiable bulges of the sphere with the attached half sphere. The pictures taken from above of the half sphere facing the front in both nets are nearly identical - although mirrored - to the ones described above. For the pictures taken from the front with the half sphere facing down, the following observations can be made: the bulging in the net hose with quadratic holes when the half sphere faces down is extreme and hardly quantifiable and usable for any applications, while the net with the hexagonal hose in the same situation is still analyzable. Therefore it is concluded that the net with the hexagonal holes is more suitable for future applications of this method.

3.2 Biomimetic Locomotion Systems

All systems described below use cables of different length and the EV3 Brick of the LEGO® Mindstorms® EV3 Set. The EV3 Brick was programmed appropriately for backwards and forward motion as well as turning when using two motors. The names of the interlocking bricks were taken from [Kmieć, 2013].

An important point, which is common sense and instinctive for animals is the continuous shifting of the balance point. This is hard and nearly impossible to achieve in robots. This was very interesting to observe in the prototypes, by simply pushing the front or the back of the prototype and observing its behavior.

All prototypes were updated and enhanced over the course of the diploma thesis and may look different than originally described.The details of the enhancements are described in the respective sections. Note that the principle of movement stays the same and is not affected by the improvements.

In the following sections, these prototypes are described in detail: The SNAKE prototype, inspired by snakes, the MOLE prototype, inspired by moles and the FOOTSTEP prototype, inspired by tetrapod vertebrates.

3.2.1 SNAKE Prototype

Snakes move their slender bodies forward using their scales, which flatten smoothly, when the muscles pull them forward and drill into the ground, when the snake pushes of the ground to move forward (Figure 26). Inspired by the scales of snakes, a locomotion system was designed, which may not be very efficient and fast, but smooth and minimal in parts and undesirable extra motion. By simply attaching three parts on each side in opposing holes on the rotating disc of the large motor, a creeping motion similar to a snake pushing forward on its scales is achieved. The three parts are: a blade of 7.5 cm length with the saw-toothed side facing the ground, a height of the saw-teeth of 0.5 cm and a distance between two tips of the saw-teeth of 0.7 cm, a part with a round and a cross hole with a 90° angle (connection piece) and a connector peg without friction to connect the last part to the rotating disc. All interlocking bricks are from the LEGO® Mindstorms® EV3 Set. It is important that the middle part can spin on the last part, to allow the bioinspired snake scales to touch the ground at all times, so the motor can push off of them and move the whole prototype. Since a mechanical solid part cannot change its scales and move the smooth scales forward by muscle contraction, the two saw-toothed blades need to be attached in a shifted manner, so one of the blades can lift up and move forward, while the other one on the ground pulls the system forward. However, unlike the snake, the upgraded system has an additional technical feature: it can also move backwards, due to the fixed and symmetric scales. An elastic band is needed in this simple prototype to keep the system stabilized and the parts from slipping away under the motor. The tip of the saw-toothed blade can move back and forth, but is restricted in its vertical movement by the rubber band. Because one motor is used, the system cannot turn by itself. However it turns very easily when encountering a barrier. This is addressed in detail below. A small issue concerning the use of the interlocking bricks is the rigidness of the cable connecting the motor to the EV3 Brick, which powers the motor. The cable is twisted and the rigidness of it countersteers against the twisting, therefore twisting the motor. Hence the cable has to be supported by hand, to avoid the tilting and overturning of the motor. The locomotion systems can be build by using either the motors of the Mindstorms® NXT Set or the new updated motors from the Mindstorms® EV3 Set.

It is very interesting to observe the behavior of the SNAKE prototype when changing the balance point. By pushing on the front of the prototype, the SNAKE prototype moves forward as described, when the motor operates in forward mode. By pushing on the back of the prototype and shifting the balance point to the back, the prototype moves backwards even though the motor still operates in forward mode. For further experiments the prototype was adapted with wheels at the back to shift the balance point permanently to the front and also prevent the prototype from overturning.

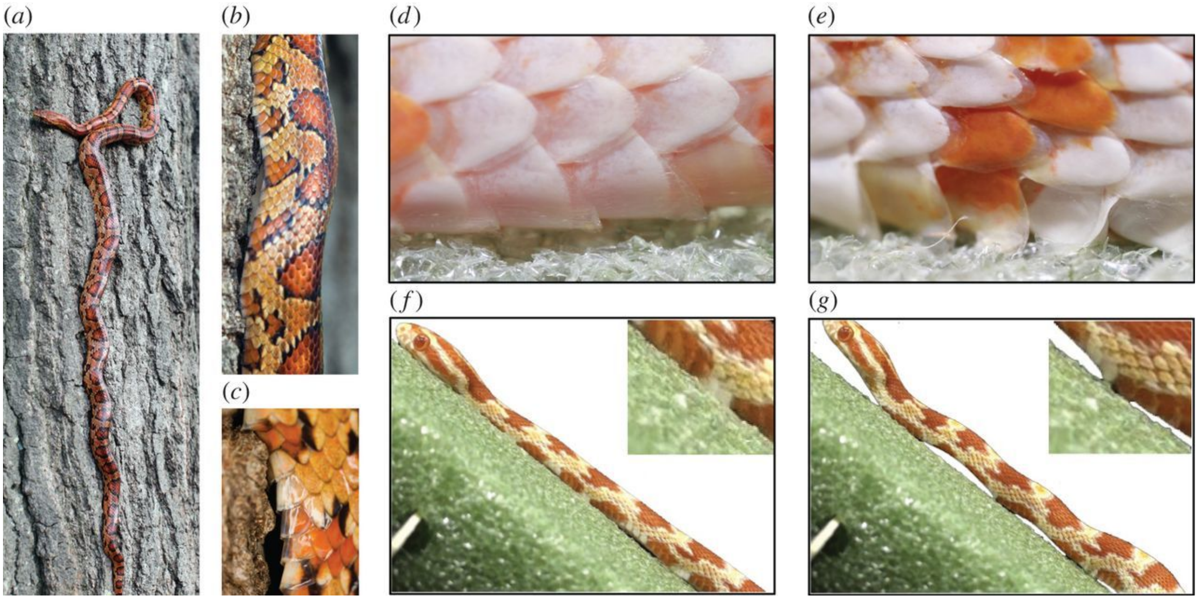


Figure 26: (a) A corn snake ascending a tree. (b,c) Scales are used to grip tree bark asperities. Snake scales at their (d) minimum and (e) maximum angles of attack (flat). (f,g) A snake climbing an inclined surface. Sliding is prevented by emergency braking associated with lifting of the body. © 2012 The Royal Society. Figure and caption directly taken from [Marvi and Hu, 2012]

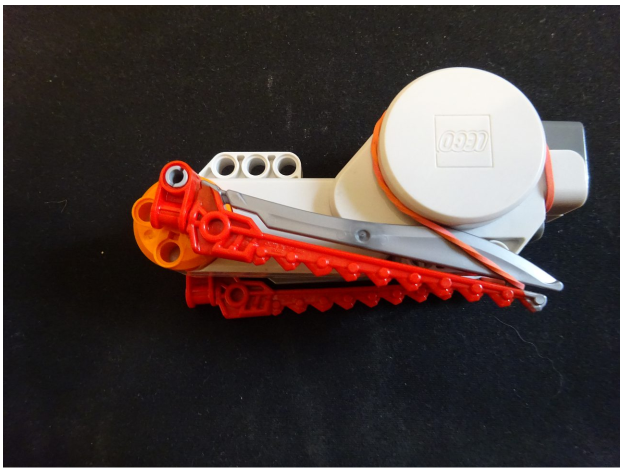


Figure 27: SNAKE: Locomotion system inspired from snake scales

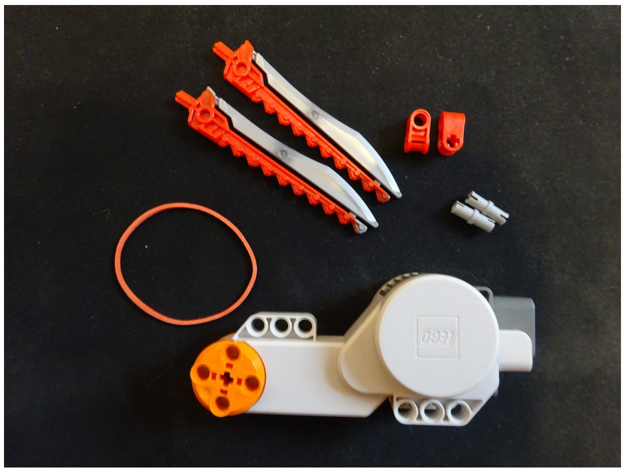


Figure 28: LEGO® Bricks used for the locomotion system in figure 27

The issue of the missing ability of the SNAKE prototype to turn was attempted to be solved by a second identical system fixed to the first one by a rectangular frame-like interlocking brick. Although the issue of turning was not correctable by this attempt, neither by using one motor in backwards or forward mode to turn nor by driving one motor backwards and the other one forward, the modified system behaved in odd ways. The system still moved forward, while both motors were in reverse mode. Therefore this modified system was not considered any further in this study and the snake scales imitating locomotion system was further used in its original simple form.

At https://owncloud.tuwien.ac.at/index.php/s/FCKvH4j2R86Mhba the SNAKE prototype can be watched in action (3 s video).

3.2.2 MOLE Prototype

The MOLE prototype was inspired by an animal wandering through tunnels, which is comparable with an endoscope and therefore very interesting: the mole. The mole pulls its body through the ground with large hands similar to shovels (Figure 29). The system designed with the mole in mind works accordingly. The system, consisting of twelve parts and a large motor from the LEGO® Mindstorms® EV3 Set, lifts itself up on the tips on the straight part of the bent beams, which can be compared to the mole lifting itself up on its elbows or its underbelly, to bring the pulling arms forward, where LEGO® blades with the saw-toothed side down are attached to provide a better grip on the ground, similar to the shovel-like hands of the mole. Two wheels at the back of the motor enhance the mobility of the system, because the pulling arms are not very strong and slip easily on the ground. The arms are attached parallel to each other or shifted by 180° to the rotating disc of the motor with rotating parts at the second circular hole counted from the tip on the straight part of the bent beam, thereby providing the system with the ability to lift itself from the ground to advance the system forward, while the arms stay on the ground. The system should function properly in both directions. Similar to the snake scale locomotion system, the system in its current form cannot turn by itself, due to the fact that only one motor is used. A small inconvenience concerning the systems usability for an endoscope is the large width of the shovel hands. A solution for a future model could be an interlocking part with saw-teeth attached not at the sides of the beams, but in-between when the arms are attached parallel to each other to the rotating disc of the motor. (Although no such part exists as interlocking brick, this was solved by constructing a usable part with a 3D printing Pen. (3DPEN1, Velleman, Gavere, Belgium)) The system also works perfectly as intended when replacing the individual printed part with a cross axle between the two arms.

