8/17/2021

Bioinspired Design of a Soft Self-Propelling Radially Expanding Mechanism for Flexible Colonoscopes

Sebastiaan P. van Gelder

Bioinspired Design of a Radially Expanding Soft Self-Propelling Mechanism for Flexible Colonoscopes

By

Sebastiaan P. van Gelder

in partial fulfilment of the requirements for the degree of

Master of Science
In Mechanical Engineering
at the Delft University of Technology,
to be defended publicly on Tuesday August 24, 2021 at 13:30h.

Master: Mechanical Engineering
Track: Bioinspired Design (BMD)
Specialization: Bioinspired Technology (BITE)

Student:	Sebastiaan P. van Gelder	
Student nr.:	4237404	
Supervisor:	Dr. ir. Aimée Sakes	TU Delft
	Ir. Fabian Trauzettel	TU Delft
Thesis committee:	Prof. dr. ir. Paul Breedveld	TU Delft

An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft

Acknowledgements

This thesis has been a valuable learning experience throughout. Therefor I wish to express my gratitude to the individuals who supported me along the way. Firstly, I would like to thank my supervisor Aimée Sakes for all her help and guidance in completing this project from start to finish. I am also grateful to Fabian Trauzettel for his assistance in creating the prototype and his help with the experiments. Thanks also to Paul Breedveld for his detailed feedback on the report.

Abstract

Background: Currently colonoscopies are difficult procedures to complete without complications. Due to the limitations in the state of the art flexible colonoscopes specialized maneuvers are required in order to allow the colonoscope to travel into the colon and reduce colon stretching. This thesis proposes a novel self-propelling mechanism designed to enhance the current flexible colonoscopes allowing for a better completion rate and fewer complications in colonoscopies.

Methods: First an analysis was made of the fundamental types of propulsion and how well they could be used for locomotion inside the human colon. In order to determine the conditions the design has to meet a list of requirements was made. A wide variety of concepts were considered, which were then reduced to the three most promising concepts. These concepts were further developed and out of these, the most promising design was chosen. This design was adjusted in order to create a proof-of-principle prototype which was used to validate the design and give new insights into the type of self-propulsion used.

Results: The prototype is able to perform locomotion in all tested tube/instrument diameter combinations, including tubes with a significant larger diameter than the instrument. Furthermore, the prototype is also able to perform well in tubes with an irregular shape and with a conical shape, both with and without lubrication. The effect of added weight to the tubes was also investigated and showed no significant effect. The efficiency of the prototype, as determined by the slip ratio, showed no significant variation during these tests.

Discussion and Conclusion: The proof-of-principle experiments demonstrated that the design is capable of performing locomotion in the tested scenarios with better than expected efficiency. The lack of significant variation of slip ratio in tubes with a larger diameter than the prototype itself were unexpected and could significantly change the design of future iterations of the instrument. The issues which came up during the experiment gave new insights into the working of this type of locomotion which were used to make recommendations for future iterations of the design and recommendations for further tests, which could be performed to investigate unexplained results. The current design meets all the requirements set out for it and gave valuable new insights which will be useful for future iterations of the design making it a good first step towards developing a better colonoscope.

Table of Contents

1. Introduction

1.1. Background

1.1.1. Colonoscopy

An endoscopic examination of the large bowel or the distal part of the small bowel is called a colonoscopy. During the procedure as shown in Figure 1 a camera on a flexible tube, an endoscope, passes though the anus into the large bowel in order to allow the endoscopist to give a visual diagnosis and the taking of biopsies or removal of suspected cancer lesions. Different types of endoscopes exist for different types of endoscopic interventions. The endoscope type used for colonoscopy is called a colonoscope.

Colonoscopy is considered to be a very safe procedure, the overall risk of complications, such as colon wall perforation, for routine colonoscopy is estimated to be about 1.6% [1]. However, with 14.2 million colonoscopies performed in 2002 in the United States alone [2] many patients are nevertheless suffering from those complications. Of all the types of endoscopic examinations colonoscopy is one of the most difficult due to the nature of the colon walls and the length and the shapes of the bends found in the large bowel. As a result colonoscopies are time-consuming and difficult to master procedures, which requires endoscopists to frequently train in specialized maneuvers which reduces case throughput and increases costs [3]. In order to obtain competence in colonoscopies between 175 and 400 performed colonoscopies are required.

1.1.2. The Large Bowel

The large bowel, or large intestine, is the last part of the gastrointestinal tract and consists of the cecum, colon and rectum. The average length of the colon in men is 166cm and 160.5cm in women [4]. The colon is almost at the end of the gastrointestinal tract, right before the rectum and the anus. It is responsible for extracting water and salt from solid wastes before they pass out of the body through the rectum and the anus. Fermentation of unabsorbed materials also occurs in the colon. The entire length of the colon has a wrinkled inner surface in order to increase the surface area which helps with the extraction of water and salt.

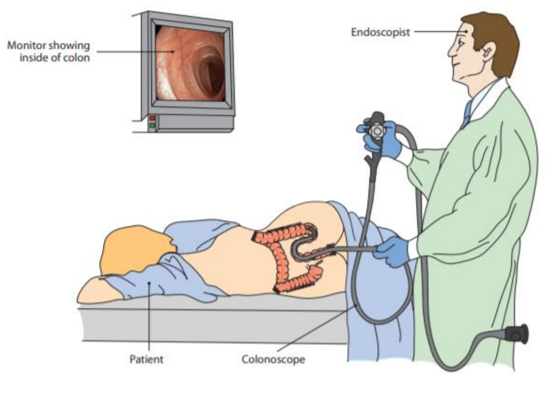


Figure 1: Impression of a colonoscopy. From: A.J. Loeve 2012 [5].

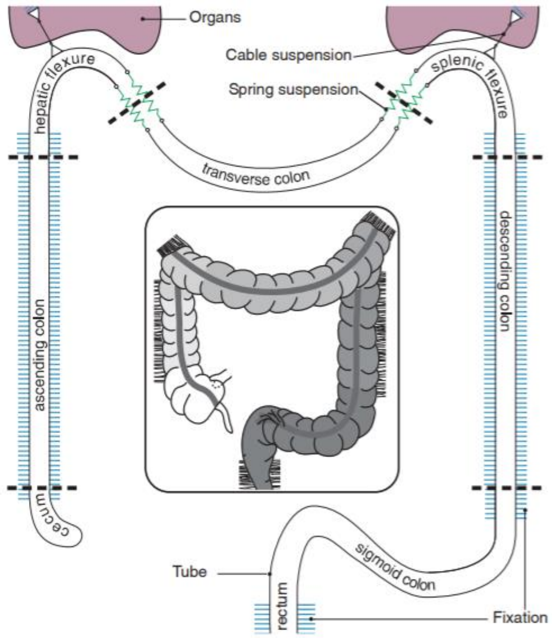


Figure 2: Average colon anatomy (center frame) and modeled colon (around center frame). From A.J. Loeve 2012 [5].

Figure 2 shows the average anatomy of the colon and a model used to represent the mechanical properties of the colon. For a detailed explanation of the model consult A.J. Loeve 2012 [5]. The length and shape of the colon can make a colonoscopy very difficult as the endoscopist has to guide the colonoscope through a long path with some corners that are difficult to navigate. Sometimes the patient's position is altered during a colonoscopy in order to let the colon drop into a better position or to let gravity help propel the colonoscope.

1.1.3. Flexible Colonoscopes

Flexible colonoscopes are long, thin and flexible tubes. The state of the art flexible colonoscopes have a steerable tip which the endoscopist can use to guide the colonoscope through the colon. The tip of the colonoscope has a small camera with lights so the endoscopist can visually observe the patient's internal tissue. The steerable tip is controlled with a handle as can be seen in Figure 1, for single or multidirectional steering. In the case of single directional steering tips the tube needs to be rigid in axial torsion so the endoscopist can add a degree of freedom by rotating the colonoscope.

The center of the colonoscope has multiple hollow tubes, called lumens, running to the tip. These lumen are used to flush the colon with water, inflate the colon with air or CO2 for improved view and workspace, and to insert instruments for taking biopsies or performing surgery. Bowden cables and electronic wires run from the handle to the tip of the colonoscope in order to actuate the steering tip and power the electronic equipment in the tip. While the length and diameter of different types of colonoscopes differ they are generally about 1.8 meters long and have a diameter within the 5 to 15 millimeter range [5].

1.2. Problem statement

1.2.1. Problem Introduction

During colonoscopy the endoscopist advances the colonoscope through the large bowel by manually pushing it forward. The bends of the large bowel are navigated by pushing the colonoscope against the intestine wall, which will stretch due to its flexible nature and provide a counter force which guides the colonoscope through the bend, as can be seen in Figure 3. Excessive stretching of the colon can be painful for the patient [5] and causes the colon wall to thin and puts it under tension, which increases the risk of colon wall perforation [6]. The colonoscope's stiffness can be modelled with ideal spring properties [5], therefore the amount of force

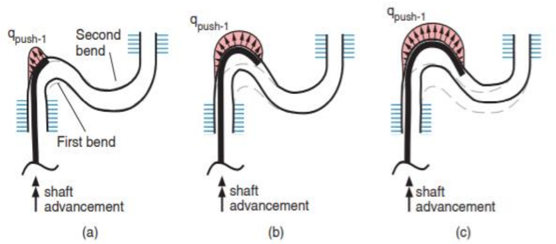


Figure 3: The three stages of scope advancement through the first bend of the sigmoid colon and the normal forces (q_{push-1})that are exerted by the scope shaft on the colon wall. (a) First stage: bend enlargement is mainly caused by moving the colon. (b) Second stage: bend enlargement is mainly caused by stretching the colon. (c) Third stage: equilibrium. From A.J. Loeve 2012 [5].

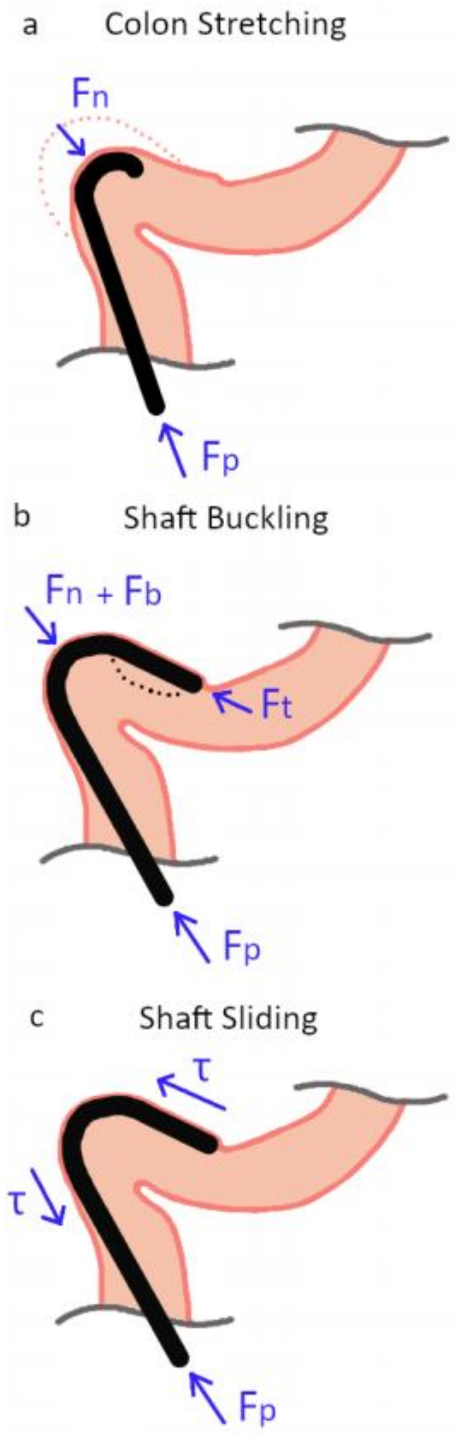


Figure 4: (a) Colon stretching due to partial transmission of the colonoscope's push insertion forces (F_p) applied to the colon in the form of normal forces (F_n) at the contact point. (b) Shaft buckling and the subsequent transmission of bucking forces (F_b) due to the combination of reaction forces at the tip (F_t) and the push insertion forces at the handle (F_p). (c) Transmission of shear forces (τ) due to the frictional nature of the contact interaction between the sliding colonoscope shaft and the stationary colon wall. From D. Verheijen 2021 [7].

the colonoscope applies to the colon wall is dependent on how far the colonoscope bends and its stiffness.

Another force affecting the colon wall is the force at the tip of the colonoscope as shown in Figure 4. This force in combination with the posterior insertion pushing force causes an axial compressive load on the tip of the colonoscope. Due to the long, slender and flexible nature of the colonoscope it is very prone to buckling when loaded with axial compressive loads. The buckling will also cause the buckled area to act as a spring pushing back into the bend of the colon which will increase the force acting on the intestine wall. This increases the discomforted of the patient as well as the chances of wall perforation.

The colon wall is also affected by the shear forces which result from the sliding contact of the colonoscope with the colon wall. Because there are membranes inside the colon which secrete mucus, this friction is initially very small due to the natural lubrication. However during prolonged sliding contact between the colonoscope and the colon wall the mucus will be gradually pushed away from the contact area. Like the normal forces these shear forces further increase the stretching of the colon wall and thereby increase the discomfort of the patient and the chance of complications such as wall perforation [7].

Many different methods have been developed in order to straighten different types of bends and loops encountered in the large bowel and a lot of care is taken to make sure the loops are properly straightened before moving on the next part of the bowel. This both reduces the stretching of the colon and is necessary for the colonoscope to be pushed all the way to the back of the large bowel. This is especially important in the sigmoid colon as this is one of the first parts the colonoscope passes through, it being connected to the rectum, and it is also very loose compared to the rest of the colon. When the loops in the sigmoid colon are not properly straightened before advancing through the descending colon, recurrent looping might occur due to buckling in the shaft as shown in Figure 5. This is not only an issue due to the stretching of the sigmoid colon but also because it causes the tip of the colonoscope to go backwards while the proximal shaft is pushed forwards. Because the endoscopist has no visual on the behavior of the colonoscope this can significantly complicate scope insertion. For example if the endoscopist is trying to navigate the loop further in the bowel those

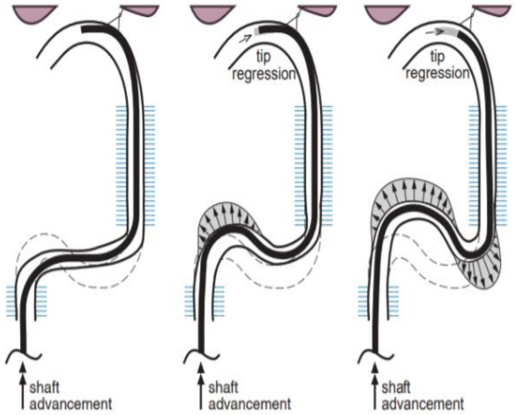


Figure 5: Starting recurrent looping. When loops in the sigmoid colon form, the tip can go backwards while the proximal shaft is pushed forward. From A.J. Loeve 2012 [5].

maneuvers might cause loops in the sigmoid colon to reform.

Currently the problems described in this chapter need to be prevented by the application of highly skilled maneuvers such as N-loops and α-loops. These maneuvers require a lot of practice to master which makes colonoscopies difficult, expensive, time consuming, painful for the patient, and reduces the success rate [3]. By improving the design of the flexible colonoscope the procedure could be made significantly easier which in turn could decrease cost, reduce procedure time, reduce the chance of complications during the procedure, increase success rates and reduce the pain experienced by the patient. By reducing the pain the need for anesthetic is also reduced which will further diminish the risk of complications during the procedure.

1.2.2. Limitations of Flexible Colonoscopes

The current method of performing colonoscopies requires the bending stiffness of the colonoscope to be both flexible and rigid. It needs to be flexible to reduce the forces applied to the colon wall when navigating bends. It needs to be rigid in order to be able to transmit the posteriorly applied push forces, prevent buckling due to the compressive loads and facilitate the tip stability required to perform medical procedures with the instrument that runs through the lumen.

Due to the long, thin and flexible nature of the colonoscopes, an example of which is shown in Figure 6, buckling is a recurring problem both in the navigation of loops by the tip and preventing recurrent loops from forming. The buckling issue can be addressed either by increasing the bending

Figure 6: A State of the art flexible steerable colonoscope.

stiffness, reducing the inserted length of the colonoscope, increasing the diameter of the colonoscope or changing the way the force is applied to the colonoscope. The issues with the bending stiffness have already been discussed and the diameter of the colonoscope cannot be increased due to the size of the colon. The inserted length of the colonoscope also cannot be changed as it is determined by how far the procedure needs to reach into the colon.

The way the force is applied however could be changed by adding a self-propelling element to the colonoscope. By having the colonoscope propel itself forward near the tip of the instrument the compressive load will not be acting on the instrument behind the self-propelling element and the length of the instrument which is loaded in compression will be much smaller which significantly reduces the chance of buckling. By having multiple of these elements placed along the length of the instrument the overall load can also be reduced as each element will have to produce less force. If the self-propelling element can be used to anchor the colonoscope near the tip it will also provide the tip with the stability required to perform medical procedures. Because of this the colonoscope will no longer have the need for a rigid bending stiffness which should reduce the stretching of the colon walls and make colonoscopies easier to perform.

1.3. Scope & Goal

In order to reduce the complexity of colonoscopies, and by doing so increasing the success rate, patient comfort and reducing endoscopist skill requirements an improved colonoscope needs to be designed. A major improvement on the current flexible colonoscope would be the addition of a self-propelling element. This thesis will focus on designing such a self-propelling element and creating a proof-of-principle prototype.