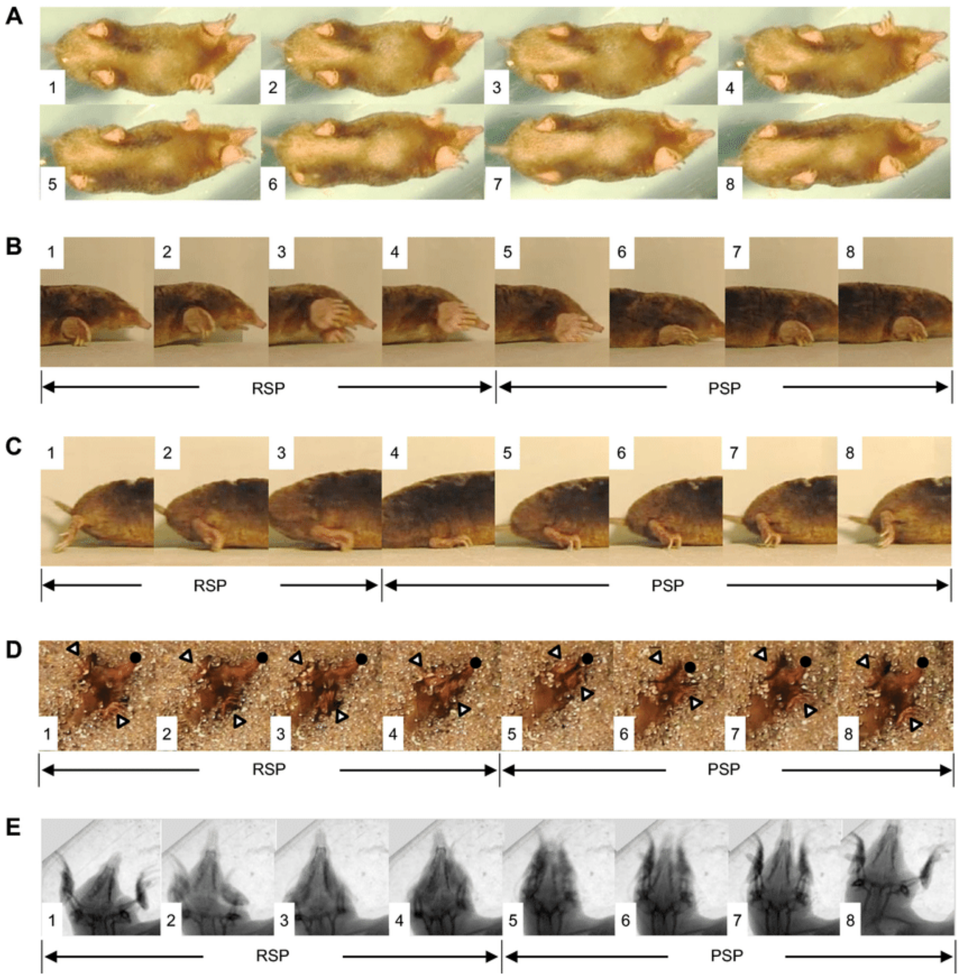


Figure 29: Motion sequence of crawling and burrowing locomotion. Images show: a ventral views of a mole during crawling, b, c lateral views of crawling with the forelimb and hindlimb, respectively, d ventral views of a mole during burrowing, e contemporaneous image of burrowing from X-ray video. During crawling, the movements of the four limbs are coordinated (a). A single cycle of a forelimb (b) and a hindlimb (c) movements consists of a recovery stroke phase (RSP, b: 1–4, c: 1–3) and power stroke phase (PSP, b: 5–8, c: 4–8). Triangles and filled circles in d show the position of the forefoot and nose. Note the synchronized outward then inward movement of forelimbs on both sides. © the Author(s), under exclusive licence to Springer-Verlag GmbH, DE part of Springer Nature 2021. Figure and caption directly taken from [Wada et al., 2021]

Figure 30: Mole imitating locomotion system

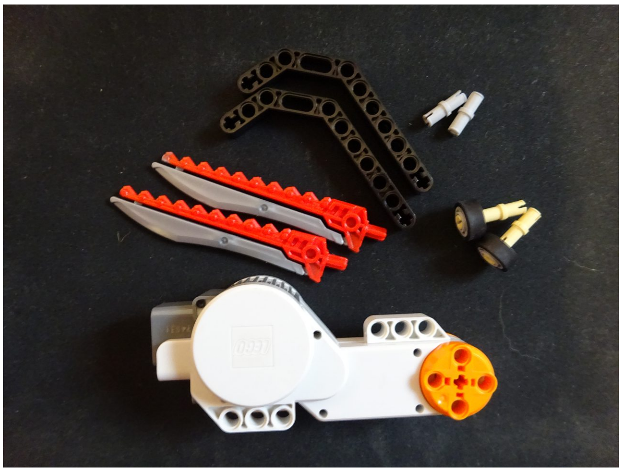


Figure 31: LEGO® Bricks used for the locomotion system in figure 30

By attaching two large motors to each other, adding two additional wheels and attaching one of the shovelarms of the original system to each on the outside of the rotational discs of each of the motors on the new doubled system, a system was created which can propel itself forward, backwards and turn in both directions.

At https://owncloud.tuwien.ac.at/index.php/s/0qwsn2u6vTAGI2U the MOLE prototype can be watched in action (4 s video).

3.2.3 FOOTSTEP Prototype

One commonality in many animals is the existence of legs, the number and form may differ, but nearly all of them are used for movement via steps. This concept is complicated to achieve in robotic design and is sometimes based on complex programming of the motors. The FOOTSTEP prototype is trying to condense the principle to its simplest form, with a single large motor from the Mindstorms® EV3 Set in forward mode and four legs.

The two legs in the front are directly powered and moved by the motor via a connecting rod, which allows the front legs to move in a back and forth motion in a half circle, even though the motor spins in a full circle in forward mode. The two back legs are moved passively parallel to the legs in the front by two gear wheels, respectively.

The two connecting rods are fixed rotary to the rotating disc of the motor shifted by 180°. This movement of the legs on each side moving parallel and in unison is called pace, when talking of tetrapod vertebrates, which can be seen in Figure 32.

Figure 32: An icelandic horse ambling (PD)

Figure 33: FOOTSTEP locomotion system

Figure 34: Legs and gears used for the locomotion system in figure 33

In Figure 34 the legs and gears of the side of the locomotion system which is facing the camera in Figure 33 can be seen in detail. The legs are fixed in an inflexible way on the two large gears. These large gears are connected by a small gear to arrange for the parallel movement. The front legs are attached to the rotating disc of the motor via a connecting rod, which also can be seen in Figure 34, and which can turn at both ends via a ball and socket joint respectively. The legs, connecting rod and gears are the important design of the prototype, all further parts are used for stabilization, scaffolding and to shift the balance point to the front.

The balance point is crucial in this prototype. A simple robot has not the same abilities a creature has: it has no ability to shift its balance point, its legs are fixed and it has no instincts to prevent itself from falling. Of course one can complicate a robot as much as one wants, but in some respects it will never be comparable to a living creature. The interesting characteristic of the FOOTSTEP is the shifting of the balance point: in first editions of the prototype, the motor was parallel to the ground and did not move at all. After shifting the balance point by applying pressure at different points of the robot it became clear that the balance point needs to be in the front for the robot to move forward. Therefore the back of the robot was elevated and the motor tilted forward to achieve a shift of the balance point in the desired direction. In its current state, which is documented in Figure 33, the system slowly moves forward. When applying a little bit more pressure to the front it moves quicker.

The reason why the internal name of the FOOTSTEP prototype, which is FOOTSTEP-MONSTER, includes the word "monster" is as follows: it disassembles easily and it is intricate to reassemble, because of the delicate nature of the movement of the legs and gears.

The system is slow, aggressive in its movements and gets easily caught on bumps, which leads to undesired turning or tipping. Because its weight is only transferred to four small bearing surfaces the system is unsuitable for endoscopy in sensitive areas of the colon.

At https://owncloud.tuwien.ac.at/index.php/s/wp2fDU6vOyFN8Ix the FOOTSTEP prototype can be watched in action (4 s video).

3.3 Movable Wall Experiments

In this section the results of the experiments conducted with the movable wall described above are given and discussed.

3.3.1 Initial Force

In the first experiment the initial force of the single motor prototypes at the first contact with the movable wall was measured with the movable wall. The MOLE prototype was tested in two configurations: firstly with the 3D printed part on the cross axes between the two arms and secondly without the 3D printed part. For comparison a single motor track system with two tank tracks was measured. The SNAKE and MOLE prototypes were mounted on the NXT large motor, while the FOOTSTEP and track system operated with an EV3 large motor. The SNAKE and MOLE systems produced the same initial force, when fixed to the EV3 large motor. In a second run of the experiment a 3D printed half sphere was attached to the front of the systems to imitate the spherical camera of an endoscope in order to observe changes resulting from the modification of a nearly flat contact surface to a rounded contact surface which allows a smoother and easier turning when in contact with the wall. Each run was repeated four times to gain comparable data.

In Table 2 all measured data of the initial force of the prototypes both with and without the attached half sphere are presented. Due to the poor reading precision of only 0.01 N steps on the spring balance the slight differences between the prototypes are not measurable when measuring the initial force. The initial force of all prototypes ranges between 0.01 N and 0.03 N. There is also no drastic difference between the measurements of the prototypes with the half sphere attached and without it. Although when comparing the prototypes to the system with tank tracks, which has an initial force of around 0.18 N, it becomes clear that the prototypes are a lot gentler by a wide margin, while using the same motor. This is very promising for endoscopy design due to the fact that the colon walls are less endangered by the systems when there is contact.

Table 2: Measured Initial Force for the different prototypes

MOLE with claw	**MOLE**	**SNAKE**	**FOOTSTEP**	**Tracks**
without attached half sphere				
(0.01 ± 0.01) N	(0.03 ± 0.01) N	(0.02 ± 0.01) N	(0.01 ± 0.01) N	(0.18 ± 0.01) N
(0.02 ± 0.01) N	(0.02 ± 0.01) N	(0.02 ± 0.01) N	(0.02 ± 0.01) N	(0.18 ± 0.01) N
(0.03 ± 0.01) N	(0.01 ± 0.01) N	(0.02 ± 0.01) N	(0.01 ± 0.01) N	(0.18 ± 0.01) N
(0.02 ± 0.01) N	(0.02 ± 0.01) N	(0.02 ± 0.01) N	(0.01 ± 0.01) N	(0.17 ± 0.01) N
with attached half sphere				
(0.02 ± 0.01) N	(0.02 ± 0.01) N	(0.01 ± 0.01) N	$0.01 \pm 0.01)$ N	(0.17 ± 0.01) N
(0.02 ± 0.01) N	(0.01 ± 0.01) N	(0.01 ± 0.01) N	(0.02 ± 0.01) N	(0.18 ± 0.01) N
(0.02 ± 0.01) N	(0.02 ± 0.01) N	(0.01 ± 0.01) N	(0.01 ± 0.01) N	(0.18 ± 0.01) N
(0.01 ± 0.01) N	(0.01 ± 0.01) N	(0.01 ± 0.01) N	(0.01 ± 0.01) N	(0.19 ± 0.01) N

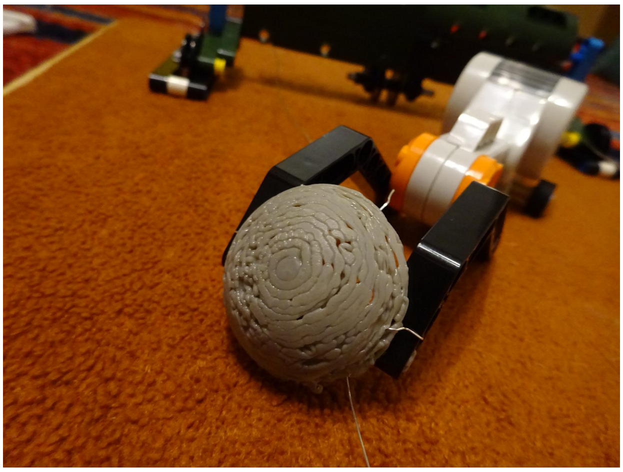


Figure 35: MOLE imitating locomotion system with claw with attached half sphere specifically fabricated with the 3D printing Pen

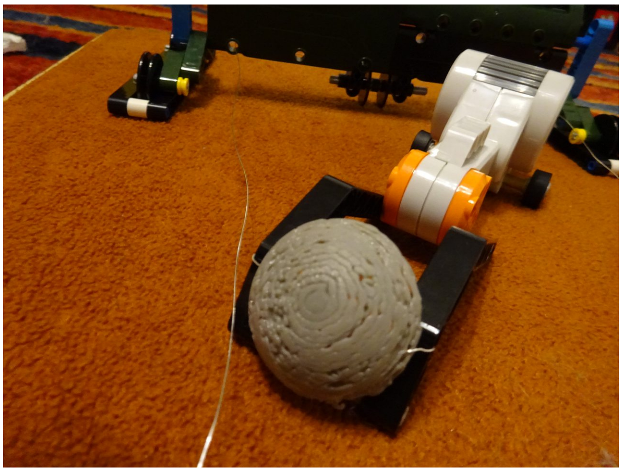


Figure 36: MOLE imitating locomotion system without claw with attached half sphere specifically fabricated with the 3D printing Pen

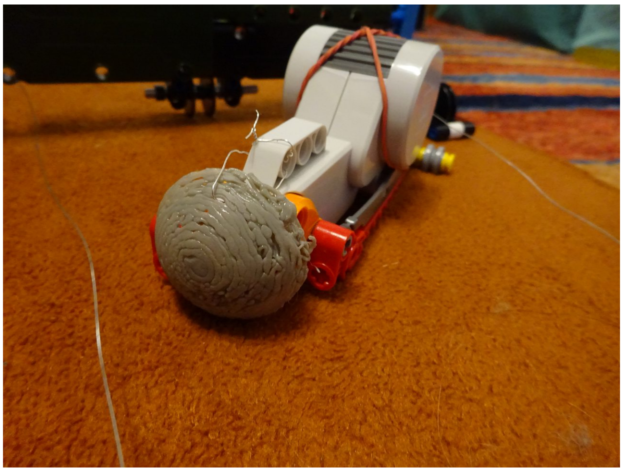


Figure 37: SNAKE scales imitating locomotion system with attached half sphere

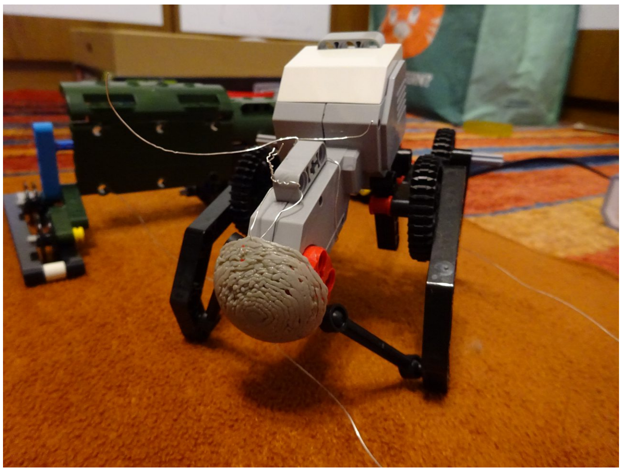


Figure 38: FOOTSTEP system with attached half sphere

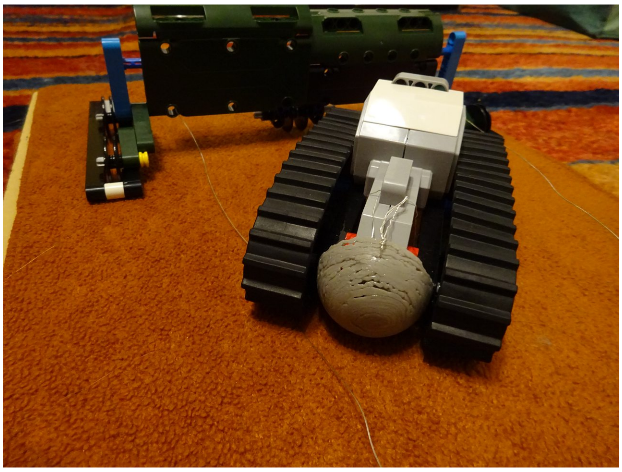


Figure 39: Tracks system with attached half sphere

3.3.2 Maximum Force

In the second experiment the maximum force of the single motor prototypes was measured with the movable wall. The MOLE was again tested in two configurations, firstly with the 3D printed claw and secondly without it. There were two runs of the experiment either with the attached half sphere or without and each run was repeated five times. The maximum force was measured with the spring balance, when the movable wall no longer moved under the influence of the locomotion system or the system started to turn by itself. In this experiment the comparison to the track system is no longer given, due to the fact that its maximum force exceeds the limit of the spring balance of 1 N.

In Table 3 all measured data of the maximum force experiment are presented. The seemingly high fluctuations between the measurements of each prototype result from small differences in the angle of the approach of the prototype to the movable wall. Although it was attempted to maintain a 90° angle, small differences, due to placement errors of the prototypes or the wall as well as tilting from the rigid cable connecting the prototype to the EV3 brick, could not be prevented. The resulting uncertainties are reflected in the error bars, with additional 0.1 N due to the reading precision of the spring balance.

The MOLE with claw has an average maximum force of (0.088 ± 0.033) N, while the MOLE without the claw has an average maximum force of (0.096 ± 0.019) N. The average of the MOLE with the claw is brought down due to the first two values, which were the first two measurements in the series, where the prototype was angled and restricted by the cable. The higher maximum force of the MOLE prototype without the claw is confirmed by the measurements of the prototype configurations with the attached half sphere, where the MOLE prototype with the claw scored an average maximum force of (0.092 ± 0.026) N, while the MOLE prototype without the claw exceeded all prototypes with an average maximum force of (0.178 ± 0.026) N. The prototype in both configurations as well as with and without the attached half sphere never turns by itself. The higher averaged values when attaching the half sphere can be explained as follows: the movable wall has a small gap between the ground and the lower edge of the wall, due to its construction with the interlocking bricks. This gap cannot be closed by interlocking bricks and when closing the gap with cardboard or similar materials the cardboard gets bend, which results in the same problem. When using thicker cardboard, the movable wall is not as stable and tips easily. The prototypes get caught in this gap with their arms, when there is no half sphere attached and therefore cannot execute a high force on the wall. By attaching the half sphere to the arms, the contact surface of the prototype with the wall is larger and shifted upwards, which results in the fact that the arms no longer get caught under the wall. Another reason for the higher maximum force is the weight of the half sphere getting attached to the front of the arms, which prevents slipping and provides a better grip between the arms and the ground. This is similar to the described version in the prototype section, where this weight is provided by the two hands replacing the cross axis with or without the claw.

For the SNAKE prototype the maximum force was measured before the locomotion system started to turn. While the SNAKE prototype without the attached half sphere with a maximum force of (0.080 ± 0.02) N compares well to the MOLE prototype with the claw, the maximum force is reduced to (0.068 ± 0.018) N when attaching the half sphere to the SNAKE prototype. This means the SNAKE prototype turns easier when a half sphere is attached to the front, which is not surprising, but now verified by the data. This is promising for the design of endoscopes. An endoscope which turns easily by itself by simply making contact with the colon walls is less dangerous for the patient. And it can be helpful for the examining medical doctor.

Compared to the other prototypes the FOOTSTEP has a very small maximum force of (0.022 ± 0.014) N without the attached half sphere and (0.028 ± 0.018) N with the attached half sphere. Therefore attaching the half sphere does not make a lot of difference, while the process of turning seems random and could be accredited more to the rigid cable than to the contact with the wall. The maximum force is due to the reading precision in the same range as the initial force of the FOOTSTEP. When observing the prototype on the cloth, it can be seen clearly that the FOOTSTEP is hardly able to move on the fleece and gets caught in the cloth.

All results can be seen in the graph below (Figure 40).