This type of improvement of the colonoscope has remained largely unexplored. This thesis will act as a starting point to develop new types of colonoscopes capable of self-propulsion. Therefore, the focus will be on assessing the functionality of the proof-of-principle prototype, analyzing how the mechanical principles it uses for self-propulsion work in practice and making recommendations based on that analysis.

In order to focus on the mechanical principles of the self-propelling system the readiness of the design to be used for application in a human colon is outside of the scope of this thesis. Furthermore the proof-of-principle will be tested in a straight tube as adding the ability of navigating bends would greatly complicate both the design and production of the prototype. Consideration will be given to the ability to add this functionality in later design, but it will not be included in the prototype of this thesis.

The goal of this thesis is to design and evaluate a self-propelling probe for the purpose of propagating a flexible colonoscope through a human colon in a way that prevents shaft buckling and inherently limits the forces acting on the colon wall.

1.4. Layout of this Study

In Chapter 2 the different types of self-propulsion will be explored and analyzed in order to determine how suitable they are for use in the human colon. Next a set of requirements will be discussed in Chapter 3. These will be used in the design method which is explained in Chapter 4, followed by the three most promising concepts which came out of the process. One of those concepts will be selected, and based on that a design will be made for the instrument. In Chapter 5 the development of the proof-of-principle prototype will be discussed. Chapter 6 explains the proof-of-principle experiments which were performed to validate the design. The results of the experiments and the recommendations based on those results are discussed in Chapter 7. Finally the conclusion will be drawn about how well the design meets the requirements set out for it in Chapter 8.

2. Self-Propulsion in the Colon

2.1. Self-Propulsion: Fundamental Mechanisms

New concepts for surgical instruments are continually being developed all over the world. Most of the self-propelling concepts designed for use in the colon or a similar environment can be categorized in the methods shown in Figure 7. The current state of the art flexible colonoscopes use the application of external force by having the endoscopist manually push the colonoscope forwards. There are other ways to apply an external force on the instrument, such as electromagnetic fields, but those methods are difficult to apply inside the human body and are difficult to control. These types of propulsion are not self-propulsion because they use an external force to move the instrument. For the purpose of this instrument self-propulsion will be defined as "the ability to move the tip of the instrument forwards though the colon without external forces". The types of self-propulsion can be divided in two categories: self-propulsion through interaction with the environment or self-propulsion through internal instrument interactions. If a method works in a vacuum it uses internal interactions, if it does not it relies on interactions with the environment.

Most designs which incorporate self-propelling mechanisms use the environment for locomotion by manipulating friction in some way. Friction always works in the opposite direction of the direction of movement which generally hinders propulsion instead of enabling it. However by moving parts of the instrument backwards and increasing the friction in those parts significantly, the friction can be used to move the instrument forwards as a whole. These instruments can be divided into 3 categories: manipulating the normal force, manipulating the friction coefficient and manipulating the contact area.

There are also ways to achieve self-propulsion by internal instrument interactions. By changing the shape of the instrument and the resultant inertial forces the tip of the instrument can be propelled forwards. These types of prolusion can be categorized as creating a reaction force by reducing the mass though ejecting it from the instrument at speed, redistributing the mass of the instrument or increasing the mass of the instrument. Very few designs use mass ejection as a means of propulsion due to the inherent difficulties in controlling such systems in a small enclosed space. There are some concepts which increase the length of the instrument instead of moving the instrument forward. By increasing the length and keeping the center of mass at the same point the front end is forced to move forwards. The length of the instrument can either be changed by redistributing the mass or by increasing the mass. This type of instruments generally needs a way to decrease their length back to the original size as the increase in mass, and the resultant increase in volume, can also cause the instrument to anchor itself to places inside the colon which would complicate pulling the instrument out.

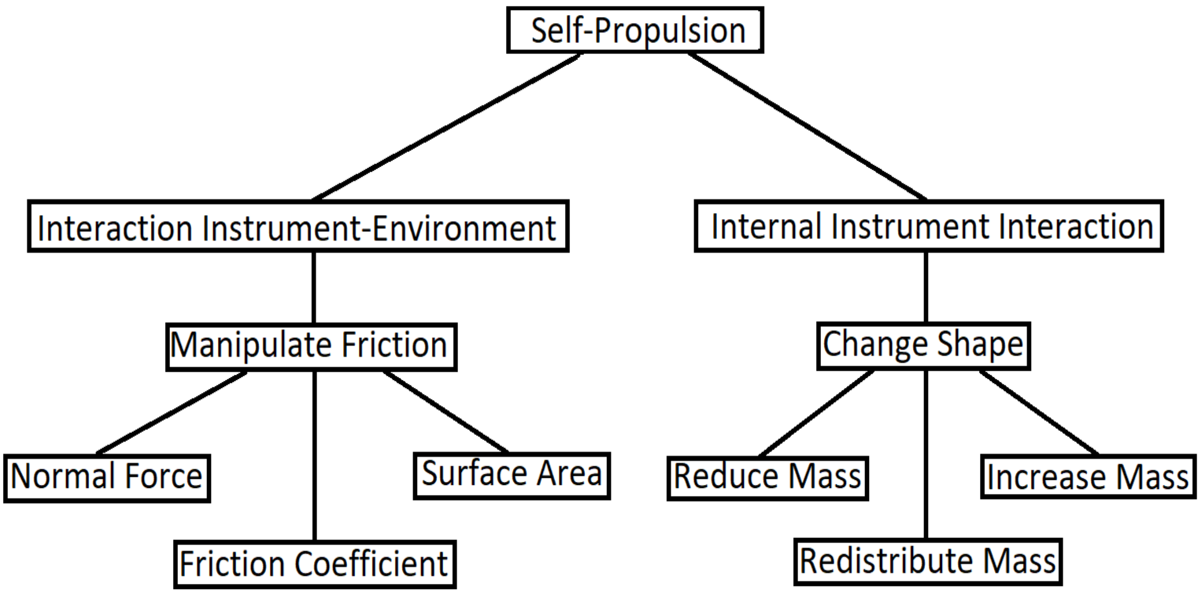


Figure 7: Tree of different fundamental types of propulsion.

2.2. Self-Propulsion by Manipulating Friction with the Environment

2.2.1. Normal Force

When looking to nature for inspiration the earthworm seems like an excellent example to take inspiration from. Both the shape and locomotion method of the earthworm are very similar to what the instrument could be. The earthworm uses peristaltic contractions of its segments in order to perform locomotion: when segments contract they become wider in the radial direction and shorter in the axial direction. These contractions move in the opposite direction of the movement, which causes a friction force on the earthworm in the direction of movement, as shown in Figure 8. About half of the worm's length is contracted during the peristaltic movement, but because the contracted part is thicker its normal force is greater. The earthworm also has small hairs which extent when the segments contract to increase the friction coefficient called setae. The friction force of the contracted part is therefore greater than the friction force of the non-contracted, resulting in a movement against the direction of contraction.

Both snake-like movement and stepping use a similar fundamental mechanism by having the part which supports the most weight, and therefore has the most normal force in the contact area with the surrounding, move in the opposite direction as the movement of the body as a whole. The resultant friction force propels the body as a whole forward after which the weight is shifted to a new part of the body which repeats the process.

Another way to create a forward friction force is by having the outside of the instrument moving

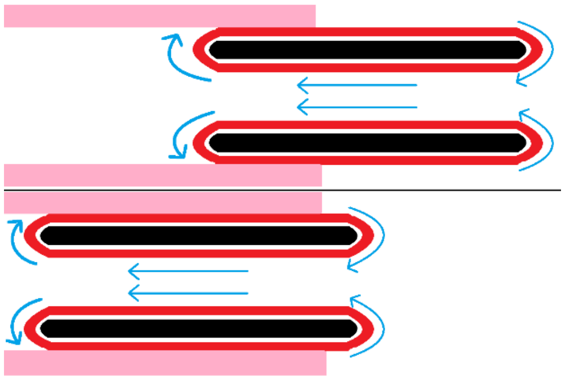


Figure 9: Schematic of an instrument using circular tracks.

in the opposite direction, in the same way a track vehicle moves forwards [8]. By using a tube which is stiff in axial direction and bendable in two directions, a soft film can be pushed from the inside of the tube and be pulled at on the outside of the tube as shown in Figure 9. This method of locomotion has the advantage of using the entire surface area of the instrument. One of the issues with these types of locomotion is that they require continues rotations which are more difficult to create than axial translations in such a narrow instrument.

2.2.2. Friction Coefficient

Manipulating the friction coefficient is mainly done using structures which have an anisotropic friction coefficient. What this means is that the friction coefficient changes depending on the direction of movement. By increasing the friction coefficient in one direction movement can be created in the opposite direction. This can be done by moving back and forth in the direction of movement, because the increased friction force will prevent the

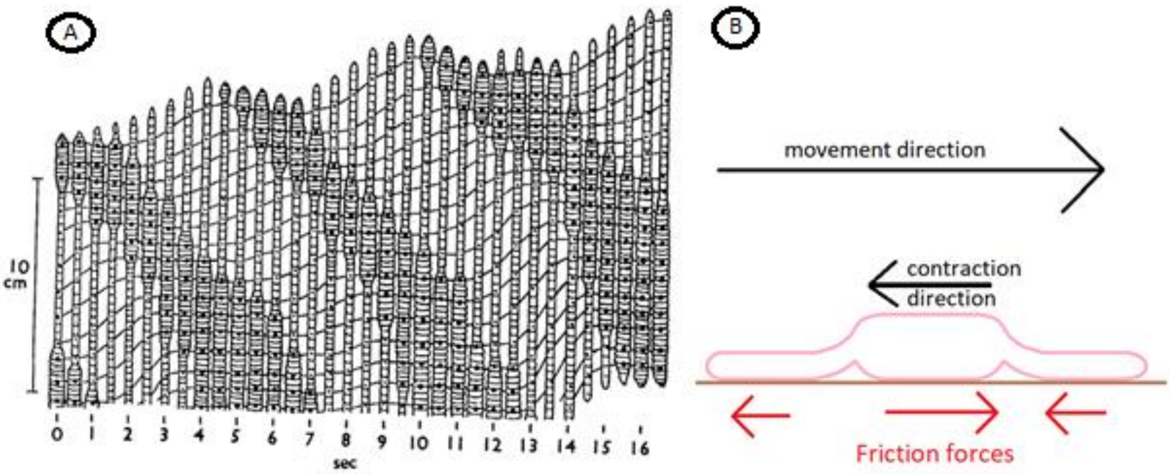


Figure 8: (A) The stage of peristaltic locomotion of a earthworm. Figure adapted from Gray et al. [9]. (B) Friction forces of peristaltic locomotion.

slip in one direction which results in locomotion, or it can be done by using a structure which has a larger friction coefficient in one of the perpendicular direction as the direction of movement. An example of the latter would be a corkscrew structure. By applying a corkscrew structure to the outside of a cylinder and rotating it against the environment, locomotion in the axial direction of the cylinder can be achieved. The locomotion is caused by the anisotropic friction coefficient in the perpendicular direction to the direction of movement of the outside of the cylinder. One of the main issues with this type of self-propulsion is retracting the instrument. If the anisotropic friction cannot be reversed it will hinder the retraction of the instrument potentially causing it to get stuck in the patient. The corkscrew structure solves this problem because can be used to go either forwards or backwards depending on the direction the cylinder is rotated in.

2.2.3. Contact Area

There are several species of parasitoid wasps which use ovipositors to inject their eggs into wood or fruit. Ovipositors are long, thin and flexible needle like structures which are capable of locomotion inside the wood and fruit and are even capable of limited steering in two directions. The needle-like ovipositor is made out of three longitudinal segments. These segments can slide forward one at a time using the wasp's abdominal muscles. By pushing one of these segments forward at a time the static friction force of the stationary segments will be greater that the dynamic friction force of the moving segment due to the greater surface area. This extra friction force is used as the grip required to overcome the resistance force of the tip of the moving segment. The ovipositors also have serrated extrusions to give additional grip. These types of ovipositors have a limited steering ability. This is done by extending one segment of the ovipositor ahead of the others, this will result in an unbalanced friction force to be applied on the ovipositor which results in a torque being applied and the bending of the ovipositor.

2.3. Self-Propulsion by Changing Shape

2.3.1. Reducing Mass

Reducing the mass of the instrument by ejecting it from the instrument at speed causes a reaction force which can be used to achieve self-propulsion. A few designs use mass ejection as a means of propulsion. The design made by L. Yin et al. 2018 [10] is an example of this concept. It uses the reaction force of ejecting water through a water jet to control the tip of an endoscope, as shown in Figure 10. The downsides to this kind of actuation is that it is very difficult to control, it requires a continued supply of water or other kind of material and the ejected material is left behind in the patient's body. This concept would be even harder to use in the colon compared to the stomach as there is much less space to work with. The example also uses the water jets for the control of the tip and not propulsion, as using this method for propulsion would require even more material as the amount of mass that needs to be moved and the distance of which it needs to be moved increases greatly.

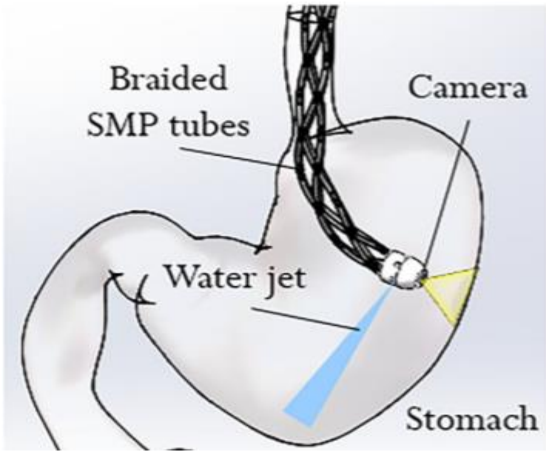


Figure 10: An example of a design using mass ejection as a means of propulsion. From: L Yin et a;. 2018 [10].

2.3.2. Redistributing Mass

Another way to move the tip of the instrument forward is by expanding the length of the instrument. This can be done by redistributing the mass of the instrument, increasing the length by decreasing the width or creating hollow spaces in the instrument. The center of mass does not need to change position for this type of propulsion to work because we only care about the position of the tip of the instrument. Moving the center of mass will result in inertia forces which could move the rest of the instrument however the inertia forces are unlikely to overcome the friction forces the colon would force on the instrument. This type of self-propulsion is unlikely to be useful for locomotion in the colon as it is very limited in the amount of force it can apply and the instrument would have to increase its length by multiple time its original length which would be very challenging.

2.3.3. Increasing Mass

Another way of increasing the length of the instrument is by increasing the mass and thereby the volume. An example of this would be using an inverted tube. By twisting a flexible tube into itself a structure which “grows” can be created. By inflating the tube, the volume will try to increase which it does by pushing the inverted part out of the front end. This causes the instrument to become longer and so simulate forward locomotion as can be seen in Figure 11. One of the advantages of this design is that the entire outside surface area is used to prevent slip and that it can remain stationary. The surface area will still need to provide a friction force in order to overcome resistance of the point which is being pushed. This type of growth can also be reversed in order to remove the instrument by pulling the inverted part backwards.

2.4. Self-Propulsion: Mechanisms Comparison & Design Direction

All of these methods can enable locomotion however some of the methods more suitable for self-propulsion in the colon than others. The most viable methods are those which manipulate friction, though some of these methods still have their own challenges. The surface area method for example is depended on the friction forces acting on the surface area to be distributed relatively evenly. While the growing concept would not have this challenge it will be difficult to create a stable tip for this concept, as the part of the instrument which is the tip will constantly change. The normal force and contact area methods are the most viable concepts here as they combine best with the environment in which the instrument will be used.

3. Requirements

3.1. Categories

This chapter will discuss the design requirement for the soft self-propelling element for the flexible colonoscope. The requirements are split into 3 categories: size, locomotion and soft behavior. The size category will discuss the limits of the different geometric requirements of the instrument. The atraumatic navigation category discusses the requirement for the instrument to propel itself through the human colon without causing harm or serious discomfort to the patient. Some of the requirements apply differently to the design and to

Figure 11: Schematic of a concept using a growing type of locomotion.

the proof-of-principle prototype in order to not introduce unnecessary complexity in the fabrication of the prototype. Because this thesis is only meant as an initial stepping stone for further exploration of a new type of colonoscope some aspects which are important for the functioning of a colonoscope have not been taken into account such as the biocompatibility, bending stiffness, lumen and the steerable tip.

3.2. Size

3.2.1. Size in the Colon

Most self-propulsion mechanisms rely on contact with the environment to push themselves forward. However if the instrument has a smaller diameter than the colon the contact area might either be too small for effective locomotion or it could be effected by some other abnormality like a particularly sticky patch. By adding a mechanism which allow the instrument to expand its radius the diameter of the instrument can always match the diameter of the colon. This will ensure the maximum available contact area is used and reduce the risk of small abnormalities effecting the locomotion. By expanding the instrument’s radius even further the normal force between the instrument and the environment will increase which will increase the grip of the instrument. Another benefit would be the ability to anchor the tip of the instrument to the environment which gives the endoscopist the stability required to take biopsies or perform surgery.

3.2.2. Instrument Diameter

The diameter of a colonoscope is usually up to 15 mm. This will be used for the maximum outer diameter of the instrument. This requirement does not apply to the parts of the instrument which can expand the diameter. These parts do not have a requirement for a maximum outer diameter in their extended modes though they should be able to precisely control the size of their diameter. In their minimal diameter mode they should not be larger than 15 mm diameter.

3.2.3. Instrument Length

The colonoscopes used in colonoscopies are up to 1.8 meters long [5]. However the instrument designed in this thesis is intended as a proof-of-principle prototype which means it does not need to be that long. It should be able to either move the entire 1.8 meter colonoscope with it. Alternatively it should be repeatable along the length of the colonoscope so it can break the length down into smaller part which it can move.