Table 3: Measured Maximum Force for the different prototypes

MOLE with claw	MOLE without claw	SNAKE	FOOTSTEP
without attached half sphere			
(0.06 ± 0.01) N	(0.09 ± 0.01) N	(0.07 ± 0.01) N	(0.02 ± 0.01) N
(0.07 ± 0.01) N	(0.09 ± 0.01) N	(0.07 ± 0.01) N	(0.02 ± 0.01) N
(0.12 ± 0.01) N	(0.10 ± 0.01) N	(0.09 ± 0.01) N	(0.02 ± 0.01) N
(0.10 ± 0.01) N	(0.11 ± 0.01) N	(0.09 ± 0.01) N	(0.03 ± 0.01) N
(0.09 ± 0.01) N	(0.09 ± 0.01) N	(0.08 ± 0.01) N	(0.02 ± 0.01) N
with attached half sphere			
(0.11 ± 0.01) N	(0.18 ± 0.01) N	(0.06 ± 0.01) N	(0.02 ± 0.01) N
(0.08 ± 0.01) N	(0.19 ± 0.01) N	(0.06 ± 0.01) N	(0.03 ± 0.01) N
(0.07 ± 0.01) N	(0.15 ± 0.01) N	(0.07 ± 0.01) N	(0.02 ± 0.01) N
(0.10 ± 0.01) N	(0.18 ± 0.01) N	(0.07 ± 0.01) N	(0.04 ± 0.01) N
(0.10 ± 0.01) N	(0.19 ± 0.01) N	(0.08 ± 0.01) N	(0.03 ± 0.01) N

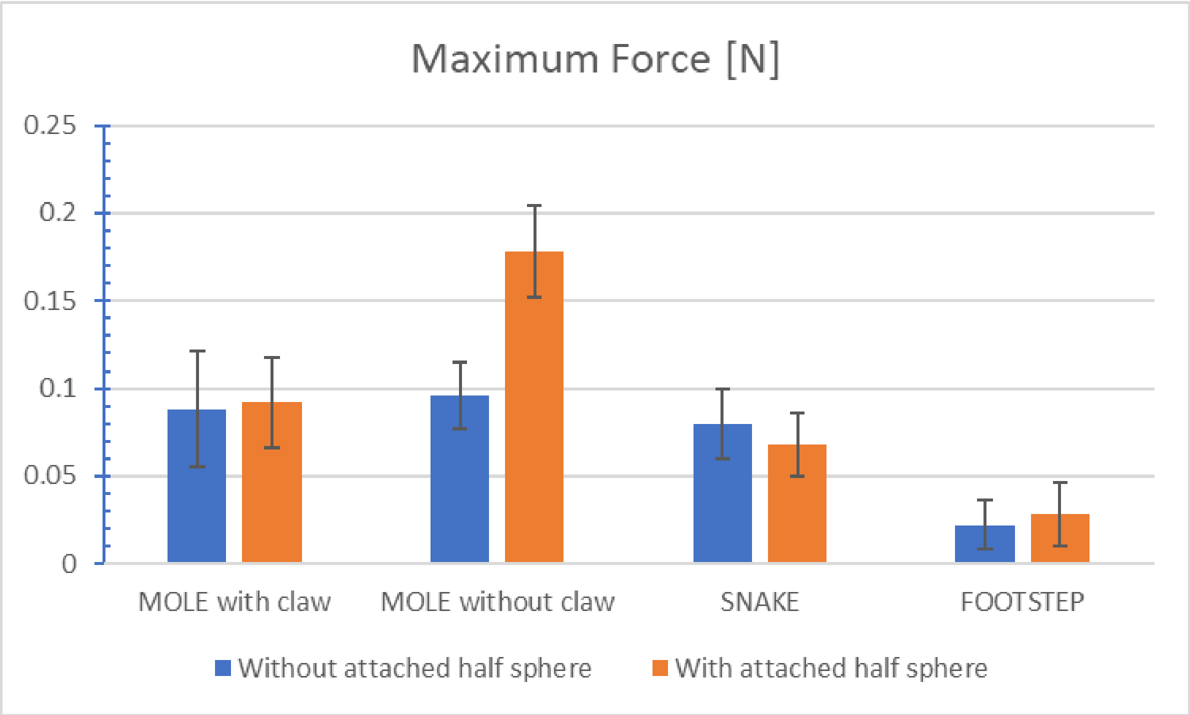


Figure 40: Results of the Maximum Force measurements

3.3.3 Maximum Weight

In the third experiment the maximum weight a single motor locomotion system can move, was measured with the movable wall. The MOLE was again tested in two configurations, firstly with the 3D printed claw and secondly without it. There were two runs of the experiment either with the attached half sphere or without. The maximum weight was determined by adding sand to a bag which was fixed on the movable wall until the tested system was no longer able to move the wall or when it started turning by itself. The sand was measured with an Electronic Pocket Digital Scale (Aosai® Electronic Pocket Digital Scale ATP168). The comparison to the track system is no longer given in this experiment, due to the fact that the maximum weight of the track system exceeds the limit of the movable wall, which disassembles under the strain. The movable wall itself was not included in the weight measurements to guarantee better comparison, due to the fact, that it was also used in the maximum force experiment without considering its own weight in the measurements.

In Table 4 all measured data of the maximum weight experiment can be found. Comparing these data to the data of the maximum force experiment, the results are mostly in agreement. The SNAKE locomotion prototype is an exception because the results of the prototype with and without the half sphere seem to be interchanged. A reason for this may be that maybe the SNAKE prototype was not perfectly aligned at a 90° angle to the wall and therefore turned earlier. At every experiment the EV3 Brick was held directly above the prototype to reduce interference with its movement due to the cable. It is possible that this was not the case for the SNAKE prototype with the attached half sphere and the maximum weight was therefore increased by the cable pushing the prototype forward and adding additional force.

The SNAKE prototype turned itself in both configurations and the MOLE prototype with the attached half sphere turned as well with claw and without it. All explanations of the results described in the chapter above also apply for this experiment and therefore do not need to be repeated.

Table 4: Measured Maximum Weight for the different prototypes

MOLE with claw	MOLE without claw	SNAKE	FOOTSTEP
without attached half sphere			
(80.49 ± 1.00) g	(92.89 ± 1.00) g	(68.78 ± 1.00) g	(16.04 ± 1.00) g
with attached half sphere			
(94.96 ± 1.00) g	(160.27 ± 1.00) g	(83.22 ± 1.00) g	(23.24 ± 1.00) g

3.4 Pressure Foil Measurements

The idea behind these measurements was to compare the pressure profile of the SNAKE locomotion prototype and that of a living snake.

The weight and length of the subjects - in this case: three snakes - were used in estimating the pressure and therefore choosing the proper Prescale Foil. However, the snakes were young snakes, so only one foil, the ultra extreme low (5LW) Foil was roughly in the right range. The experiments were executed on 15.12.2020 in their temporary home, the pet shop Terra Reptilia in 1070 Vienna. Unfortunately it quickly became apparent that all of the test subjects were too light to be displayed on the foil. Snakes are able to distribute their weight very well and the foil was therefore not exposed to pressures above 0.006 MPa. In Figure 41 the heaviest subject, a young ball python is pictured on the small white pressure test foil. The test foil was used to quickly deduce if the foil can display the snakes, without wasting the foil meant to display the movement of the snake.

Even though the comparative aspect of this chapter is no longer given due to the pressure limit of the foils, the prototypes are still displayable on the foils. The difference between the snakes and the prototypes is the contact surface. Although the prototypes are even lighter than the snakes, their contact surface is only a few mm^2, while the snakes have a contact surface in a range of a couple of cm^2.

Figure 41: A Ball Python from the Terra Reptilia Shop in 1070 Vienna on the Prescale Ultra Extreme Low Foil

The pressure markings which the SNAKE locomotion prototype left while traversing from left to right on the Prescale foil Ultra Extreme Low (5LW) are not what was expected, but nevertheless interesting. The dots which can be seen clearly in the upper half of Figure 42 can be assigned to the prototypes imitating feature of the snake scales (a). If the figure is inspected more closely the same dots (c) can be detected in the lower half of the figure to the lower right of the parallel stripes (b). These parallel stripes originate from the wheels, which were fixed to the back of the prototype to guarantee better stability and easier movement. The slight shift which can be seen in the figure comes from the slipping nature of the prototype on the extremely smooth surface of the foil. This is also the reason, why only few dots are visible. Due to the very smooth surface, the saw teeth behind the first saw tooth of the prototypes imitated snake scales are not able to catch a grip. It is also possible that the saw teeth do add to the movement, but the pressure is below 0.006 MPa and therefore their impact cannot be seen. The visible dots result from the first saw teeth on each side and the shift of 180° on the rotating disc is visible on the foil. This shift is also visible in the markings of the wheels, which are alternately tilted to both sides and therefore not always in contact with the ground. Remarkable to observe is the clear nature of the dots. If the saw tooth would be slipping, one would rather see a line than a dot, which in this case means that the saw tooth is making contact with the foil at the same point the whole time it is touching the ground.

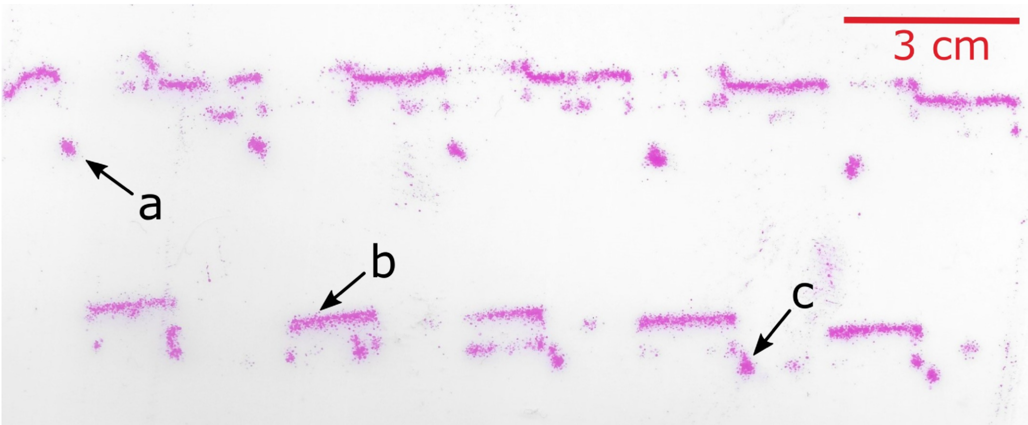


Figure 42: Prescale foil Ultra Extreme Low (5LW) after the traversing of the SNAKE prototype: (a) and (c) saw teeth (b) wheels

In an updated version of the SNAKE locomotion prototype a few details could be improved based on the results described above. The angle of the saw tooth blades could be changed in such a manner that more of them come in contact with the foil. Although they definitely do add to the movement in a rough environment, there is no harm done if the weight of the prototype is distributed to more saw teeth and the pressure is therefore reduced, while the higher contact surface aids to prevent slipping. Maybe the tilting of the prototype could be also reduced by adding suspension so that the wheels are in contact with the surface at all times to prevent the sensitive colon wall from violent impacts from the wheels and reduce the overall pressure.

The pressure markings which the MOLE locomotion prototype with the cross axle without the 3D printed claw or the arms left while traversing from left to right on the Prescale foil Ultra Extreme Low (5LW) are also not what was expected. The two lines framing the middle of Figure 43 can be assigned to the wheels (a) supporting the motor itself. The barely visible dots (c) below the upper line and above the lower line are not the cross axle, as hoped, but the end of the arms, which can be compared to the elbows of the animal. Unfortunately the cross axle as well as the front of the arms are not heavy enough to be pictured on the foils and therefore leave no pressure markings. This did not change when adding weight by fixing a half sphere to the front as used in the maximum force and weight experiments. The spots (b) between these dots come from the motor, which seems to be lower at one side. These seemingly meaningless spots give us the opportunity to display the lifting of the motor by the "elbows": the spots stop when the dots of the elbows begin.

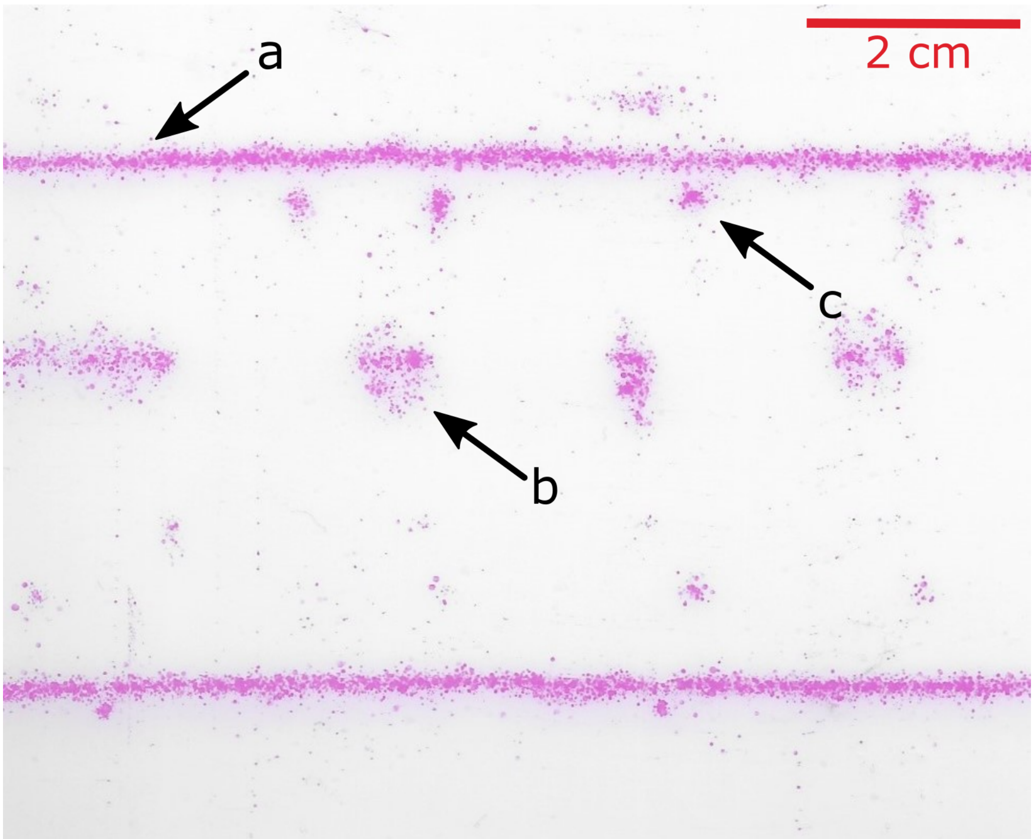


Figure 43: The Prescale foil Ultra Extreme Low (5LW) after the traversing of the MOLE prototype: (a) wheels (b) motor (c) elbows

In an updated version of the MOLE locomotion system, the weight of the front of the arms could be increased. This is a very delicate process, because the prototype still has to be able to lift the arms and move the arms forward without getting caught on irregularities of the surface or burying the arms into the sensitive colon walls. The system itself could be balanced more so there are no longer unwanted spots by the dragging motor.

The FOOTSTEP prototype has pressure markings as expected. In Figure 44 the outlines of the feet can be seen clearly. The feet are never lifted but shifted forward. Thanks to the small turn at the upper right side of the figure one can even distinguish the front foot from the back foot on the left side of the prototype. The prototype traversed from left to right. The lower curve of the upper lining and therefore left side of the prototype can be assigned to the front foot (b) and the upper curve can be assigned to the back foot (a). This can be stated because of the slight curving of the legs towards the prototype and the position of the legs. The front legs push themselves off at the front of their contact surface and the back legs from the back.

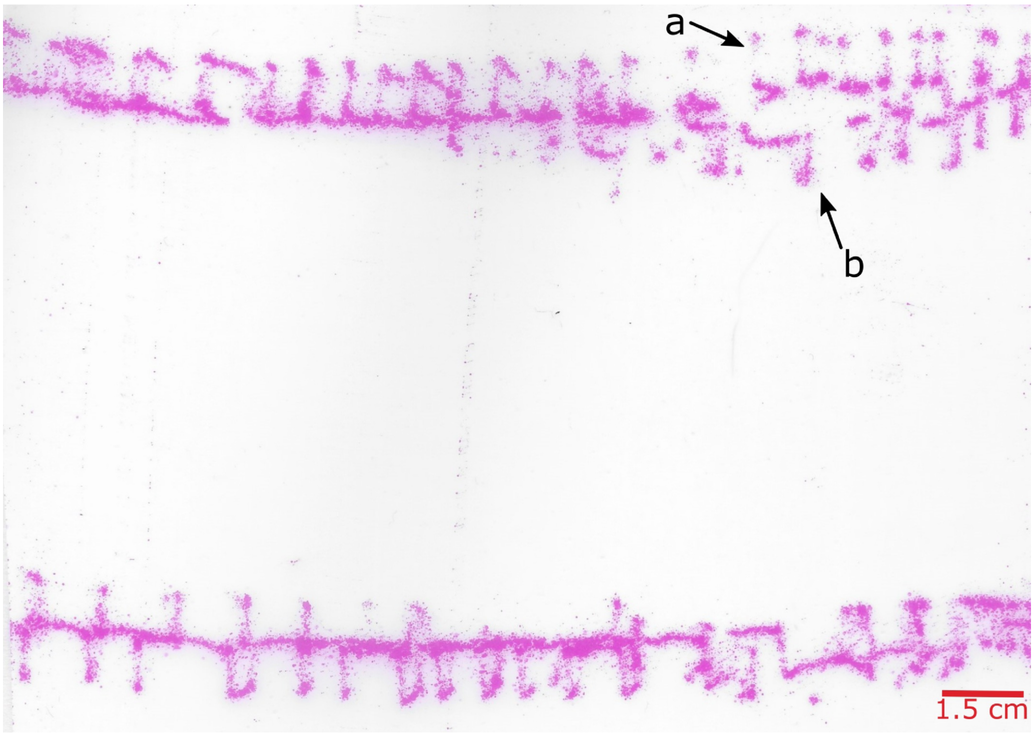


Figure 44: The Prescale foil Ultra Extreme Low (5LW) after the traversing of the FOOTSTEP prototype: (a) back foot (b) front foot

The fact that the FOOTSTEP prototype was displayable is a lucky coincidence. If the feet were using their whole contact surface as intended, the pressure would have probably been below the limit of the foils (0.006 MPa to 0.05 MPa). Ideally the FOOTSTEP should be using the whole contact surface of its feet to reduce the strain on the colon wall, even though the FOOTSTEP prototype was already stated above as not usable for the endoscopy design.

3.5 Autonomous Maneuver through a Simple Maze, Imitating the Gastrointestinal Tract

A simple and fast way of moving a system is tank tracks. They can be easily adapted, easily steered with two motors and have a smooth movement. They can be built with soft rubber tracks or solid link chain tracks. Although these tank tracks are not bioinspired, they can be used to test other systems, like the maneuvering system presented in this chapter, which is inspired by whiskers or feelers in the fauna of the Earth, without interfering or manipulating the system which is tested.

The navigation through the gastrointestinal tract, especially the large intestine, with its sensitive colon walls, is a challenging and risky task for the examining medical doctor. The vision through the camera is confusing and distorted, therefore human piloting errors can easily occur and sometimes result in fatal injuries. Therefore it would be preferable if the human errors can be erased by using autonomous driving of the endoscope or the medical staff can at least be supported by such a system.

The infrared sensor contained in the LEGO® Mindstorms® EV3 Set was tested and then rejected for the matter at hand. At first glance, the idea of the application of the infrared sensor for an autonomous driving system seems obvious. As soon as the sensor detects an obstacle, in the case of an endoscopic examination the colon walls of an intestinal loop, it should turn until the path is clear. By testing the LEGO® infrared sensor it becomes apparent that the sensor detects the surrounding colon walls and ceiling of the straight path and would therefore turn perpetually.

The solution presented in this thesis is a system similar to the feelers of insects or whiskers of cats and similar mammals. The following prototype resembles the vehicle being afraid or in love - depending on the perspective - described in the book by Valentin Braitenberg. It is fascinating that not only humans can develop feelings for machines, which can fulfill simple and few tasks, like moving or sensing their environment, but that these machines appear to have feelings themselves. This behavior, which is part of the cybernetics can be used in the endoscopy. [Braitenberg, 2013]

Two touch sensors of the LEGO® Mindstorms® NXT Set are mounted opposite to each other, facing outwards, in a 90° angle to the direction of movement. The sensors are mounted on two curved LEGO® Technic Beams, which can be moved by few degrees. In the closed position, when the two sensors are closest, the sensor tips align with the outline of the tank tracks. The beams and therefore the sensors are extended in an open position using a rubber band, so the sensors can follow the slight winding of the colon walls, without losing contact, yet still stay in a position of nearly 90°. Due to the systems resemblance to whiskers and feelers, the system shall be named WHISKERS. It can be seen in Figures 45 and 46.