3.3. Locomotion

3.3.1. Self-Propulsion

The instrument needs to be able to navigate the colon on its own power. It needs to be able to generate enough force to propel itself forwards in the test environments without any outside force being applied.

3.3.2. Retraction

The design of the instrument needs to be able to propel itself both forwards and backwards. In order to simplify the fabrication of the proof-of-principle prototype, this requirement will not apply to the prototype but type of propulsion used will have to be able to theoretically navigate both forwards and backwards.

3.4. Soft Behavior

One of the main concerns for the design of this colonoscope is how to reduce the deformation of the colon walls. Having the endoscopist keep the deformations below the threshold where they could cause significant patient discomfort would be almost impossible because the feedback the endoscopist gets from the colonoscope is very limited. Therefor a solution is required which inherently limits the deformation the instrument can apply on the colon walls. By making the colonoscope soft the forces the colonoscope applies on the colon wall gets distributed over a larger area which will limit the deformations they cause. Soft instruments are inherently safer due to this force dissipating property, which should reduce the risk of complications and increase completion rates of colonoscopies.

There is no generally accepted definition of when an instrument is soft as it is a very relative term. In the case of the colonoscope it would mean having a stiffness comparable to or more flexible than the stiffness of the colon wall. There is also the directions to take into considerations. Just like the degrees of freedom an object has, 3 translations and 3 rotations, you could also give an object degrees of softness, though this is a simplification of reality as soft objects have infinite degrees of freedom. The translations would change into how easily the object deforms in a certain direction. The rotations would change into the bending stiffness of the object in the same directions. In the case of the colonoscope you would require it to be soft in both radial directions so the colon wall can push back against the instrument. It cannot however be soft in the axial direction as that would hinder the self-propelling aspect of the instrument by causing it to compress instead of move forward. The bending stiffness would remain unchanged from the flexible colonoscope. The bending stiffness in the radial directions still needs be to flexible in order for the colonoscope to follow the shape of the colon and the bending stiffness in the axial direction would still need to be rigid in order to prevent the lumens and other internal mechanisms from getting jammed due to axial twist. Another aspect to take into consideration with soft objects is if the degrees of softness are connected in some way. For example a balloon filled with water has a constant volume which means the compression in one direction affects the compression in another. Whether this is relevant for the colonoscope is mainly dependent on how it will be controlled.

A hard material can be made soft by using a structure which makes it soft, for example a piece of paper is made out of wood which is a hard material but due to how thin it is it becomes soft in 2 directions and 2 rotations. Conversely soft materials and structures can also be made hard, for example by inflating a car tire it becomes hard in all directions where it was soft while deflated.

The instrument needs to be soft in both radial directions and rigid in the axial direction. No overall guidelines as to when an instrument is considered soft have been established as the term is often relative. For the purpose of the colonoscope it would have to be about as soft as the colon. However for the proof-of-principle prototype presented in this thesis that would complicate the fabrication unnecessarily. Instead the prototype will need to be compliant relative to the environment it will be tested in which will be a rigid UV-hardened resin.

4. Design Process

4.1. Abstracting and Categorizing

The relevant types of self-propulsion were abstracted and categorized in Chapter 2. Promising examples of locomotion found in nature and engineering were also abstracted and used as examples of those categories. The categories were analyzed to find out if they are suitable for use in colonoscopies. For every example found an analysis was made to figure out how the force which leads to locomotion is generated and how this relates to the other examples. This was done both to explore the different solutions which already exist and gain increased insight into how forces can lead to locomotion. The categories are: Normal Force, Friction Coefficient, Surface Area, Redistributing Mass, Increase Mass and Reduce Mass.

4.2. Morphological Diagram

In order to extensively explore the different possibilities of self-propelling mechanisms the morphological chart of Figure 12 was used. The purpose of this chart is to take an abstracted concept on each axis and create a simple design of how those concepts would combine. In this case the first abstraction was about the types of Self-Propulsion. Because of the large amount of examples in the Normal Force category this was further divided into: Stepping, Snake, Earthworm, Wheels/Tracks. The second abstraction was the different types of actuators which could be used to power those types of locomotion. By creating this morphological table and filling in the existing designs, further possibilities can be discovered by exploring the design void. The design voids are the combinations of the axis for which no design exists yet. The axis with different types of actuators consists of: electromagnetic fields, linear actuators, cables, SMA springs, bellows, the patients muscles and rotary actuators. Short descriptions of the different types of actuator will be given below.

Electromagnetic fields

Using the repulsion effect of two same sided poles or the attracting effects of two different sided poles of electromagnetic fields, propulsion forces can be generated by moving magnets close to each other or generating electromagnetic fields near magnets. Because the human body is not made out of magnetic material the electromagnetic field can pass through it which allows part of the actuators to be outside of the body.

Linear actuators

Linear actuators are any type of actuator which create motion in a straight line. These are often powered either by hydraulics/pneumatics or electromotors though other types like piezoelectric linear actuators also exist. Because these types of actuator are so widely used they come in all sizes, are very simple to control and are able to produce a large amount of force for their size.

Cables

A lot of surgical instruments are powered by cables which run through the instrument. These cables can be pulled or relaxed by some outside mechanism. Because cables cannot be loaded in compression, an antagonistic force is required to keep the cables taut. This is usually done with either a spring system or other cables providing an antagonistic force.

SMA spring

Shape-memory alloys (SMA) are alloys that can be deformed when cold but which return to their undeformed shape when heated. A compression spring made out of shape-memory alloy can be turned into an actuator by controlling the temperature. The temperature is often controlled by running an electrical current through the spring which heats it up due to the electrical resistance of the alloy. The spring is cooled down by letting the heat dissipate to the surroundings.

Bellows

Bellows can be used as different types of actuators depending on the type of fibers embedded in the bellow. A bellow without fibers will expand in all directions when the pressure inside is increased. By adding fibers under different angels different results can be achieved. Bellows which increase in length and reduce in width can be made as well as bellows which reduce in length and increase in width, depending on the angle of the fibers. Fibers can also be used to cause a bellow to increase in only one direction. Often bellows are filled with air but other gasses or liquids can also be used.

The patient's muscles

The colon wall can cause peristaltic waves of muscle contraction to occur in order to expel feces. This peristaltic contraction is used to push material out of the colon, but by changing the way the instrument reacts to these contractions a way to propel the instrument further into the colon instead of out of it could be achieved.

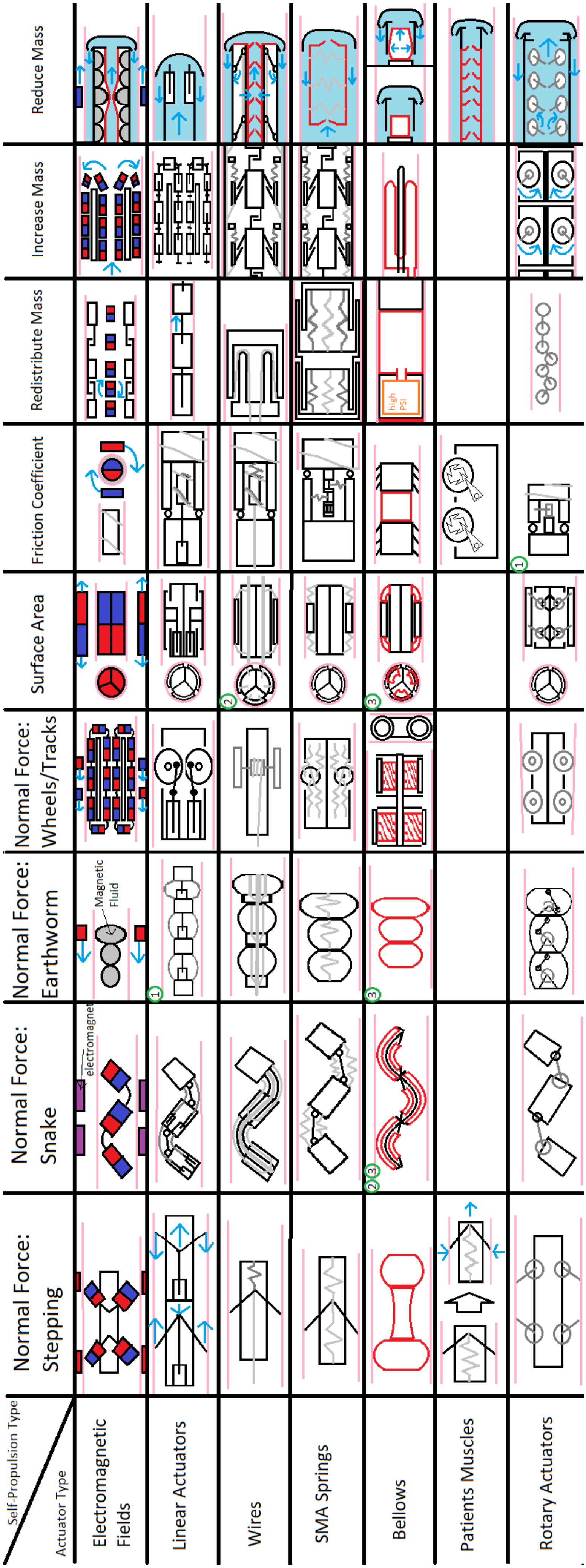


Figure 12: Morphological table of the locomotion types and actuator types. The number in the top left of a cell indicates the idea was used for the corresponding concept.

Rotary actuators

A rotary actuator is an actuator which produces a rotation or torque. Just like a linear actuator this type of actuator sees wide usage, can be found in all kinds of sizes, is very easy to control and produces a lot of force for its size. The most common rotary actuators are also powered by electricity or hydraulics/pneumatics but other types also exist.

4.3. Concepts

4.3.1. Morphological Chart to Concepts

The results from filling the morphological chart were used to design concepts for the soft self-propelling element. By combining and expanding on the ideas from the different combinations new concepts were developed. Figure 12 shows what solution from the morphological chart were used for which concepts with the numbers at the top left of the cells. The most promising three concepts will be discussed in this chapter. The concepts are limited to the self-propelling element of the probe as the control mechanism will be developed in a later stage. As mentioned in the requirements steering will not be included in this design, but in order to make later integration possible consideration has been given to the ability of the instrument to bend.

4.3.2. Concept 1: Rotating Core Mechanism

The first concept uses peristaltic locomotion based on the earthworm. By contracting the segments in a wave pattern which travels in the opposite direction of the direction of movement, as shown in Figure 13, peristaltic locomotion is achieved. The theory behind peristaltic locomotion has been discussed in Chapter 2.2.1. Figure 8 shows the same peristaltic wave which is used by the earthworm for locomotion. In the example below the instrument uses three segments, this being the minimal amount of segments required for this type of locomotion. There is no maximum amount of segments for this type of locomotion. The parts between the segments allow the instrument to bend with the shape of the environment.

The instrument consists out of two layers. The inner layer is made of cams connected by compression springs. The outer layer consists of sliders which are constrained except for movement in the axial direction, as shown in Figure 14. These sliders are connected to each other with two types

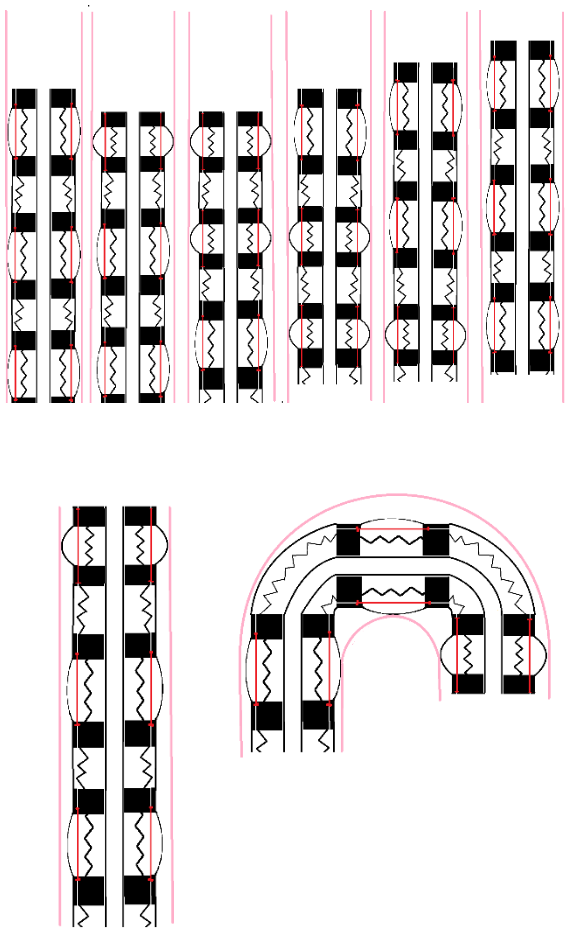


Figure 13: Schematic showing the peristaltic locomotion used in Concept 1 and the way the first concept can bend.

of alternating extension films. One causes the axial contraction of the segments to result in a radial expansion of the segments. The other type of film compresses and extends in the axial direction to allow the instrument to bend. The compression of one of the segments is achieved by connecting two cam slider systems with segments of extension

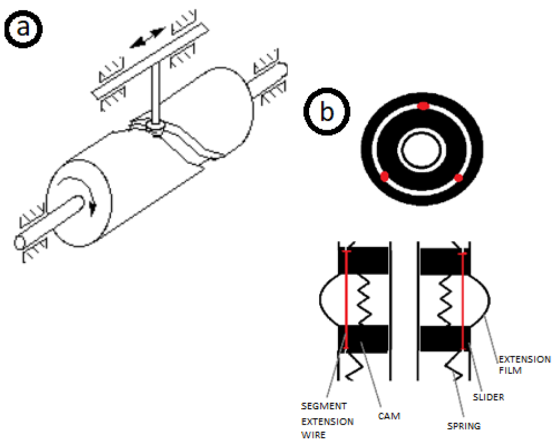


Figure 14: A cam slider system figure adapted from Zhang et. al. [11] (a)]. And the names of the parts of Concept 1 (b).

wires and setting them in a way that the ends of those wires get pulled apart when the inner layer rotates relative to the outer layer. The sliders and wires need to be spaced around in such a way they maintain a torque equilibrium when they get pulled taut. Therefore there will be three of them spaced at an equal distance from each other.

Though the type of locomotion allows for an infinite number of segments to be used, each segment will cause the friction in the instrument to increase. This will require a greater torque to power the instrument, which will be limited by the internal stress the instrument can handle.

4.3.3. Concept 2: Ovipositor Needle Mechanism

This concept uses the same type of locomotion as the ovipositors of parasitoid wasps, which is discussed in chapter 2.2.3. By moving a segmented outer surface in a certain sequence the locomotion can be achieved by causing and preventing slip at the right times. As shown in Figure 15 the outer surface of the instrument is divided into nine segments. These nine segments are divided into three groups of three as shown by their colors. When one of the groups is moved forward the grip of the other two groups is greater, therefore the moving group will slip against the environment. This is then repeated with the two other groups after which all the groups are moved back together. Because they all move back together the entire surface area is used which should provide enough grip to allow the movement to occur with minimal slip. Figure 16 visualizes how this sequence results in locomotion with 3 segments.

The segments consist of bellows. These bellows can be inflated to match the shape of the environment they are used in, and more evenly distribute the normal forces over the segments. The risk with this mechanism is that due to the shape of the environment the distribution of surface area per segment group, or other effects which alter the friction, could change too much, which in extreme cases could cause the instrument too stop working. This risk is reduced by dividing the surface area into nine parts instead of the minimally required three, should this still prove insufficient than the sliding sequence can be changed to overcome the problem. Another advantage of using nine segments in the current distribution instead of three is that when a group gets pulled forward the forces are distributed in such they don't cause any torque by canceling each other out.

The segments need to be kept in their place in order to avoid the wires from getting tangled. This can be done by having a thin flexible material connecting the bellows. In this way the bellows will still be able to move independently from each

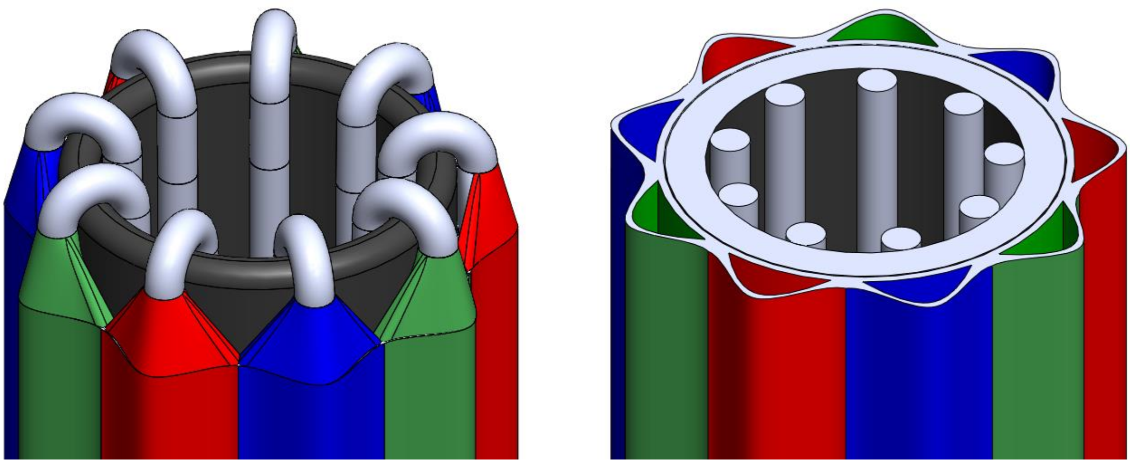


Figure 15: Render of Concept 2 with color coded segments.