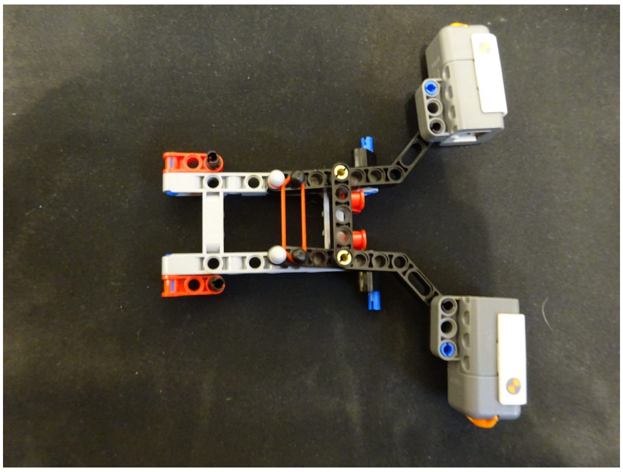


Figure 45: The movable feelers with the touch sensors of the autonomous driving system WHISKERS

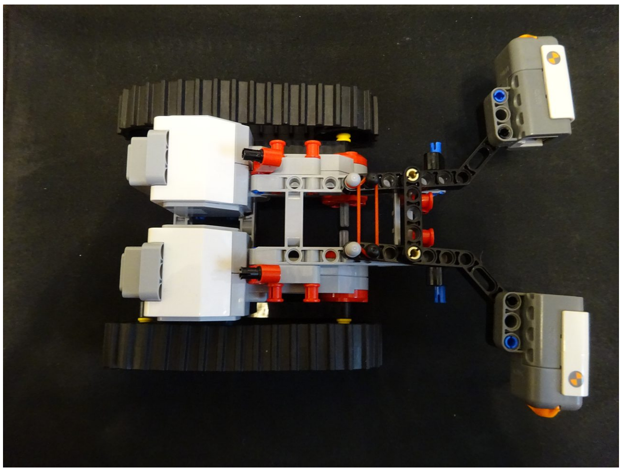


Figure 46: The autonomous driving system WHISKERS mounted on simple tank tracks with the EV3 Stone removed for better visibility

The programming of WHISKERS is as follows: When both touch sensors are in the pressed position and therefore in contact with the colon wall, the system moves straight ahead. When the colon opens up and the system loses contact to both sides and the sensors are therefore in a not pressed position, the heading of the system stays the same and the prototype advances straight ahead. As soon as one of the sensors gets pressed and therefore gets in contact with the colon wall, the system turns in the opposite direction until both sensors loose contact or get pressed. The idea for this behavior is as follows: if the system slides along the colon wall and a curve in the colon occurs, the sensor in the direction of the curvature of the colon is losing contact to the wall, while the other one stays in contact. Therefore the path in this direction is free and the system can follow the curve of the colon. If the colon is larger than the dimensions of the system and the system is not lined up with the colon walls, the system turns as soon as a colon wall is touched and aligns with the colon, with as little contact as possible. The program can be seen in Figure 47.

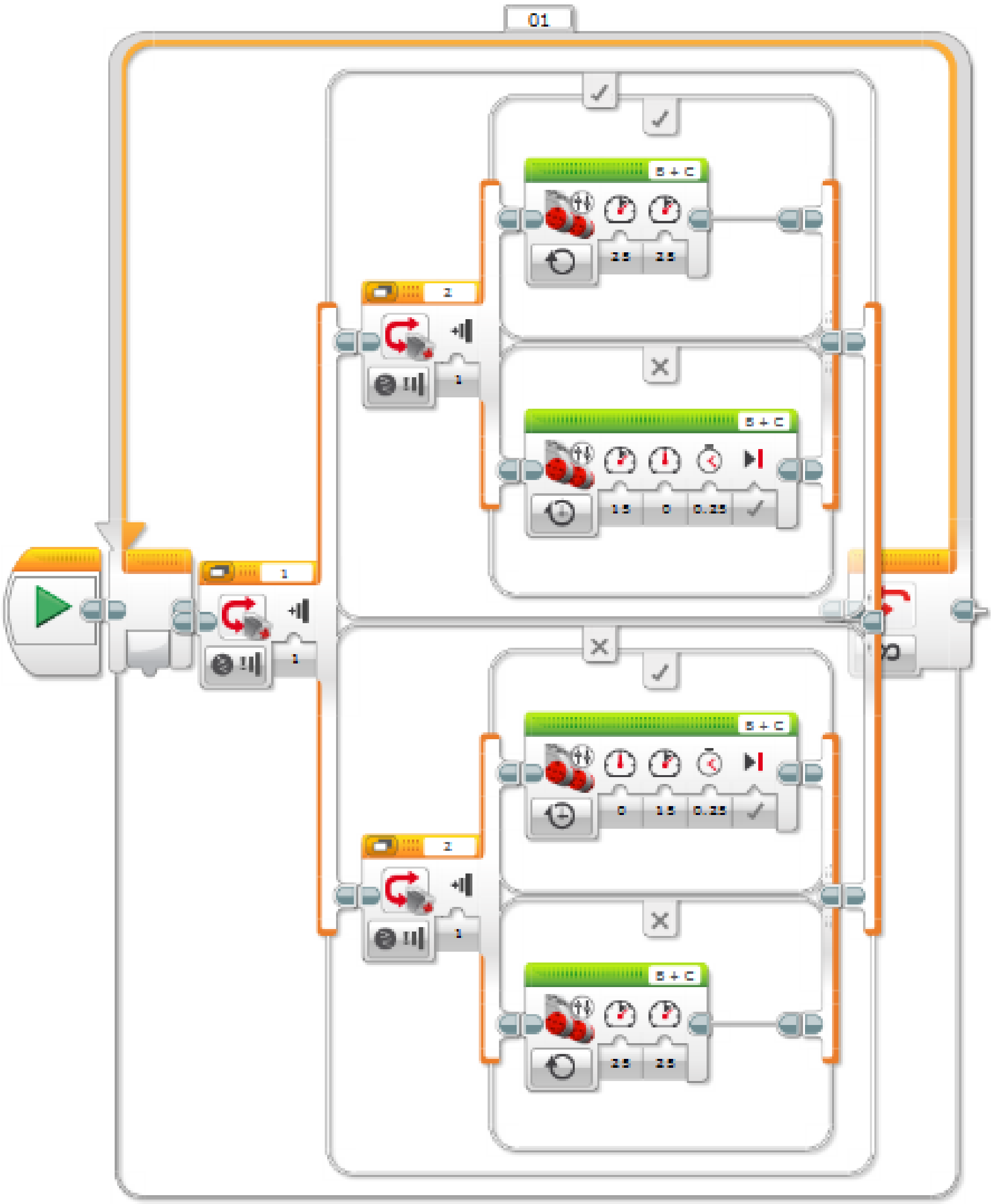


Figure 47: Program operating WHISKERS

The properties and tasks of this prototype were tested in several test tracks made of cardboard, acting as a model for the colon, and behaved as imagined and desired. Nevertheless, it has to be mentioned, that the touch sensors are not very sensitive and need to be pressed all the way to react to the cardboard walls. Therefore the system sometimes slides along a wall without reacting at first, before turning in the opposite direction. This of course has to be considered, when miniaturizing the system, so that the colon walls will be treated adequately. Figure 48 is a sketch of the wished behavior. For simplicity's sake the system has been adopted as a point.

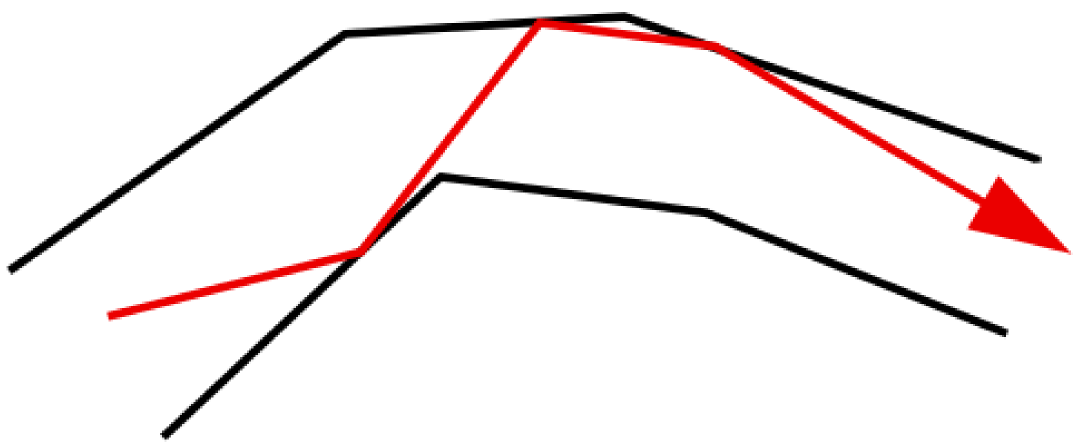


Figure 48: Sketch of the wished and achieved behavior of WHISKERS

An alternative to WHISKERS could be created with two infrared sensors mounted parallel to each other facing opposite colon walls. As long as the infrared sensor is triggered in a specific distance and both infrared sensors detect the colon walls, the system advances forward, as soon as the specific distance is exceeded in one infrared sensor, the system turns in that direction. The system advances as well, when both infrared sensors are not triggered. This simple system follows exactly the same procedure as WHISKERS with touch sensors, created in this thesis, without any contact or impact of the colon walls. The only challenge this system would pose is the unknown specific distance, which the infrared sensors should detect, but field tests could solve this problem. Unfortunately, there is no possibility to test this hypothetical system within this thesis, due to a missing second infrared sensor, since there was only one sensor contained in the set, and the far bigger problem of the LEGO® infrared sensor, which also detects the colon wall above. Due to this inaccuracy the infrared sensors would be invariably triggered by the colon wall above or the surrounding structure of the system. Nevertheless, the concept should be mentioned here regarding the similarity to the above described tested system.

Both described systems only work in an expanded colon as it is the common practice at the moment in endoscopy anyway.

The prototype in action maneuvering in a cardboard bend can be watched at the following link (9 s video):
https://owncloud.tuwien.ac.at/index.php/s/kwQP3110hOfk7WW

3.6 Biomimetic Locomotion System Ideas not yet Realizable with Interlocking Bricks

3.6.1 Wheat Awn

Animals have a lot to offer regarding the biomimetic design of endoscopes. Plants also have developed amazing methods to bury and move their seeds passively which can inspire further innovation in endoscopy.