Figure 16: Schematic showing the locomotion mechanism of Concept 2

other, while also being constrained enough so that they won't be able to tangle the wires with their movement.

4.3.4. Concept 3: Earthworm Mechanism

This concept uses the same peristaltic wave type of locomotion as the first concept discussed in this chapter. Instead of the rotation based mechanism used to contract and expand segments it uses connected bellows. These bellows can be constrained by fibers in such a way that they contract in the axial direction and expand in the radial direction, or the other way around, when inflated. As shown in Figure 17 the instrument consists out of three layers divided into a center ring, a middle ring and an outer ring. The center ring is kept at a high pressure and connects to the outer ring via the blue valves. The middle ring is kept at room pressure and connects to the outer ring via the green valves. The outer ring can be inflated and deflated by opening the blue or green valves respectively. Figure 18 shows how Concept 3 performs locomotion by inflating the segments. The outer layer is divided into three segments. This is done to allow the instrument to steer on its own or bend as required by inflating the segments on one side and deflating the segments on the other side. Just like the first concept this concept requires a minimal amount of segments, nine instead of three,

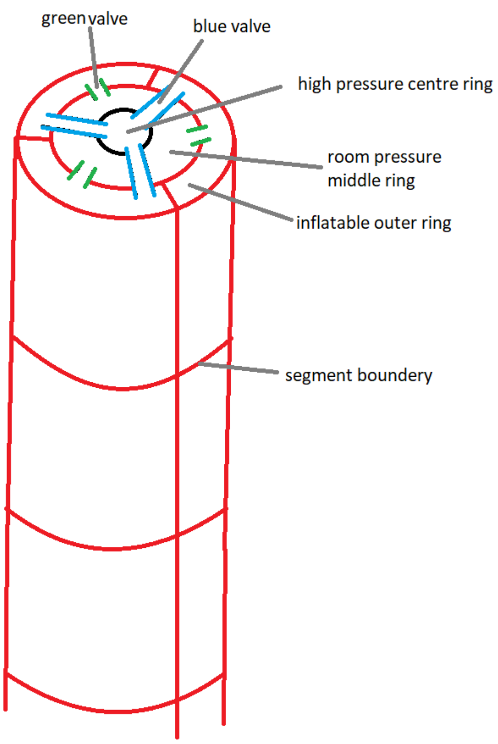


Figure 17: The parts of Concept 3 and their names.

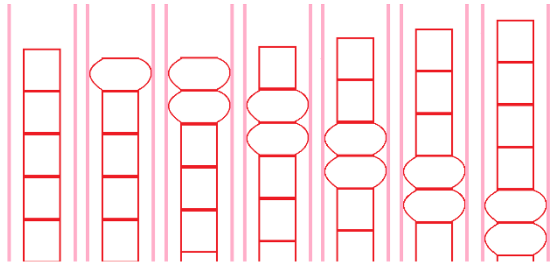


Figure 18: Schematic showing the locomotion of Concept 3.

because in this concept they are divided into three to allow for steering or bending. Unlike the first concept the maximum number of segment is not limited by the friction as this concept is not mechanically powered. There is however the issue of how to control the valves. If this is done by way of electrical wires the number of segments will be limited by the number of wires that can fit through the center and middle rings.

4.4. Concept Selection

4.4.1. Grades

In order to choose between the concepts, they were graded in multiple categories. This grading scheme was meant as a tool to help make the best choice and not to make the choice itself. The categories in which the concepts were graded are: Adjustable length, Locomotion Speed, Soft Behavior and Fabrication. Because the concepts are not yet worked out into designs no numerical values can be assigned to the categories and the grading will be done by assigning either a + or a – depending on how they compare to each other. These comparisons are based on estimates by the designer of how the concept will perform compared to the other concepts. This table is not used as a system to make the choice between the concepts but an aid to make the contrast between the different designs more concrete for the designer.

Table 1: Grading scheme of the concepts.

	Concept 1: Rotating Core	Concept 2: Ovipositor Needle	Concept 3: Earthworm
Adjustable Length	+	-	+
Locomotion Speed	-	+	-
Soft Behavior	-	+	+
Fabrication	-	-	-

4.4.2. Adjustable Length

In order for the instrument to be used in colonoscopies it has to be able to pull the rest of the 1.8 meter colonoscope with it. This would be difficult to do for a part attached at just the tip of the colonoscope but if the self-propelling element can be repeated over the length of the colonoscope it would not have to pull as much of it with each element. However not all colonoscopies will travel the entire 1.8 meters to the end of the large bowel and having the colonoscope be much longer than required could unnecessarily complicate the procedure. Therefor it is useful to consider if the length of the self-propelling concept can be easily adjusted for the required procedure. The rotating core concept and the earthworm concept are made out of multiple segments in the axial direction of which a minimum of three are required. There is however no upper limit on the number of segments this type of locomotion would support allowing the self-propelling element to match the length of the required colonoscope. The length of the ovipositor needle concept cannot increase its length in the same manner but it can still be repeated over the length of the colonoscope. All of the concepts can also be made with adjustable length by repeating the self-propelling element along the length of the colonoscope. With this in mind the ovipositor needle concept cannot adjust its length as needed but it should still be able to pull the entire colonoscope by using multiple propulsion elements.

4.4.3. Locomotion Speed

The locomotion method used by the rotating core concept and the earthworm concept is the same form of peristaltic locomotion as is used by the earthworm. The ovipositor needle concept uses a method inspired by the ovipositors of parasitoid wasps which works by dividing the surface area and sliding parts forward in a sequence which manipulates the surface friction to enable locomotion. When determining the locomotion speed, you need to look at the step size, cycle speed and the slip ratio. The step size of the rotating core concept and the earthworm concept should be similar as they use the same type of locomotion. The step size is the distance traveled by the instrument in one cycle of movement. The step size of the ovipositor needle concept is probably larger than the rotating core concept and the earthworm concept, as it can be made directly in the axial direction of the instrument instead of having to rely on the deformation of the segments. The cycle speed is the speed at which the instrument completes one cycle of movement. This is probably the fastest in the ovipositor needle concept, as the wires can be actuated the quickest. The slip ratio is the ratio of how far the instrument can theoretically move compared to how far it actually moves in one movement cycle. Unfortunately, this is very difficult to determine beforehand as it is dependent on the environment and the materials used in the instrument. Taking all of this into account the ovipositor needle concept will likely be the fastest concept of the three.

4.4.4. Soft Behavior

The soft behavior of the concepts will be determined by the materials and structures used on the outside of the instrument. In the rotating core concept the extension films are soft, however the rest of the instrument is hard. Because the extension films are the parts that come into contact with the environment this should still result in a soft behavior of the instrument, but this will only be maintained under the best of circumstances. Almost all of the outside of the ovipositor needle concept is made out of entirely soft material, which results in the entire instrument, except for the head having soft behavior in most circumstances. The earthworm concept is made entirely out of soft material except for the valves used near the center of the instrument, resulting in soft behavior in all circumstances.

4.4.5. Fabrication

Unfortunately creating parts for instruments on this scale can be very difficult. Which becomes even more of a problem for the rotating core concept as there are a lot of small parts that need to fit together very well in order for the instrument to work properly. The earthworm concept has the problem that making the types of connected bellows on that scale is also very difficult, as the casting has to be done with great precision. The ovipositor concept is somewhere between the other concepts, as the parts that need to be made are not as small and don’t need to fit together as well as the rotating core concept, and the bellows that would need to be cast are not as small or as complicated as the earthworm concept, however it does have the added complication that it has both. Therefore the conclusion is that all of the concepts will be hard to create.

4.4.6. Selection

As can be seen in Table 1 the rotating core concept scores the worst out of the three concepts while the ovipositor needle concept and the earthworm concept score equal to each other. While the ovipositor needle concept and the earthworm concept both don't score well on fabrication, the ovipositor needle concept should be easier to adapt if it should prove too difficult to produce. The ovipositor needle concept also has a more direct form of locomotion, which should make it significantly faster than the earthworm concept. The earthworm concept is easier to adjust in length, but the ovipositor needle concept should still be able to reach all the way to the end of the large bowel by repeating the self-propelling element along the length of the colonoscope. Taking all this in consideration the ovipositor needle concept was selected as the concept to develop further.

4.5. Design Development: Expandable Ovipositor Probe

4.5.1. Iterative Design

Though the concept generated in Chapter 4.3.3. is a good starting point there are still design challenges which need to be solved in order to develop the concept into a prototype. These problems will be discussed in this chapter. The following sections present the challenges that were tackled during the design process and were solved by using an iterative design process. The iterative design process focusses on identifying a problem of the design and redesigning it to solve that problem. This process is then repeated until no more problems with the design can be identified, or more likely the problem become small enough that they are deemed acceptable. For ease of reading the individual challenges will be discussed here instead of the different iterations of the designs.

4.5.2. Radial Expansion

In order for the sliding surfaces type of locomotion to work efficiently, all surfaces need to make contact with the environment. To facilitate this the instrument can expand in the radial direction to match the diameter of every part of the colon. The concept solution of using bellows for radial expansion proved to be extremely difficult to fabricate, even more so due to the limited facilities available because of the COVID-19 pandemic measures during the design and construction phase of the prototype. Therefore easier to construct

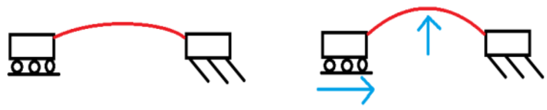


Figure 19: A schematic of the radial expansion mechanism.

alternatives were considered. The main issue with the fabrication of the bellows was their size. The first alternative was to replace the nine bellows with a single larger bellow with separate sliders. Unfortunately this larger bellow was still too difficult to fabricate with the available facilities. The final radial expansion mechanism uses nine beams which are clamped at the ends. The ends of the beams, are moved closer and further away from each other in order to bend the beams which causes a radial expansion as shown in Figure 19. The beams are under pre-tension to make sure they bend in the right way.

4.5.3. Slider Movement

Where previously the bellows were used for both radial expansion and the longitudinal movement, which enables the locomotion of the device, these functions will require separate parts when using the beams as an expansion mechanism. These sliders will need to be kept in place on the radial expanding beams during movement. This can be achieved by adding some side rails to the beams to prevent the slider from falling off as shown in Figure 20. Due to the force of the beam pushing radially outward against the wall of the environment, both the normal force and the contact area between the slider and beam could be very large for such a small instrument. With this in mind the materials for these parts should either have a small friction coefficient with each other or allow for lubrication of some kind. The number of sliders are kept at nine as this keeps an equilibrium of torque in the radial directions and gives a better distribution of the moving and stationary surface area over the instrument.

Figure 20: A cross-section of the radial expansion beam and slider system.

4.5.4. Non-Coulomb Friction

The standard Coulomb friction model, which is often used to explain friction behavior, unfortunately does not apply to the situation in which the instrument will be used. Namely it assumes a form of dry friction which will rarely be found inside the body and also does not account for the complicated shape and compliant nature of the inside of the human body. The instrument uses a type of propulsion which works by dividing the surface area into parts in order to manipulate the friction between the instrument and the environment. However, when for example some part of the environment has a much larger friction coefficient, this type of propulsion might not work because the relation between surface area and friction changes. The chance of this occurring is reduced by dividing the surface area of the instrument in nine parts instead of the minimally required three. This can mitigate the problem by having multiple parts touch the area with an increased friction coefficient, which will keep the balance between the friction of the moving parts and the stationary parts. Another potential issue is the friction inside the instrument which could be too strong for the instrument to move smoothly, however this can be solved by increasing the force of the actuation to overcome the internal friction.

4.5.5. Actuation Wires

Concept 2 uses a mechanism with wires that moves the bellows by pulling on them from the front of the instrument. The wires need to make a tight bend at the tip of the instrument which could be smaller than the minimum bending radius of the wires. It also increases the radius of the instrument by having the wires run past the bellows before pulling on them. In order to solve those problems the wires are attached to the bottom of the sliders which replace the bellows. Some elastic material is used to connect the top of the sliders to the tip of the instrument to provide an antagonistic force to the wires and keep them under tension.

The wires are pulled back and released in a specific sequence. First they all need to be pulled back in order to move the instrument forward. Then they are released three at a time in order to reset the mechanism, which enables the next step. The releasing does not necessarily need to be done three at a time, but the stationary surface area needs to be larger than the moving surface area during this step. Doing this in three steps is the fastest way, it neutralizes the torque of each of the

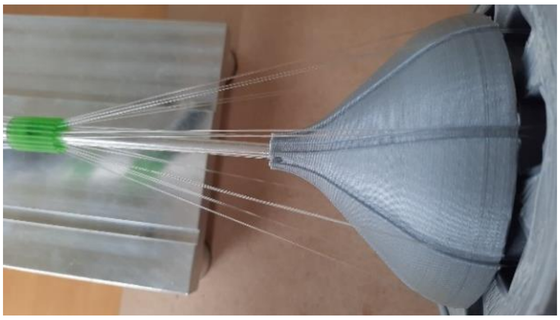


Figure 21: The wires going form the handle to the instrument.

moving parts and distributes the moving surface area, as discussed in the previous section. This sequence can be realized by a cam and sliders mechanism. Figure 21 shows the actuation wires.

5. Prototype Development

5.1. Prototype Design

5.1.1. Instrument Spine and Wire Guiding Rings

In order to validate the design of the radially expanding soft self-propelling mechanism a prototype was constructed to perform a proof-of-principle experiment. This section will elaborate on how the design of the instrument spine and wire guide rings was adapted to create the prototype, how the parts of the prototype were made and how the prototype was assembled. The spine of the instrument consists of 4 mm diameter 0.45 mm thick aluminum tubes connected by wire guiding rings. The wires are guided to prevent them from getting tangled. The bottom ring has two layers of holes. The inner layer is also present in the bottom bellow ring and the top bellow ring. The constraint ring also has holes, but those remain from a previous design and serve no purpose now. These wires, as shown in red in Figure 22, pull on the top

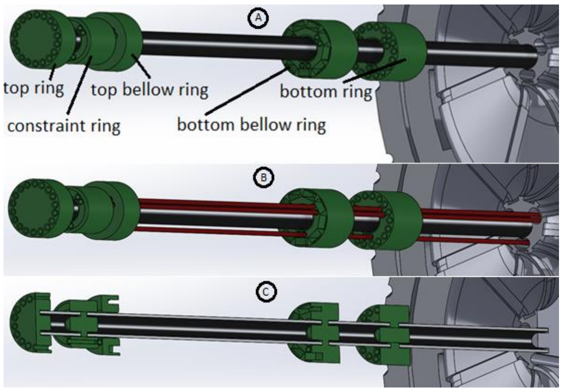


Figure 22: (A) The wire guiding rings used in the spine of the instrument. (B) The spine of the instrument and the wires of the radial expansion mechanism. (C) The cross-section of the spine of the instrument.

bellow ring to expand the radial expansion beams as will be explained in Chapter 5.1.2.

The outer layer of holes on the bottom ring is for the wires connecting the sliders in the handle with the sliders enabling the locomotion. As shown in Figure 23 these holes are needed to have the sliders which enable the locomotion follow the shape of the radial expansion mechanism. The slots in the top bellow ring and the bottom bellow ring are to constrain the ends of the thin beams of the radial expansion mechanism. The holes in the top ring are to connect the rubber bands on top of the sliders to the rest of the instrument.

5.1.2. Radial Expansion Mechanism and Sliders

As mentioned in Chapter 4.5.1. the silicone radial expansion bellows proved to be very difficult to make. Therefore, the design for the proof-of-principle prototype was changed to allow for easier fabrication.

The radial expansion mechanism consists of thin beams facing the axial direction which are fully constrained on the ends. These ends are pulled closer to each other, which causes the beams to expand outward in the radial direction as was explained in Chapter 4.5.1. Figure 24 shows how the mechanisms works, the wire guiding rings are in green, the wires are in red, the spine in is grey and the thin beams are in blue.

The red wires are pulled and released by turning a bolt and nut mechanism inside the handle as shown in Figure 25. This mechanism is chosen because it can exert a lot of force and because it allows for very small adjustments while pulling the wires. These small adjustments are needed because the ratio of how far the instrument expands radially versus the axial contraction of the mechanism is large and increases when the mechanism contracts. The wires are held in a 3D printed wire ring. This ring is held in place by two nuts twisted together tightly to keep them in place. The wire ring has enough space to enable rotation around the bolt, so

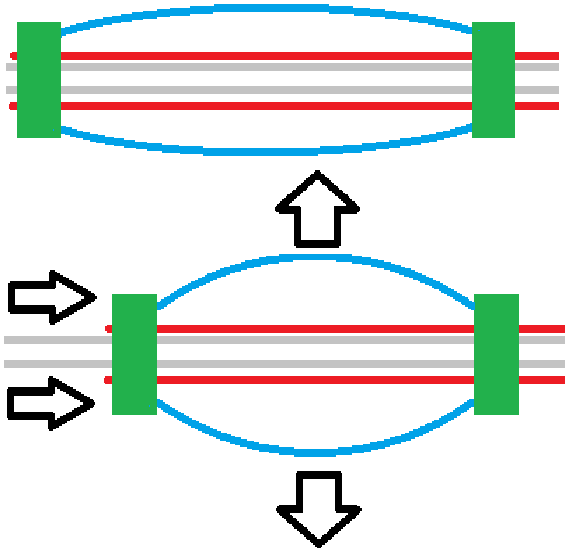


Figure 24: Schematic of the radial expansion mechanism.

the wires do not twist with the bolt when it is turned.

The sliders run over the expanding thin beams because for this type of locomotion to work the sliders need to make contact with the surrounding area. In order to keep the sliders on the expanding beams, small rails are added to the sides of the beams as shown in Figure 26. These parts need to be bent in their elastic domain as plastic deformation would not only prevent the parts to return to their original position properly, but also cause the material to quickly grow weaker over repeated use. Using thin structures allows for a flexible part that can bend in its elastic domain as long as the angles are kept relatively small. The sliders however need to be high enough to extend over the rails on the beam. The solution for this problem was to make parts of the slider higher than the rails and other parts thin so these parts can bend easily. This also gives the sliders a bit of a texture which will increase the grip. The ends of the sliders have holes for the wires to run through. They also are a bit wider than the rest of the sliders due to limitations of the 3D printer used to make them.

Figure 23: The radial expansion mechanism and the sliders.

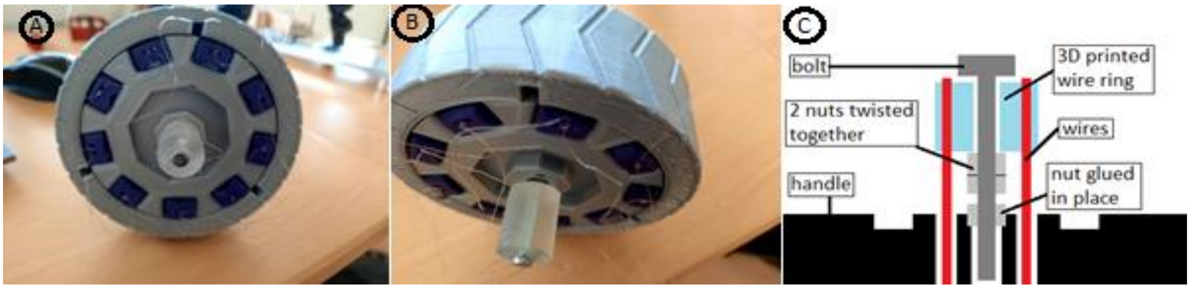


Figure 25: (A&B) Pictures of the mechanism for tightening and releasing the wires for the radial expansion mechanism. (C) A schematic of the mechanism for tightening and releasing the wires of the radial expansion mechanism.

The parts of the sliders near the tip of the instrument are attached to the tip with small latex bands, as shown in Figure 27. These bands are tied to the sliders and the tip of the instrument with fishing wires. The purpose of these latex bands is to provide an antagonistic force for the cam and slider mechanism explained in the next section. Technical drawings can be found in Appendix A.

Figure 27: The tip of the instrument.

5.1.3. Cam and Slider Mechanism

The cam and slider mechanism, intended to pull and release the wires in the required sequence, consists of nine sliders. These are constrained in all rotations and translations except in the axial direction, as can be seen in Figure 28. The cam guides the sliders through the sequence, which enables locomotion through the engraved path inside the cam. This path is designed this way to make sure the sliders are all pulled back at the same time and released three at a time. The first manufactured cam pulled the wires back using a slope of 45 degrees. This proved to be too steep, so a lot of force was needed to turn the cam. The second cam had slopes at a 35 degree angle and the start of the slopes were rounded in order to realize a smoother acceleration of the sliders. The openings at the top of the cam allow the sliders to be inserted into the cam during assembly. The profile at the outside of the cam is meant to provide grip and indicates the direction in which the cam needs to be turned. The handle is made in two parts

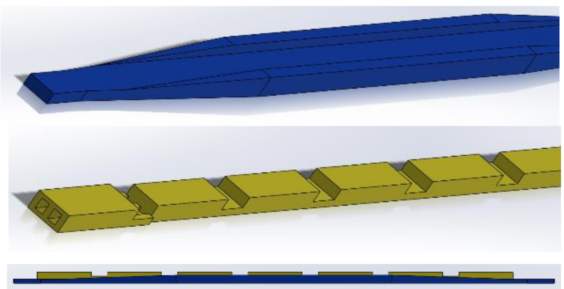


Figure 26: Renders of the radial expansion beam (top), slider (middle) and how they fit together (bottom).

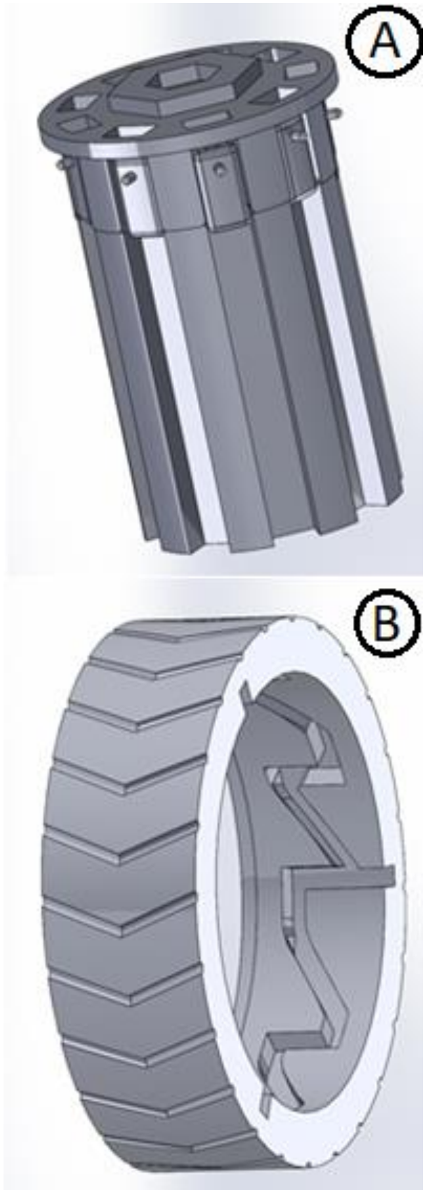


Figure 28: (A) The handle and sliders assembled. (B) The cam.

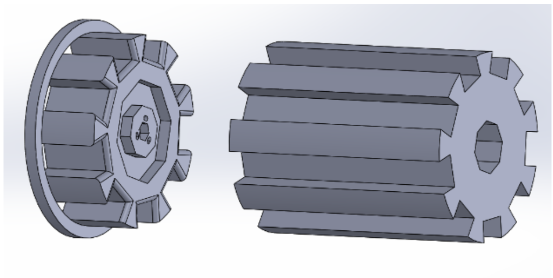


Figure 29: Renders of the two parts of the handle with the part that holds the sliders on the left and the one the operator holds on to at right.

to facilitate the assembly. The connection between the two parts of the handle is an octagon shape, see Figure 29. While the connection between the handle and the wire guide is hexagonal because medical instruments should always be designed in such a way that they cannot be assembled incorrectly.

The track of the cam consists of a slope that pulls the wires back, followed by a section that releases the wires in a sequence. The slope at the end of one track overlaps with the slope at the beginning of the next track. Figure 30 shows the dimensions of this track. The three different tracks follow each other three times for a total of nine times over the entire rotation. The middle section is divided in three columns for the three different tracks. In the first track the drop happens in the first column, in the second the drop happens in the second column and in the third track the drop is in the third column. Because this is repeated three times, the wires are relaxed three at a time which is the required sequence for locomotion as shown in Figure 31. The way the drops are set in the track ensures that one set of wires needs to be fully relaxed before the next one starts relaxing. As shown in Figure 30 the sliders travel 10.50 mm back and forth for each pull and relaxation cycle, resulting in a 94.50 mm travel distance for each full rotation of the cam.

As shown in Figure 32 the sliders are designed with rounded corners to avoid them getting stuck in case they twist a little in their tracks. At the back a part has been cut out to minimize the contact area with the track. The sliders are made relatively tall to reduce the angle they can make in their tracks due to the little space they have due to the tolerance.

The wire guide shown in Figure 33 is designed to keep the angle of the wires small by using round transitions. In order to have the wires follow this path the original design had a cap over the wire guide, but the tension of the wires pushed the cap off the wire guide. Fortunately the wires run

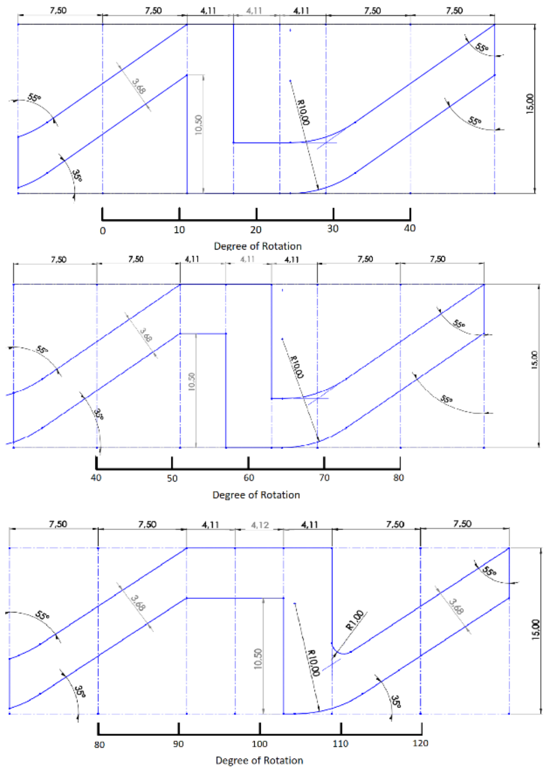


Figure 30: A third of the path engraved on the inside of the cam.

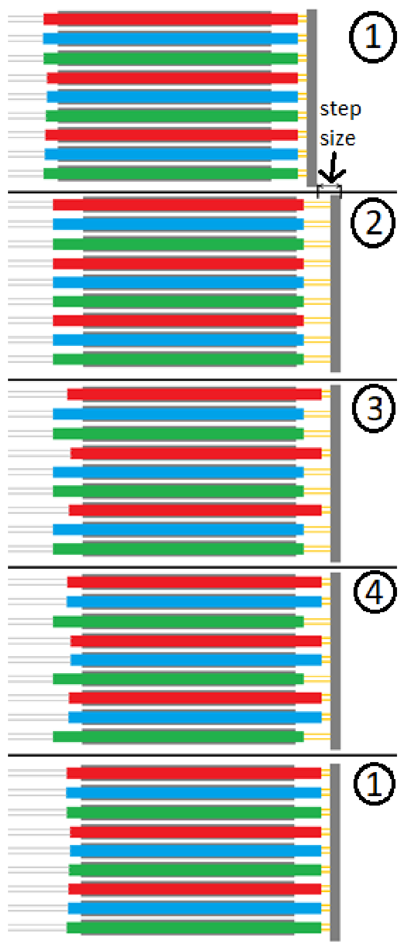


Figure 31: The sequence of pulling and releasing the sliders.

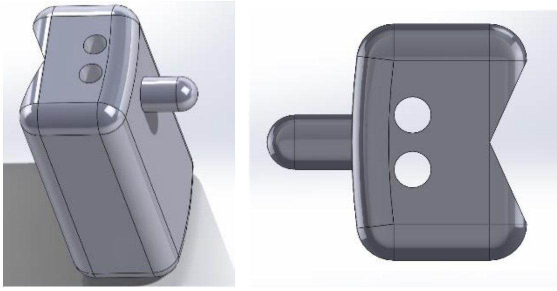


Figure 32: Render of the sliders used in the handle.

smoothly even if they do not follow the tracks completely so the cap was removed. Figure 34 shows the fully assembled handle.

5.2. Prototype Manufacturing

Except for the tubes forming the spine of the instrument, the latex bands that keep the wires under tension and the wires the instrument is entirely 3D printed. 3D printers were used for almost all parts because it is a fast production method that allows for a rapid design cycle, which is ideal for manufacturing prototypes. Another reason was that because of the COVID pandemic measures all other manufacturing methods were either not available or difficult to access. Except for the wire guiding rings all parts were made using a FDM printer, the Ultimaker 3, printing PLA. The wire guiding rings were printed by an SLA 3D printer with UV light sensitive resin. The rings were printed with the SLA printer because the FDM printer is not capable of printing in the required resolution. The FDM printer was used for most of the other parts because the material is very cheap, the printing is much faster, and most important the PLA of the FDM printer has much less contact friction than the

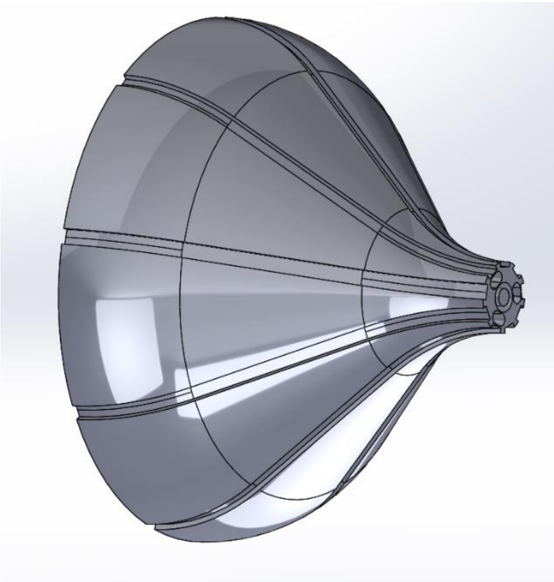


Figure 33: Render of the wire guide.

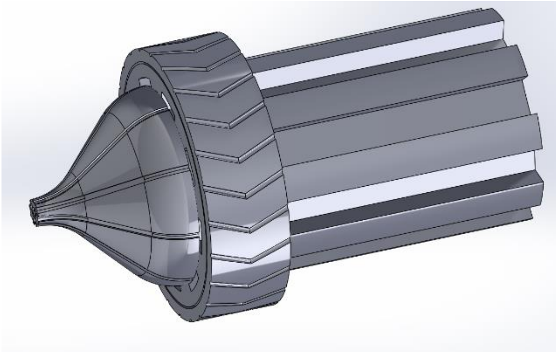


Figure 34: Render of the assembled handle.

resin of the SLA printer. Some parts also needed to be flexible and the UV sensitive resin becomes brittle after extended exposure to sunlight. The resin of the SLA printer turned out be unfit for moving parts as it has a very high contact friction both with the PLA of the FDM printer and itself. It even shows signs of galling when it slides over the same material. The tubes for the spine of the instrument were made from small aluminum tubes which were purchased at a local model building store and the wires are 0.25 mm diameter fishing wires.

The design of the prototype was adjusted to make it work well with the 3D printed parts. The dimensions of the sliders used for locomotion for example were mostly determined by the minimal resolution of the FDM printer. The orientation of the parts in the 3D printer is also important as there are textures on the parts resulting from the layers the printers build up as can be seen in Figure 35. This texture consists of small ridges along the

Figure 35: Picture of the cam with visible printing lines.

horizontal plane of the printer. These textures are not a problem as long as they are not perpendicular to the direction of movement, otherwise they can greatly increase the contact friction. Having the texture perpendicular to each other on different parts can also reduce the contact friction.

5.3. Prototype Assembly

Due to the pretension in the wires of the instrument only two parts had to be glued together, the rest of the instrument is held together by the tension in the wires. The two parts of the handle needed to be glued together as the wires stop in the first part, so the two parts would not stay together otherwise. Furthermore the nut of the nut and bolt actuation mechanism for the radial expansion is glued to the handle. These parts would still be kept together by the pretension of the wires, but for the nut and bolt mechanism to function the nut also had to be fixed to prevent rotation. Originally this would have been done by the shape of the handle but a mistake was made with the tolerances which had to be fixed by gluing the nut in place.

The tension in the wires of the radial expansion mechanism is just enough to keep the wires taut when the nut and bolt mechanism is at zero rotations. The tension in the wires connected to the sliders is enough to keep the sliders in the middle of the beams. Not all the sliders were at the exact same position as the knots in some of the wires slipped a little, this did not seem to affect the operation of the instrument as the sliders were still the part of the instrument that made contact with the surrounding.

6. Proof-of-Principle Experiment

6.1. Experiment Overview

6.1.1. Experimental Goal

In order to validate the design of the radially expanding self-propelling mechanism a proof-of-principle experiment was performed. The goal of

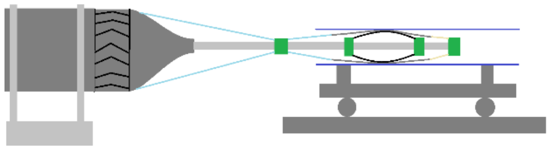


Figure 37: schematic of the experiment setup.

the experiment was to show that the instrument is capable of locomotion in tubes of varying diameters and to examine if there is a correlation between the radial expansion of the device and the slip ratio in different diameter tubes. Further experiments were performed to investigate the effect of different shaped tubes, the effect of added weight and the effect of lubrication.

6.1.2. Experimental Setup

For the experiment the handle of the instrument was fixed in place and the tube through which the instrument travels was placed on a cart as shown in Figure 37 and Figure 36. The cart was used to let the tube move freely in the axial direction of the instrument. This was done because the instrument is rigidly connected to the handle, which will influence the forces applied to the instrument because the operator needs to hold the handle to operate the instrument. Therefore, instead of having the instrument pull itself through the tube, the tube was pulled backwards by the instrument. The distance traveled by the cart was measured by a red paperclip attached to the cart, traveling along a measuring tape. The paperclip was bent in such a way as to be as close to the measuring tape as possible without touching it in order to minimize parallax error. All the measurements were filmed by a camera hanging above the set-up so the results could later be analyzed should that be required.