The Awn of Wheat is a very interesting marvel of nature (Figure 49 a). Although it has not a very appealing appearance, it is rich in tricks of nature. The wheat awn cross sections are formed like a mushroom with a cap and a ridge. Both consist of cellulose fibrils. These cellulose fibrils are all aligned in the upper part of the awn and in the cap at the bottom of the awn, while the cellulose fibrils are randomly oriented at the ridge. The awn itself is covered in silicified hair of around 0.1 mm to 0.2 mm length which point away from the seed. Usually there are two wheat awns fixed to one seed. [Elbaum et al., 2007] [Xiao et al., 2020] [Xing-feng et al., 2010]

These awns can move and even bury the seed in the ground. This happens passively and periodically due to the cyclic humidity changes surrounding the seed. Due to higher humidity the awns straighten and the hairs, which are stuck in the soil, allow the seed to bury itself deeper into the soil. When the humidity sinks, the awns dry, bend down and follow the seed in the soil. As already mentioned the orientation of the hair prevents the seed from leaving the soil and allows the seed to bury deeper and deeper. [Elbaum et al., 2007]

The wheat awns are also important for fogdrop collection and its transport from the tip of the awn to the seed. This is achieved by the conical spine, the oriented hair and gradient grooves. This can be seen in Figure 49, which is taken directly from the specific paper and shows their process of 3D printing the wheat awn system, which is not particularly interesting for this thesis. [Xiao et al., 2020]

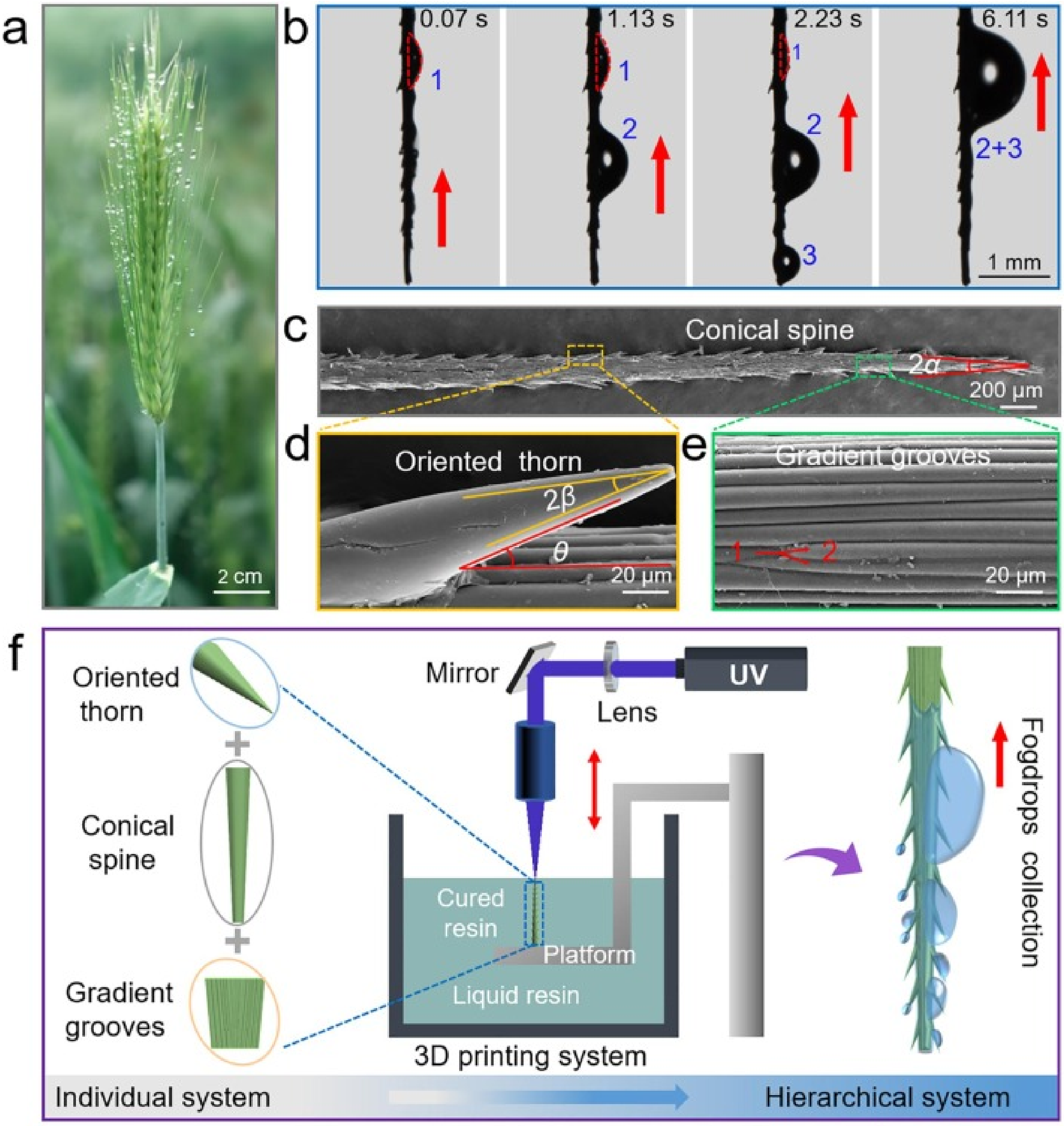


Figure 49: Natural wheat awn and the fabrication process of artificial awn systems. a) Optical image of an ear of green wheat. b) The process of fogdrop collection on awn surface. c) Magnified image of a natural awn. It is a hierarchical system including conical spine, microgrooves, and oriented thorns. d) Magnified image of an oriented thorn e) Magnified images of gradient microgrooves. One microgroove increases into two microgrooves along the spine. f) Schematic diagram of the fabrication process of artificial awn systems using an 3D printing technology. © 2020 Elsevier B.V. Figure and caption directly taken from [Xiao et al., 2020]

The method of bending and straightening awns with oriented hair or thorns is not optimal for the field of endoscopy. The colon walls are very sensitive and could be punctured in the process of the procedure by awns or their hair. This is a common health concern with dogs and other animals roaming in wheat fields or coming in contact with wild wheat in the summer. For example, a wheat spike can get caught in the fur of the animal, work its way into the skin and provoke an inflammation.

Despite the challenges described above, the concept could still be used in a different configuration similar to the product HEXBUG nano® by HEXBUG, which consists of a vibrating motor mounted on oriented rubber legs. The resulting system moves in the opposite direction of the oriented legs. This system could be adopted for the field of medical endoscopy, but could not be built with the interlocking bricks used.

3.6.2 Redstem Stork's Bill Seed

The seed of the Redstem Stork's Bill (*Erodium cicutarium*) has developed a unique way to bury itself. Similar to the wheat seed described above the movement is initiated by the humidity surrounding the seed. [Evangelista et al., 2011]

The seed of the Redstem Stork's Bill is covered in hairs which are facing the awn. The awn is long, covered in bristles and divided into an actively bending section and an inactive portion of the awn. In high humidity the awn is straight. As it dries up, the actively bending section of the awn coils for five to ten full turns, while the inactive portion stays straight. In the loose soil the inactive portion of the awn gets caught on small particles of the soil and is therefore immobile, while the actively bending section is still coiling. This coiling causes the seed to turn and, because of the hairs and the immobility of the inactive part, to drill and bury itself deeper into the soil. The seed can also move over the sandy ground to find a crack to bury itself into by wetting and therefore unwinding. The seed completely buries itself over the course of several days and several wetting and drying periods. [Evangelista et al., 2011]

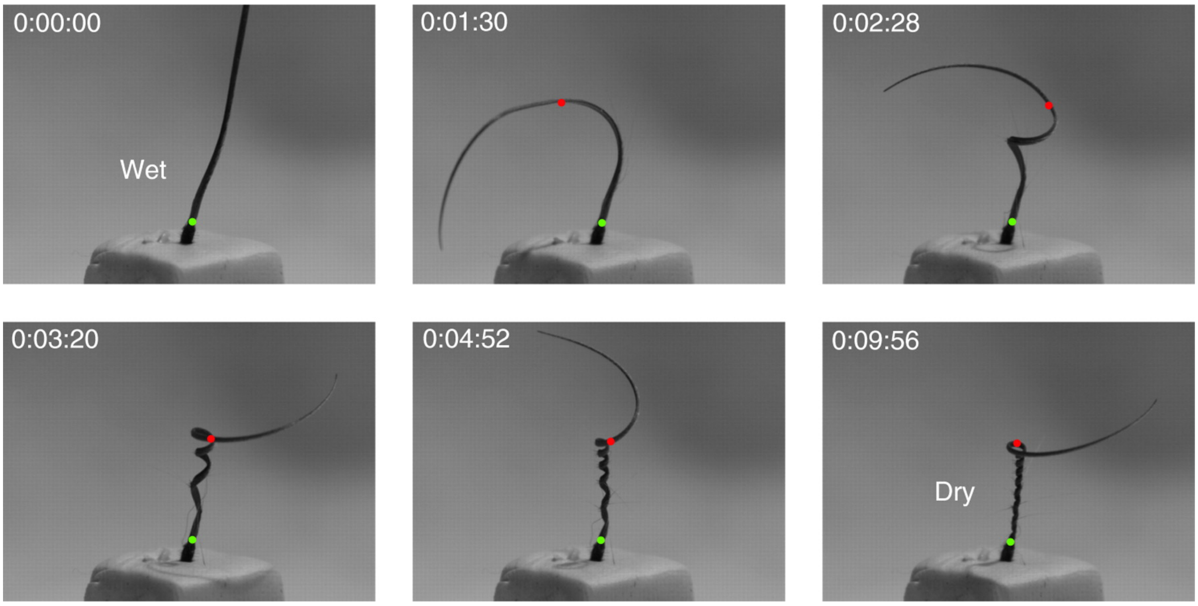


Figure 50: Representative frames showing awn re-winding upon drying. A soaked awn was placed on polymer clay at time 0:00:00 (h:mm:ss). Green and red dots mark the proximal (seed) and distal ends of the actively bending region. © 2011 The Company of Biologists Ltd. Figure and caption directly taken from [Evangelista et al., 2011]

Although this exact process can hardly be mimicked in the design of an endoscope without stretching or injuring the sensitive walls of the intestines, the drilling and spiraling motion of the seed and the finding of the easiest way are inspiring. This motion could be achieved by fixing tracks to a cylinder in a helix, which is sketched in Figure 51. The whole system should then propel itself forward in a hose, while turning. Due to the fixing of the tracks in a helix or multiple tracks bent diagonally over the cylinder, the system should be able to follow the bending of the intestines without interference from outside. This concept is yet to be tested.

Figure 51: Sketch of the system inspired by the Redstem Stork's Bill Seed consisting of tracks fixed in a helix on the endoscope to mimic the rotating movement of the Redstem Stork's Bill Seed

The self-burial of the seed is amazing to watch and multiple videos to this process can be found. It is really fantastic and fascinating to see the tricks of nature, they can be found in the most surprising places, since the plant itself is not very eye-catching.

3.6.3 Chameleon Tongue Pad

The chameleon is known and researched mostly for its color-changing abilities and its powerful and long ballistic tongue ejection. In this chapter the tip of the tongue or the tongue pad is far more interesting. The inspiration of the tongue pad is already used in the product Adaptive shape gripper DHEF by the international company FESTO.