6.1.3. Protocol

The experimental protocol was to set the back of the handle flush with the back of the plates which held it in place. Next the tube was placed so the locomotion part of the instrument was fully inside

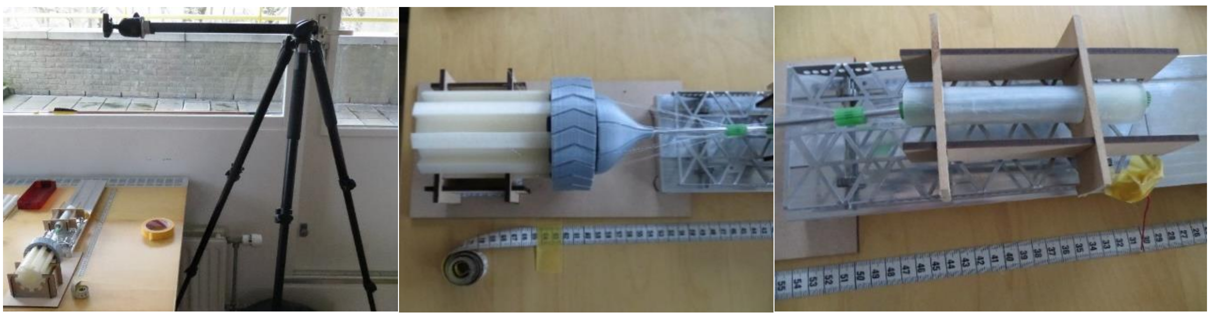


Figure 36: Pictures of the experiment setup.

and the position of the cart on the measuring tape was noted so it could be reset to the same point for every measurement. The recording would then be started and the cam rotated 1/3 of a full rotation, after which the recording was stopped. The cart was then reset to its starting position to repeat the measurement. This was done two more times for three measurements in total.

The protocol above was first performed with no radial expansion. The nut and bolt mechanism were then rotated three times to radially expand the instrument. This was repeated six times for a total of 18 measurements per tube. The radial expansion was difficult to measure accurately, therefore an estimate for the diameter of the instrument was used based on the amount of rotations of the nut and bolt mechanisms as shown in Table 2 and Figure 38.

6.2. Experiment 1: Effect of the Instrument/Tube Diameter

The goal of the first set of experiments was to investigate the efficiency of the instrument in different diameter tubes at different radial diameters of the instrument. In order to do this the experiment protocol described in Chapter 6.1. was performed in tubes with a diameter of 15, 16, 17, 18, 19 and 20mm.

The independent variables for this experiment were: the radial expansion of the instrument, the diameter of the tubes in which it was tested and the rotation of the cam. The values for the diameter of the instrument were 14, 14, 15, 16 ,18 and 22mm. The values for the diameter of the tubes were 15, 16, 17, 18, 19 and 20mm. The cam was rotated 1/3 of a full rotation. The dependent variable was the distance traveled by the cart with the tube.

6.3. Experiment 2: Effect of the Part Quality

The goal of the second set of experiments was to investigate the effect of the quality of the parts

Table 2: Correlation of the rotations of the nut and bolt mechanism and the instrument diameter.

Rotations of the nut and bolt mechanisms	Diameter of the instrument
0	14mm
3	14mm
6	15mm
9	16mm
12	18mm
15	22mm

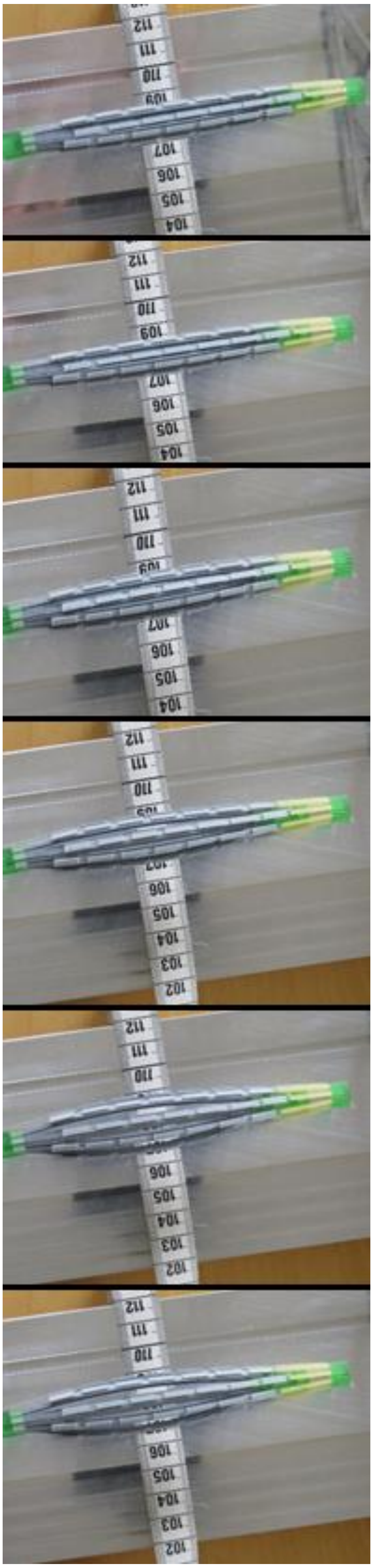


Figure 38: The radial expansion of the instrument at different rotations of the nut and bolt mechanism.

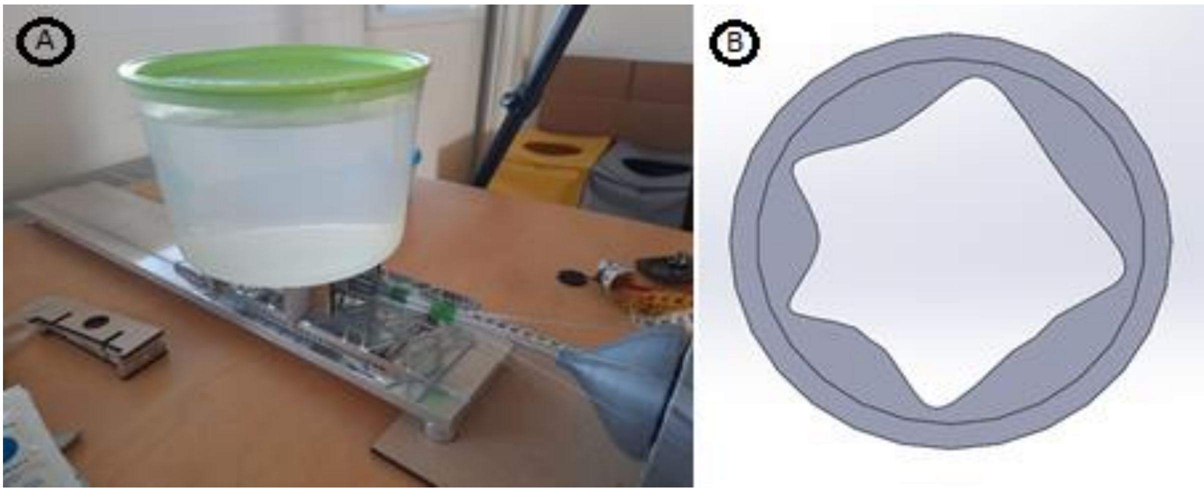


Figure 39: (A) The setup for the experiment with the added weight. (B) Top view of the irregular shaped tube.

used to hold the tube in place, the reasons for this will be discussed in Chapter 7.1. In order to investigate the difference the tests with the 17 to 20 mm diameter tubes were repeated with the new parts shown in the bottom of Figure 40.

The independent variables for this experiment were: the radial expansion of the instrument, the diameter of the tube in which it was tested and the rotation of the cam. The values for the diameter of the instrument were 14, 14, 15, 16 ,18 and 22mm. The values for the diameter of the tubes were 17, 18, 19 and 20mm. The cam was rotated 1/3 of a full rotation. The dependent variable was the distance traveled by the cart with the tube.

6.4. Experiment 3: Effect of Added Weight

The goal of the third set of experiments was to investigate the effect of the weight of the cart. In order to do so the test with a 20mm diameter tube would be repeated with and without a container filled with water on top of the cart, as shown in Figure 39. The cart without the container weighs 114 grams and the cart with the container weighs 2520 grams.

The independent variables for the experiment are the weight of the cart and the rotation of the cam. The values for the weight of the cart were 114g and 2520g. The rotation of the cam was 1/3 of a full rotation. The dependent variable was the distance traveled by the cart with the tube.

Figure 40: The parts used to hold the tube in place in experiment one and two.

6.5. Experiment 4: Effect of an Irregular Diameter

The goal of the fourth experiment was to investigate the efficiency of the instrument in a tube with an irregular shape as shown in Figure 39. The irregular shaped tube varies in diameter between 15 and 20 mm with different shapes going between those extremes, these shapes don't have any sharp edges as this would not be encounter in the colon. The shape stays the same along the length of the tube.

The independent variable was the rotation of the cam. The cam made 1/3 of a full rotation. The dependent variable was the distance traveled by the tube.

6.6. Experiment 5: Effect of a Conical Tube and Lubrication

The goal of the fifth set of experiments was to investigate the effect of a conical tube, the dimensions of which are shown in Figure 41, on the efficiency of the instrument and the effect of lubrication on the efficiency of the instrument. In

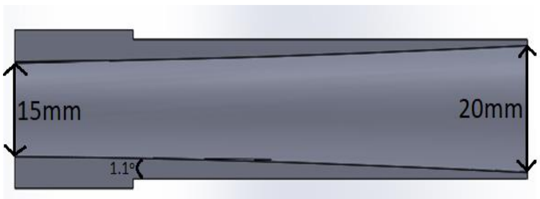


Figure 41: Cross-section of the conical tube.

order to test the effect of lubrication the conical tube was sprayed with PTFE spray. The effect of lubrication was tested in the conical tube because the effect would likely be most notable in this tube.

The independent variables for this experiment were the lubrication of the tube and the rotation of the cam. The first set of tests were performed without the lubrication and the second set with the lubrication applied. The rotation of the cam was 1/3 of a full rotation. The dependent variable was the distance traveled by the cart with the tube.

6.7. Data Analysis

6.7.1 Slip Ratio

In order to determine how effective the instrument is the slip ratio is calculated. As there is no consensus on the definition of the slip ratio, in this case it is calculated by taking the distance the cart traveled and dividing it by the theoretical distance the cart could have traveled if there were 100% effective transition of forces between the instrument and the tube. In this theoretical situation there would be no slip between the sliders and the tube when they are pulled back and a 100% slip between the sliders when they are relaxed back to their original position. As mentioned in Chapter 5.1 the theoretical travel distance for a full rotation is 94.50 mm so a 1/3 rotation will result in a theoretical travel distance of 31.50 mm.

$$R_{slip} = \frac{D_{real}}{D_{theoretical}} \times 100\% \quad (1)$$

6.7.2. Statistical Analysis

A statistical analysis was performed to investigate the correlations between data sets. Unfortunately some the datasets used for the analysis have low statistical power due to the limited amount of measurements, and as such cannot be used to draw any conclusions with certainty. In order to investigate the correlation between all the measurement sets an anova test was run. Anova tests were also performed to investigate the correlation between the test with 15-16 mm diameter tubes and the tests with 17, 18, 19, 20 mm diameter tubes. A two sample t-test was run to investigate the correlations between the tests where the instrument had a smaller diameter than the tube and the ones with a bigger diameter. Two more sample t-tests were performed to investigate the 15 and 16 mm tube diameter tests versus the tests with the 17, 18, 19 and 20 mm diameter tubes. The same with the tests with the low quality parts versus the high quality, as well as the test with and without the added weight, and the non-lubricated versus the lubricated tests. The results of these tests will be described in Chapter 6.6.

The null hypothesis for the anova test is that the samples for each test are drawn for a population with the same mean against the alternative hypothesis that the population means are not all the same. The two sample t-tests were performed for the null hypothesis that the two samples are independent random samples from normal distributions with equal means and equal but unknown variances. The alternative hypothesis states that the data in the samples comes from populations with unequal means.

6.8. Experiment Results

Figure 43 shows the results of Experiment 1. The columns show the tests with different radial expansions of the instrument and the colors show what diameter tube the test was performed in. All tests were repeated three times. Some tests only show two entries because they had two identical results. The exact values of the tests can be found in Appendix B and MATLAB the code used to analyses the data can be found in Appendix C. The entries of the graph are either circles if the diameter of the tube was larger than the diameter of the instrument, or squares if the diameter of the instrument was larger. At first glance a clear difference between the tests with the 15 and 16mm diameter tubes and the rest of the tests is observable. This unexpected discrepancy was reason for further examination of the experimental setup. Figure 42 shows the relevant results of Experiment 1, setup one, and results of Experiment 2, setup two. The results of Experiment 3, 4 and 5 can be seen in Figure 44. The results of the anova tests are shown in Table 3 were h is whether or not the test rejects the null hypothesis at the 5% significance interval. The p values and the sample sizes are also included in Table 3.

The results of the paired t-tests are shown in Table 4 with the same h, p and sample size columns as in the anova test table. The last column shows the number of samples that would be required in both samples sizes to obtain 90% power (probability of rejecting the null hypothesis when the alternative hypothesis is true) when the significance level (probability of rejecting the null hypothesis when the null hypothesis is true) is 5%.

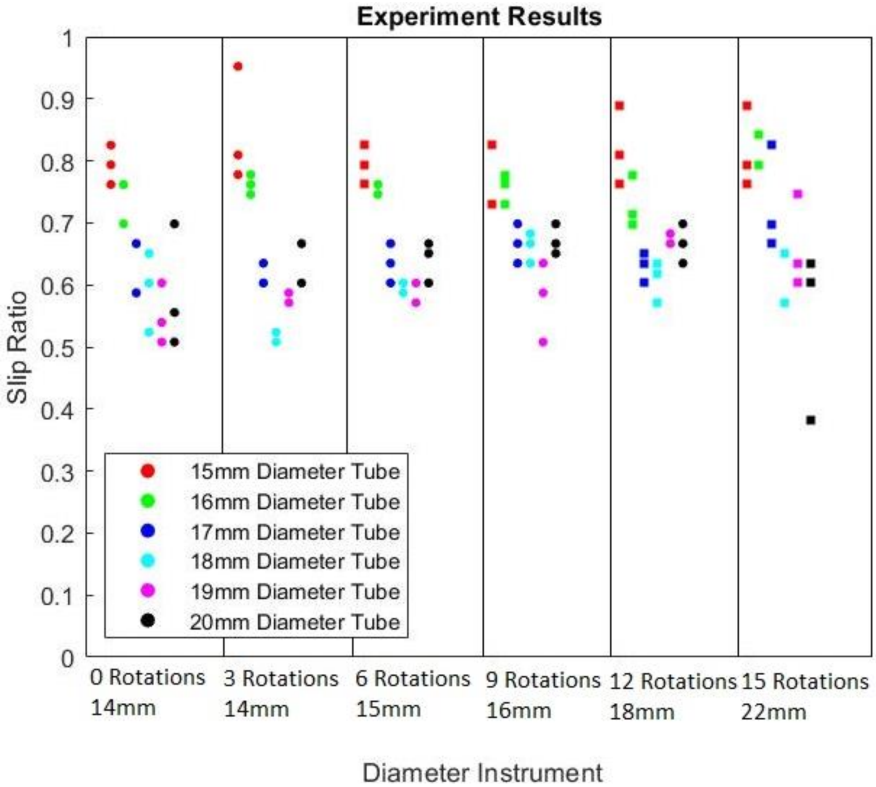


Figure 43: Scatter plot of the result of Experiment 1. The dots are measurements where the instrument diameter is smaller than the tube diameter and the squares are measurements where the instrument diameter is equal or larger than the tube diameter.

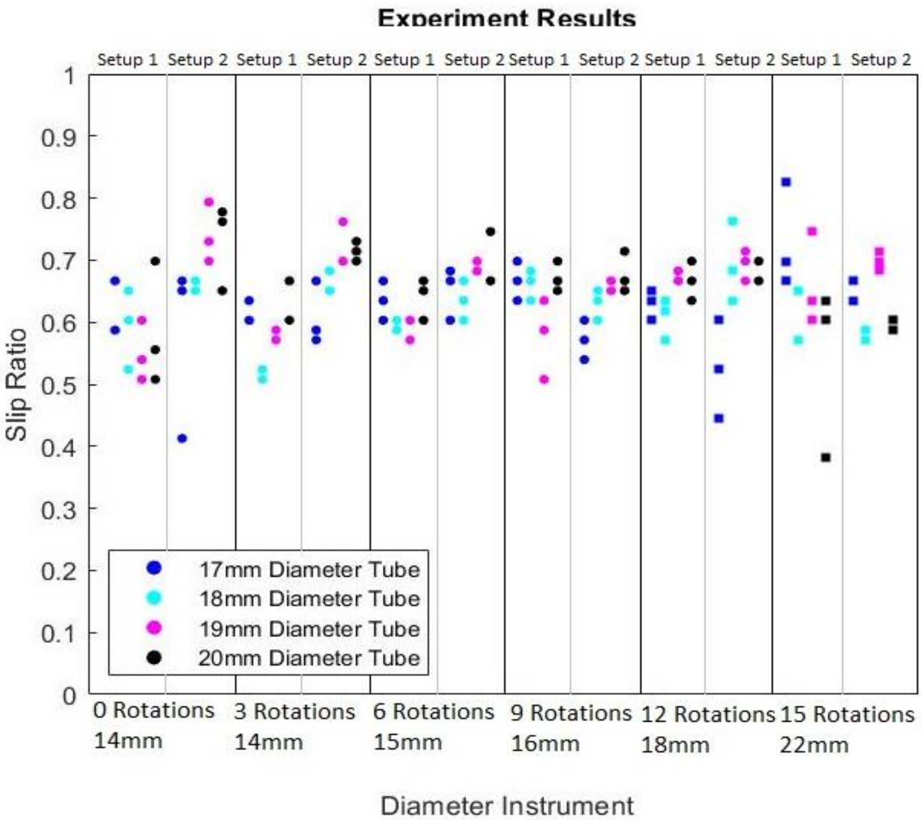


Figure 42: Scatter plot of the results of Experiment 2. The dots are measurements where the instrument diameter is smaller than the tube diameter and the squares are measurements where the instrument diameter is equal or larger than the tube diameter.

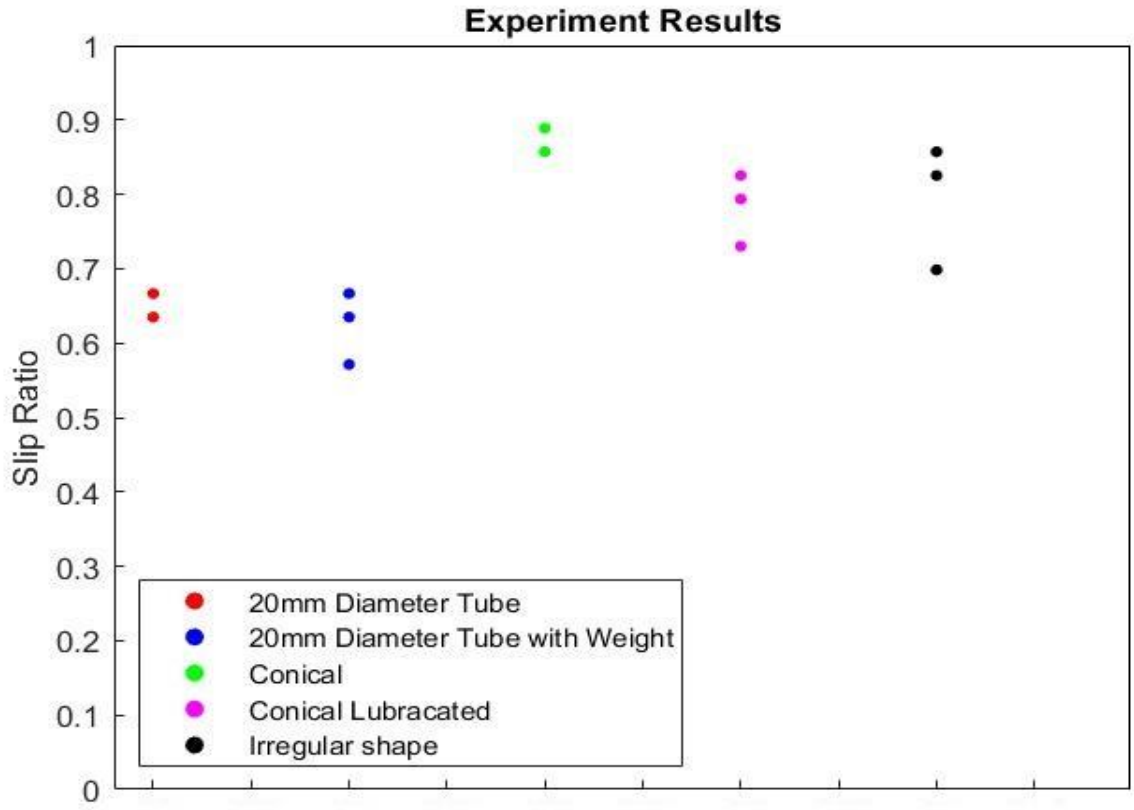


Figure 44: Scatter plot of the results of the third set of experiments.

Table 3: Anova test results.

Anova test	h	p	Sample sizes
All tests	Rejected	7.7019e-16	3x36
15mm and 16mm	Not rejected	0.0591	3x12
17mm, 18mm, 19mm and 20mm	Rejected	7.7019e-16	3x24

Table 4: T-test results.

t-test	H	p	Sample sizes used	Sample size required for 90% power
$D_{instrument} > D_{tube}$ **vs** $D_{instrument} < D_{tube}$	Rejected	7.4269e-04	69 and 39	288
15mm and 16mm vs 17mm, 18mm, 19mn and 20mm	Rejected	2.5841e-23	36 and 72	9
High quality part vs low quality parts	Rejected	9.7529e-04	72 and 72	271
With added weight vs without added weight	Not rejected	0.3486	3 and 3	4
With lubrication vs without lubrication	Rejected	0.0474	3 and 3	2

7. Discussion

7.1. Discussion of the Experiments

Due to the results of Experiment 1 the quality of the parts holding the tube in place was expected to affect the test results. This would have been caused by the difference in quality shown Figure 40, which is why the tests using those parts was redone in Experiment 2 using parts of higher quality. This meant redoing the tests in the tube with a diameter of 17, 18, 19 and 20 mm. The two top parts in Figure 40 were used for the test with the 15 and 16 mm tubes. The two in the middle were used in the first setup and the two lower parts were used in the second setup for the tests with the 17 to 20 mm tubes.

The results of these experiments appear to fall within the same range as the results of the previous experiments, a comparison can be found in Figure 42 in Chapter 6.6, indicating the quality of these parts does not affect the results significantly. Unfortunately somewhere towards the end of these tests the radial expansion mechanism got jammed, which made it impossible to adjust the diameter of the instrument. The first test already showed that the diameter of the instrument does not have a large effect on the results of the tests, therefore the comparison in these tests should still be valid.

7.2. Discussion of the Experiment Results

7.2.1. Effect of the Diameter of the Instrument and Tube

From the results of Experiment 1 the diameter of the instrument and the diameter of the tube do not appear to have a significant effect on slip ratio. This result matches the theory of this type of locomotion, as only three of the nine sliders need to make contact in order to work, although unexpectedly the efficiency of the instrument does not seem to be affected. The reason at least three

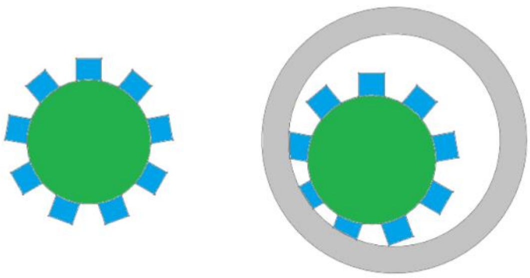


Figure 45: Schematic of the front view of the instrument.

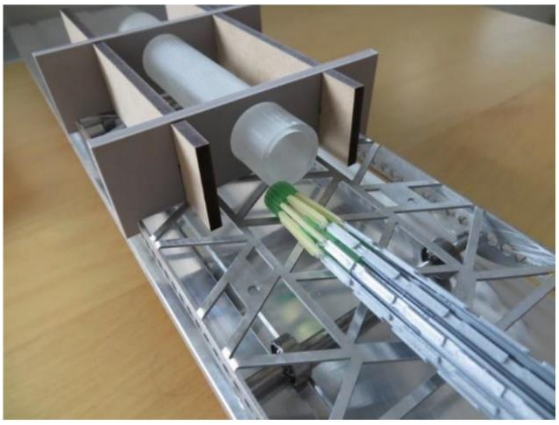


Figure 46: The offset of the experiment setup.

sliders make contact with the tube is because the instrument has a slight offset which pushes it to the side of the tube as shown in Figure 45 and Figure 46. Because the device would likely have such an offset when used in a practical setting it is realistic to have this offset included in the experiment.

Another surprising result was the increase in efficiency for the 15 and 16 mm diameter tube. An explanation for this could be that there is a contact of five or more sliders with the tube at those sizes and contact with four sliders in the other sizes. If there is contact with four sliders the relaxation step would be performed with just two sliders, which would be half the contact area. This could cause movement in the opposite direction as intended, reducing the slip ratio. This is however very unlikely though as the effect persists when the diameter of the instrument increases, which would change the number of sliders making contact with the tube. This effect only occurs when two or four sliders make contact with tube. This means that there should be a small range of tube sizes with instrument diameters that have reduced efficiency due to the four sliders contact, but this range has not been notably present in the experiment.

7.2.2. Effect of Weight of the Instrument

The experiment to test the effect of the weight of the cart, Experiment 3, showed no significant effect. This is supported by the statistical analysis, although it should be noted that the sample size was slightly too small to get 90% power. The size of the instrument and the weight used in the experiment suggest that the weight does not have to be a factor of consideration in future designs, unless it were to be made entirely out of very heavy materials. This is mainly due to the slow accelerations of the instrument, the low friction of the cart used in the experiment and the fact that the instrument uses the contact friction to move instead of being hindered by it. It should be noted that this experiment only tests the effect of the added inertia due to the weight. However, the weight of the instrument does influence other aspects of the locomotion mechanism, such as the distribution of the contact friction over the sliders. If the weight of the instrument increases, the normal force acting on the bottom of the sliders also builds up, which in turn increases the contact friction of those sliders. This can be mitigated by using the radial expansion mechanism to increase the normal force over all the sliders and therefore make the friction force distribution more equal.

7.2.3. Effect of Shape of the Environment

One advantage of soft behavior of the instrument is that it can adapt to the shape of the environment. The experiment has already shown the instrument is also capable of operating in an environment larger than the instrument itself, though this has only been tested in round tubes. The main consideration when determining whether or not the instrument is capable of locomotion in an environment is which sliders make contact with the environment. At least three slider need to make contact and these need to be part of the three different cycles. An example of this is the instrument in a round tube. An example of were the instrument would not be capable of locomotion is in a triangular tube as shown in Figure 47. The reason the instrument would not work is because the three sliders that make contact with the environment all get relaxed at the same time without any of the other sliders providing the friction needed to keep the instrument in place.

The radial expansion mechanism can help overcome these issues by increasing the number of sliders that make contact with the environment. Another solution would be to make the instrument even softer and have it adjust to the shape of the environment that way.

One of the experiments was performed in a tube with an irregular shape. The results of this

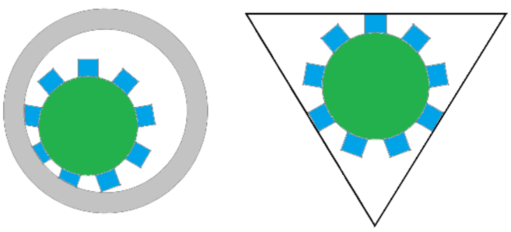


Figure 47: Schematic of the instrument in a round and triangle shaped tube.

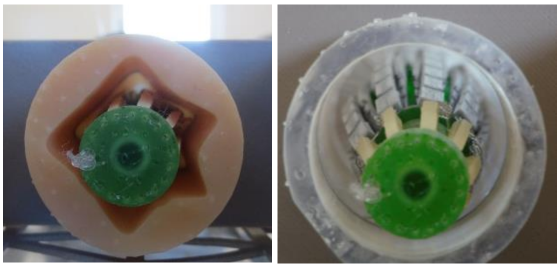


Figure 48: Picture of the instrument in a round and the irregular shaped tube.

experiment show that the instrument still performs well in this tube as it can adjust its shape to match, as shown in Figure 48.

The results of the experiment with the conical tube were expected to show the conical shape to push the instrument in the opposite direction as the intended movement and therefore to reduce the efficiency. Instead, the conical tube has one of the best slip ratios of all the tests. This may be explained by the round shape of the instrument which increases the contact area of the sliders, as shown in Figure 49. This suggests that the instrument operated better with a large contact area. This also means it probably operates well in a soft environment, as the environment would then also wrap around the instrument. Another explanation could be the increase in normal force results in better grip. However this is unlikely, because a similar result should be seen when the instrument diameter expands, and this effect is not observed in the results.

7.2.4. Effect of the Coefficient of Friction

Another way to explain the results of the conical tests is that the conical tube and the irregular one were made from a different type of 3D printing resin than the other tube, which could influence the coefficient of friction. In order to test the effect of the coefficient of friction the conical tube was also tested after being lubricated with a PTFE spray. The results of that test were more in line with those of the other tests, suggesting this was a significant factor for the variation seen in the results. The results of 3D printing with an SLA printer are dependent on environmental conditions like the temperature and the light conditions of the room. This variation might also have caused differences in the coefficient of friction of the different tubes. This

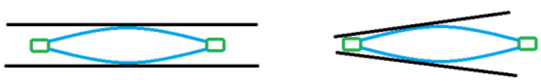


Figure 49: Schematic of the difference in contact area for conical shaped tubes.

could explains why the 15 and 16 mm diameter tubes have better results than the other sizes as they were printed together. The ultraviolet component of sunlight also hardens the resin, which could affect the coefficient of friction in the experiments.

7.3. Discussion of Design Requirements

The outer diameter of the non-expanding parts of the instrument is 10 mm, which falls well within the 15 mm limit set out in the requirement. The radial expansion system has a minimal diameter of 14 mm which also falls within the limits for parts that expand their diameter, as set out in the requirements. The expansion of the diameter can also be controlled precisely with the nut and bold mechanism. All requirements for the instrument diameter are met by the prototype.

The instrument is capable of self-propulsion, and even exceeding expectations about the conditions in which it can operate effectively. The results of the experiments suggest that the efficiency of this design will remain fairly constant while operating under different circumstances. This will be beneficial during surgery as it makes the behavior of the instrument more predictable. The self-propulsion requirement has been met by the prototype.

The prototype is not able to propel itself backwards, as it was not designed to do so. The instrument should theoretically be able to reverse its travel direction as all the mechanisms will operate in the same way, but the cam would have to be replaced in order to change the sequence in which the sliders move. Because the prototype only needed to be able to propel itself backwards in theory, this requirement has been met.

The requirements for the soft behavior of the instrument state it needs to be soft in both radial directions and rigid in the axial direction. The instrument is rigid in the axial direction but only soft in the radial direction in the radial expansion mechanism. However, the radial expansion mechanism is the only part of the instrument which make contact with environment and therefor is the only part where the softness in relevant. The results of the experiments that show the instrument works in tubes with a larger diameter than the instrument itself, indicating the instrument does behave in a soft manner as locomotion would not be possible otherwise. However this requirement is also present for the purpose of patient safety. More specifically it should distribute the normal forces which act on the colon wall. Due to the small surface area of the sliders, the current design would still result in high colon wall deformation. On top of that the current design might pinch the colon wall between the radial expansion beams. As this aspect of the design was not included in the proof-of-principle experiment, it was not considered an issue for the prototype. While the experiments have shown the benefits of soft behavior for this type of sliding surfaces locomotion it is still lacking in the safety aspects which the soft behavior was supposed to provide.

7.4. Design Limitations & Recommendations to Future Designs

The most interesting result from the experiment is that the instrument functions just as well when its diameter is smaller than the tube as when it is bigger than the tube. From this we could conclude that the radial expansion mechanism is not essential for the instrument to function. While the radial expansion mechanism does have some advantages, like allowing the instrument to better adjust its shape to the environment, this could also be accomplished by making the device softer. The downside of having the radial expansion mechanism in the instrument is that it takes up space, which makes the instrument bigger than it needs to be. It also increases the complexity of the design, and as a rule of thumb: simpler is generally better. Some of the other benefits of the radial expansion mechanism will be discussed in the following sections of this chapter.

After the experiments some of the sliders appeared to be partially stuck on the radial expansion beams. This is because the ends of the sliders are slightly wider than the space between the rails of the beams, due to the limitation of the 3D printer used to make them. This could be solved by using a 3D printer with a higher resolution so the ends do not need to be wider. Alternatively the beams could be made wider but in the current setup that would not fit. When the instrument is expanded to a larger diameter this issue is solved by the ends of the beams bending away from the ends of sliders but this is only a situational solution. Originally this problem was solved by carefully tightening the wires pulling on the sliders, so that they can move without the wider ends touching the rails of the beams. Unfortunately the knots in the fishing wire used as wires sometimes slip a little, which can slightly change the axial position of the slider, causing them to get stuck partly. This appears to be a minor effect as the instrument still functions well, but it might affect the efficiency. This could be the reason why the test with the 15 and 16 mm diameter tube gave better results, as they were performed first. In the future iterations this issue could be resolved by using less slick wires or gluing the knots into place.

The benefits of using nine sliding segments instead of the minimally required three are that only partial surface contact is required for locomotion, the torque is kept in stable equilibrium by pulling on three evenly spaced sliders at the same time and there is redundancy in the system should some of the sliders break. These benefits increase with the number of segments. As long as the number of segments can be distributed over three groups, none of which cover 50% or more of the surface area, the number of actuation steps remains the same and as such the speed at which the instrument is able to perform locomotion will not be affected. Of course as the number of sliders increases they need to be smaller to keep the same instrument diameter, which makes them harder to fabricate. Also more wires will be needed to actuate the instrument, making the construction of the instrument more complex.

Because the prototype was tested in straight tubes, the spine of the instrument was made from rigid aluminum tubes. This kind of spine cannot be used in environment where it needs to be able to round corner, like colonoscopies. The spine of the instrument is needed to absorb the force of the wires in the axial direction which is why it needs to be stiff in compression in the axial direction. It can however be flexible in other directions, though too much flexibility in the radial directions might cause buckling and if the bending stiffness in the axial direction is too flexible the wires might become tangled. A solution would be to replace the aluminum tube with a closed compression spring. This would allow bending in the radial directions, while remaining stiff in rotation of the axial direction and rigid in both the radial directions and in compression in the axial direction. The colonoscope overall should be able to have a much more flexible spine that the current colonoscopes, as it no longer has to resist buckling due to being loaded in compression.

The length of the instrument can be increased by adding a tail between the head of the instrument which enables the locomotion and its handle. As this part only needs to guide the wires from the handle to the head it does not need to be very complicated. However the friction it causes does need to be minimized when dragged by the head. As such it should have its diameter be as small as possible and if need be an outer skin which can be lubricated to minimize the friction coefficient. Another reason to keep the diameter small is to minimize the difference in the distance the wires need to travel when the tail rounds corners, as the inside of the corner has a shorter travel path than the outside and a few millimeters could make a difference to the position of the sliders. This issue could also be solved by designing the handle in a way that it makes it easy to reset the tension of the wires to a default state when the sliders are positioned correctly.