Even though most lizards rely on a sticky adhesive covering their tongue, this does not suffice for the chameleon, due to the high speed of the ejection and retraction of the tongue. Therefore to secure the prey, the tongue pad is crucial. The tongue pad can form a pouch or dimple with two muscles in the tongue. [Herrel et al., 2000]

> *Upon tongue protraction (the slow opening phase), the pouch or dimple (which is usually observed in anaesthetised animals) has disappeared and the tongue pad appears rounded. After projection, but before prey contact, the tongue deforms, and two lip-like structures are created (one ventral and one dorsal).*

Next, the tongue is decelerated and the lips are positioned over the prey. Once the prey has been grabbed, the tongue appears to continue to move over the prey, with the dorsal and ventral lips (mainly the ventral lip) rolling inwards towards the lumen of the pouch in a conveyerbelt-like way. At the onset of tongue retraction, the entire head of large prey, or the entire prey when it is small, is engulfed in the tongue. [Herrel et al., 2000]

This conveyerbelt-like movement of the tongue over the prey is interesting for the design of endoscopes. It is reminiscent of the telescope-endoscope described in Chapter 1.4. A similar idea would be to add two tongue pad-like designs back to back and connect the parts where the muscles would pull inward. This would result in a flexible tube with walls filled with liquid or air to maintain the flexibility of the tube. By pulling the inner surface of the tube backwards, the system would move forward, with the outer surface of the tube sticking to the contact surface and small risings. Due to its flexibility the tube should follow the bends of the intestines by itself without straining or hurting its sensitive walls. This could be used as locomotion system for both the flexible and the capsule endoscope.

The tricky part is fixing the endoscope to the system and the method of moving the tube. The tube could be moved by tracks or wheels which are fixed on the endoscope itself or by systems in the filled walls pushing the front of the system. The endoscope could be prevented from leaving by two discs which are fixed to the endoscope, one in front of the tube and one behind. This was shortly tested in an easy setup of a simple smartphone endoscope and two cardboard discs. Unfortunately a vacuum is created on the inside of the tube, which causes the material of the tube to get caught in every small gap on the endoscope. It was attempted to solve this issue by building a simple ball bearing like system with wire and beads. This does not solve the issue, due to the fact that the vacuum and therefore material prevents the beads from turning. The resulting system is sketched in Figure 52.

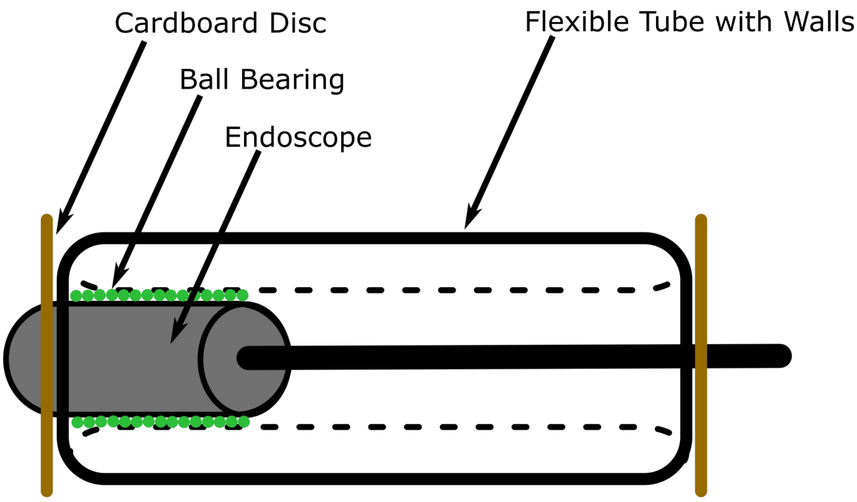


Figure 52: Sketch of the resulting test system of the chameleon tongue pad idea consisting of a flexible tube with filled walls responsible for the movement which was inspired by the chameleon tongue pad, two cardboard discs to secure the used endoscope and a ball bearing to allow the flexible tube unrestricted movement

Although the attempt to realize this idea was not successful, the idea still should be noted here as inspiration for future developments and research concerning the design of endoscopes.

4 Conclusion

In the course of this thesis different milestones in the design of novel motorized endoscopes were achieved. A new method to measure the variation of the dimensions of a moving animal or the endoscopic prototype in a tube was designed and tested. This method can be used to assess the usability of the tested animal as an inspiration for an endoscope, which does not strain the colon by excessive variations in dimensions in all directions. Three prototypes of locomotion systems for the endoscope were created and tested in the most important aspects. One prototype of an autonomous orientation system was built and tested. Three ideas for further locomotion systems for the endoscope were put down on paper.

The testing tube method was developed and tested using two different nets. In these tests it became apparent, that the net with the hexagonal holes (Insect Stop, Emil Lux GmbH & Co., Wermelskirchen, Germany) was better fitted for the method at hand due to its deformability and its ability to copy the form moving through the hole. The deformation of the net can be documented in up to five positions by darkening the hose and overlaying the pictures with different levels of transparency of the pictures with the help of GIMP. The pictures are taken from above and from the front to document as many variations in the dimensions of the test object moving through the hose as possible. This method is animal friendly and economic and can be useful in further research in this field.

Three prototypes based on different animal locomotions were built with the LEGO® Mindstorms® EV3 Set. The SNAKE prototype is based on the scales of snakes, the MOLE prototype is based on the burrowing and crawling motion of the mole and the FOOTSTEP prototype is based on tetrapod vertebrates ambling. All prototypes only use one motor and are therefore not able to turn on command.

The first measurements conducted to characterize the locomotion prototypes were the initial force measurements. These measurements were carried out with the help of the movable wall and a spring balance. The measurements of the prototypes all range between 0.01 N and 0.03 N and are considerably gentler in contact with the wall than the comparison system with tank tracks with around 0.18 N as initial force.

The second measurements conducted to characterize the locomotion prototypes were the maximum force and weight measurements. These measurements were carried out with the help of the movable wall and a spring balance or sand and a scale. Due to the poor reading precision of only 0.01 N steps on the spring balance the experiment was backed up by the measurements of the maximum weight with sand and a scale. The MOLE prototype has the highest maximum force both with and without the half sphere attached. The FOOTSTEP prototype has the lowest maximum force, but has difficulties moving over the rough surface mimicking the colon walls. The SNAKE prototype has values in the same range as the MOLE prototype. A significant difference is the ability to turn by itself when in contact with a wall, which the MOLE prototype does not possess. The value of the maximum force when the SNAKE prototype turns can be lowered by attaching the half sphere to its front. The results were in large part confirmed by the maximum weight measurements.

The pressure foils (Prescale Ultra Extreme Low (5LW), FUJIFILM) were used to document and analyze the pressure profiles of the three prototypes. An ideal endoscopic device should distribute its weight evenly without pressure peaks. All prototypes left very interesting pressure markings on the pressure foils with various indications for future improvements. The SNAKE prototype's pressure markings only showed one saw tooth on each side. Here the number of saw teeth contacting the ground could be improved as well as the supporting wheels, which could be stabilized to stay in contact with the ground in future editions of this prototype. The pulling part of the MOLE prototype was too light to be registered by the pressure foils and therefore left no marks. This could be updated in future editions of the prototype to distribute the weight and increase the pulling strength of the prototype. The SNAKE prototype as well as the MOLE prototype show no signs of slipping. The FOOTSTEP prototype's pressure markings are, as expected, a shuffling motion of the four feet. In future editions of the prototype the feet could be angled so that the prototype uses as much contact surface as possible so not only the outlines can be seen as pressure peaks on the foil.

Determined by all the tests conducted the most promising prototype is the SNAKE prototype. The colon walls are treated with care by its movement and the prototype turns by itself when in direct contact with a vertical colon wall. It should overcome the rough surface of the colon walls with ease and there is only a minimal risk of the prototype getting caught in folds of the colon wall. The MOLE prototype has promising pressure markings on the pressure foils, but the self turning when in contact with a vertical colon wall is not given. This can be an issue, especially when there is a similar situation to the measurements with the movable wall, where the arms of the prototype got caught in the gap beneath the wall, where the maximum force increased. This shows an increased risk of the prototypes arms getting caught in the folds of the colon walls. This has to be considered when improving the prototype in the future. The FOOTSTEP prototype is hardly usable for the endoscopy design. The shuffling of the feet strain the colon walls and the feet would get caught on the smallest bumps of the colon walls. Already there was almost no movement of the prototype on fleece, which was used to mimic the soft and rough colon walls.

An autonomous maneuver system was designed and tested with the help of sensors contained in the LEGO® Mindstorms® EV3 Set. Two touch sensors were mounted on movable arms opposite to each other to be able to stay in contact with the colon walls or detect these. This system was named WHISKERS due to its resemblance to whiskers and feelers in the fauna of the Earth. The system reacts as follows: as long as both touch sensors are in contact with the wall, the system moves forward, as soon as one touch sensor loses contact, the system turns in the direction of the touch sensor which lost contact until it is pressed again. This should help the system to follow the narrow passages of the colon. In the event of a wider passage of the colon, the system moves forward as long as both touch sensors are not pressed. In the event of one of the touch sensors making contact with a colon wall, the system turns in the opposite direction until the touch sensor loses contact again or the other one is pressed as well. With this simple programming of the system moving when both or none of the touch sensors are in contact with the colon wall and turning in the direction of open space, a promising and developable system was created. The first step in improving this system is the elimination of the contact to the colon walls by replacing the touch sensors with infrared sensors.

Three biomimetic locomotion system ideas were not realizable with interlocking bricks. These ideas are described and partly sketched in this thesis. The inspiration behind these ideas are the wheat awn, the Redstem Stork's Bill seed and the chameleon tongue pad.

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I want to thank Mr. Christian Gauss for letting us experiment with his fosterlings the snakes and donating us so much of his time, even though the experiments were not realizable. I hope all of our test subjects have already found a nice home.

Last but not least I want to thank my family and friends for supporting me throughout all times, even the seemingly hardest.

Glossary

gastrointestinal tract includes the four organs responsible for digestion

esophagus the tube that connects the mouth to the stomach

colon large intestine

endoscope device used to examine the gastrointestinal tract without surgery

PD Public Domain

duodenum the first part of the small intestine

villi small, finger-like projections that extend into the lumen of the small intestine (singular: villum)

chyme mass of semi-digested food

lumen the interior of the gastrointestinal tract

mucus a slippery aqueous secretion

peristalsis a radially symmetric periodic contraction and relaxation of muscles to advance the chyme

segmentation breakdown of the chyme in smaller parts

van der Waals forces relatively weak non-covalent distance-dependent interaction between atoms and molecules

cybernetics the scientific study of control and communication in animals and machines

tetrapod vertebrates animals with four legs

dorsal the back or upper side of an organism

ventral the front or lower side of an organism

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