As shown in a Chapter 7.2.3. in some environments the instrument does not work due to the actuation cycle used. This could be solved by designing the handle in a way that alternative actuation cycles become possible. These cycles could be used to get past the environments where the original cycle does not work. The current cycle can also only be used to move the instrument forward. By reversing the cycle backwards locomotion is made possible.

To increase the coefficient of friction of the sliders, textures can be added to the outside of the sliders. These textures would need to be isotropic in the axial direction, as the instrument should also be able to reverse. If the textures were to be anisotropic you would run the risk of not having the grip required to reverse the instrument, which may leave it stuck inside the patient. The textures can be isotropic so friction coefficient is larger in the axial direction than the radial directions to reduce the risk of the sliders getting pushed over the rails of the radial expansion beams. Nevertheless this could also become a problem, as static friction is generally greater than dynamic friction, which means that when the sliders start slipping in the radial direction they are also more likely to slip in the axial direction.

7.5. Experiment Limitations & Recommendations for Future Experiments

One of the issues that may occur when the instrument is used deep inside the human body is when the drag caused by the tail of the instrument becomes stronger than the locomotion forces. This can be minimized by making sure the tail is smaller than the instrument, by lubricating the tail to reduce the friction coefficient and straightening out the bends in the colon. From the experiments currently performed it is unclear how much force in the opposite directing as the direction of movement affects the working of the instrument, therefore this should be investigated further.

While quite a few theories have been introduced at the start of this chapter to explain the results of the experiments, most of these theories have not been confirmed with additional tests. Also all tests have been performed in hard tubes made from almost the same material, which seems to have a very high friction coefficient. Though the test with lubrication suggests that the instrument still operates well with a low friction coefficient, the value of the friction coefficient between the plastic sliders and the resin tube was not measured and it might still be high compared to the practical working conditions of the instrument, even when lubricated. Therefore additional experiments will be required to get a clear picture of how the environment affects the slip ratio of the instrument.

Because the prototype was operated by hand in the experiments a reasonably high variation was expected in the results. This variation might have obscured some of the effects examined in the experiments. To investigate some of the effects of interest more precisely an automated operation system could be used. Because the experiments were not performed in a randomized order it is possible that an operator skill bias has influenced the results. Though if this effect exists it would only seem to be noticeable in the difference between the 15 to 16 mm diameter tests and the rest of the experiments which is unlikely as there is a sharp jump in slip ratio and it gets worse, not better. An automated operating system could find out if there is a significant effect due to operator skill.

8. Conclusion

The goal of this project was to design a soft self-propelling probe. The project succeeded and made a good first step towards the design of a new type of colonoscope. The project started by investigating some of the limitations of colonoscopes. The second step was abstracting how locomotion can be accomplished, followed by an exploration of the viable methods. Next a wide variety of concepts based on those methods were drafted, after which these concepts were analyzed in order to find the most suitable one. Subsequently, further improvements upon that design were made. A prototype was constructed to assess the locomotion principles behind the design. Experiments were performed to analyze the performance of this prototype. The results of these experiments were further analyzed to compare the theory of this type of locomotion to the performance in practice. This information was then used to provide guidance and advice for a next iteration of this design.

Because the main purpose for the proof-of-principle experiment was to assess the capability of the prototype to perform locomotion, relatively few measurements were taken and so few definitive conclusions can be drawn from the data. It can however be confirmed that the prototype is capable of locomotion and that the theory of this type of locomotion matches the practical results. Possible explanations for the observed results have been discussed and statistical analyses have been performed to indicate the reliability of the experiments. The statistical analyses show that the sample size in most cases is inadequate to confirm the theories about the performance of the prototype with the usual level of confidence. Therefore the data has also been used to indicate the sample size required to reach this level of confidence for future experiments.

While the current design is not yet fit for use in colonoscopies, the design process and the experiments gave a lot of new insight into the operation of the design. Based on these insights recommendations have been made for the next iterations of this and other designs, which will hopefully be of use to future designers.

Bibliography

[1] Ranasinghe I, Parzynski CS, Searfoss R, et al. Differences in Colonoscopy Quality Among Facilities: Development of a Post-Colonoscopy Risk-Standardized Rate of Unplanned Hospital Visits. Gastroenterology. 2016;150(1):103-13. doi:10.1053/j.gastro.2015.09.009

[2] Seeff LC, Richards TB, Shapiro JA, Nadel MR, Manninen DL, Given LS, Dong FB, Winges LD, McKenna MT. How many endoscopies are performed for colorectal cancer screening? Results from CDC's survey of endoscopic capacity. Gastroenterology. 2004 Dec;127(6):1670-7. doi: 10.1053/j.gastro.2004.09.051. PMID: 15578503.

[3] Loeve AJ, Fockens P, Breedveld P. Mechanical analysis of insertion problems and pain during colonoscopy: why highly skill-dependent colonoscopy routines are necessary in the first place and how they may be avoided. Can J Gastroenterol. 2013;27(5):293-302.

[4] Hounnou G, Destrieux C, Desmé J, Bertrand P, Velut S (2002). "Anatomical study of the length of the human intestine". Surg Radiol Anat. 24 (5): 290–4. doi:10.1007/s00276-002-0057-y

[5] A.J. Loeve, “Shaft-guidance for flexible endoscopes”, TU Delft repository: http://repository.tudelft.nl/, pp. 101-124, 2012.

[6] Schwarzman M and Attiyeh F, "Self-inflicted sigmoid colon perforation," Dis Colon Rectum, vol. 27, pp. 199-202, 1984.

[7] Verheijen, Daan (2021) Design of a Novel Propulsion Mechanism for Flexible Endoscopes Inspired by Plant Root Growth: A Bio-Inspired Solution to Propagation through the Human Colon (Master thesis, Delft University of Technology, Delft, The Netherlands). Retrieved from http://resolver.tudelft.nl/uuid:ccc1834d-ded0-41ce-9c1e-b4ff6c2ca6b2

[8]] D. Lee, S. Joe, J. Choi, B.-I. Lee, and B. Kim, “An elastic caterpillar-based self-propelled robotic colonoscope with high safety and mobility,” Mechatronics, vol. 39, pp. 54–62, 2016. Available: https://linkinghub.elsevier.com/retrieve/pii/S0957415816300770

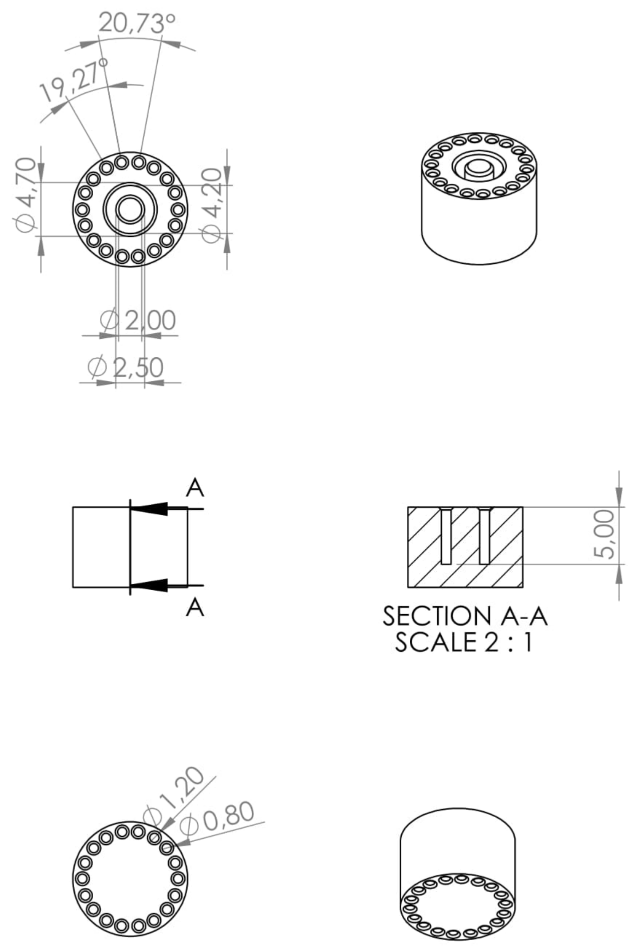
[9] Gray J., L. H. (1938). Studies in animal locomotion. VII. The earthworm`. Biol., 506-517.

[10]] Yin L, Wang S, Zuo S. Water-jet outer sheath with braided shape memory polymer tubes for upper gastrointestinal tract screening. Int J Med Robot. 2018 Dec;14(6):e1944. doi: 10.1002/rcs.1944. Epub 2018 Aug 14. PMID: 30105839.

[11] Zhang, Y., Finger, S., & Behrens, S. (z.d.). *Rapid Design through Virtual and Physical Prototyping*. cmu. Geraadpleegd op 19 juli 2021, van https://www.cs.cmu.edu/~rapidproto/mechanisms/chpt6.html

Appendix A: Technical Drawings

Part List				
Part #	Part Name	Production	Supplier	Quantity
1	Top Ring	SLA 3D Printer	n/a	1
2	Constraint Ring	SLA 3D Printer	n/a	1
3	Top Bellow Ring	SLA 3D Printer	n/a	1
4	Bottom Bellow Ring	SLA 3D Printer	n/a	1
5	Bottom Ring	SLA 3D Printer	n/a	1
6	Spine 1	Purchased + P.P.	Quartel Modelbouw	1
7	Spine 2	Purchased + P.P.	Quartel Modelbouw	1
8	Spine 3	Purchased + P.P.	Quartel Modelbouw	1
9	Spine 4	Purchased + P.P.	Quartel Modelbouw	1
10	Radial Expansion Beam	FDM 3D Printer	n/a	9
11	Slider	FM 3D Printer	n/a	9
12	Wire Guide	FDM 3D Printer	n/a	1
13	Cam Holder	FDM 3D Printer	n/a	1
14	Cam	FDM 3D Printer	n/a	1
15	Grip	FDM 3D Printer	n/a	1
16	Handle Slider	FDM 3D Printer	n/a	9
17	Pull Ring	SLA 3D Printer	n/a	1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

WEIGHT:

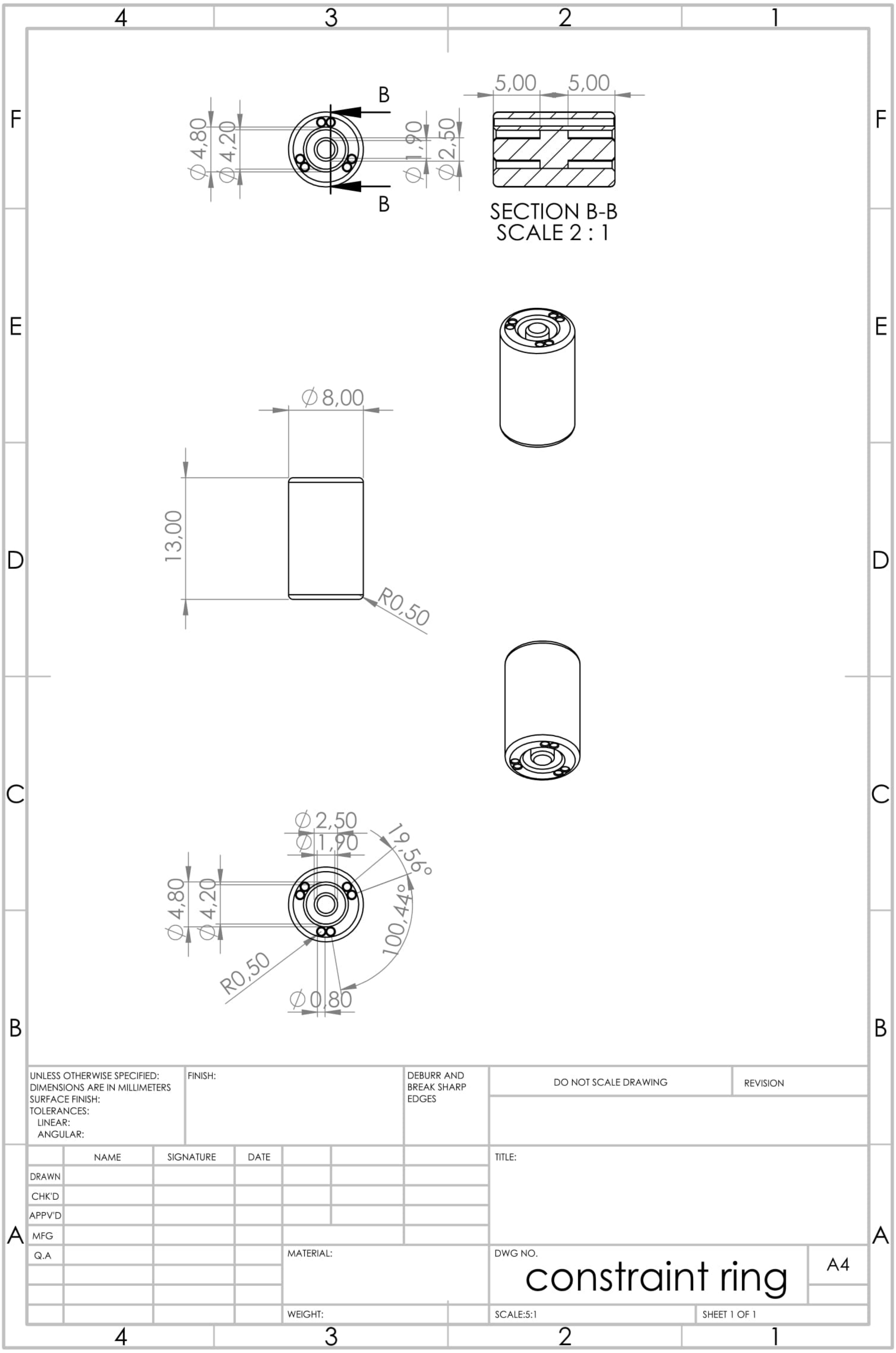
DWG NO.

top ring

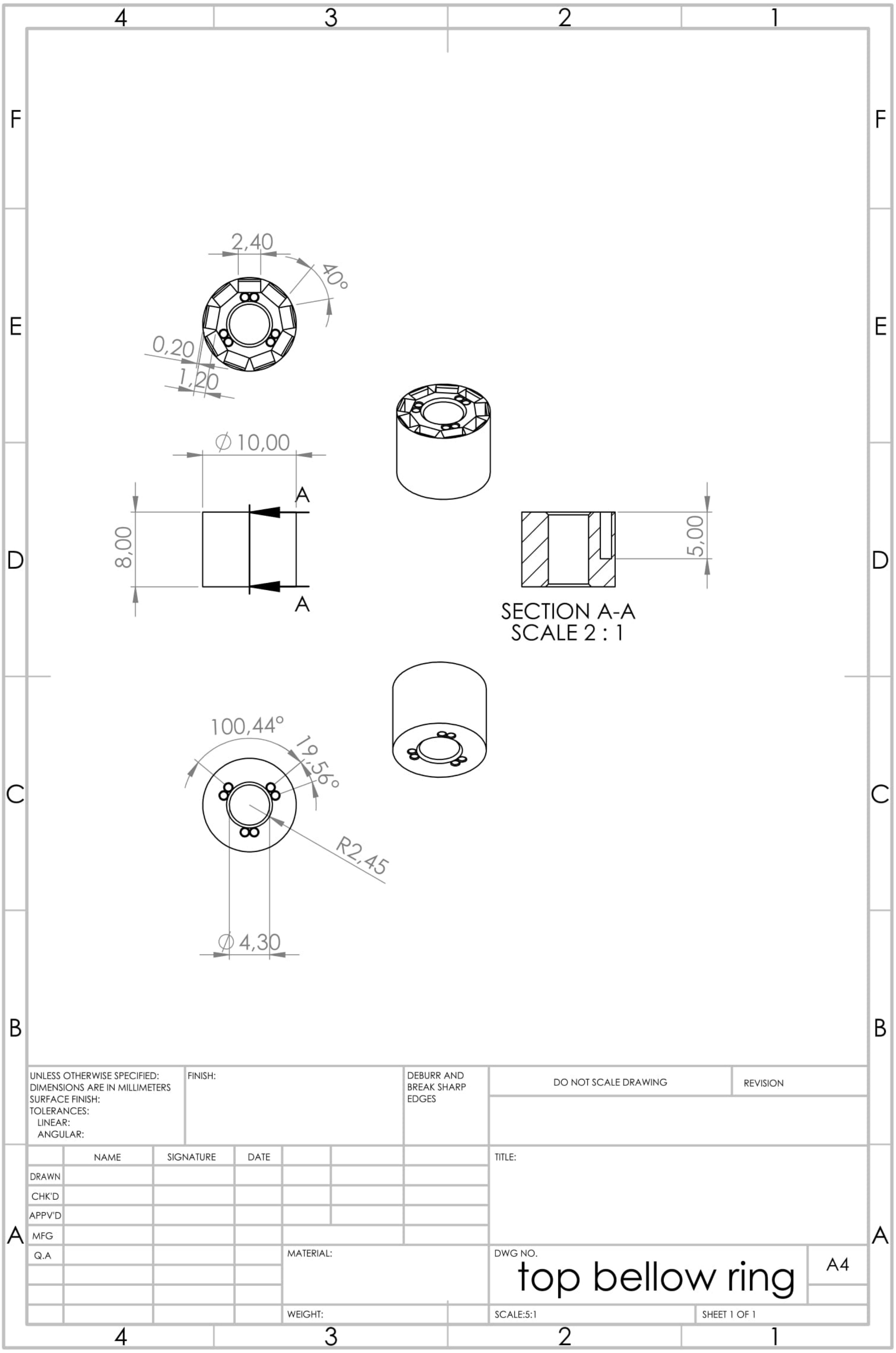
A4

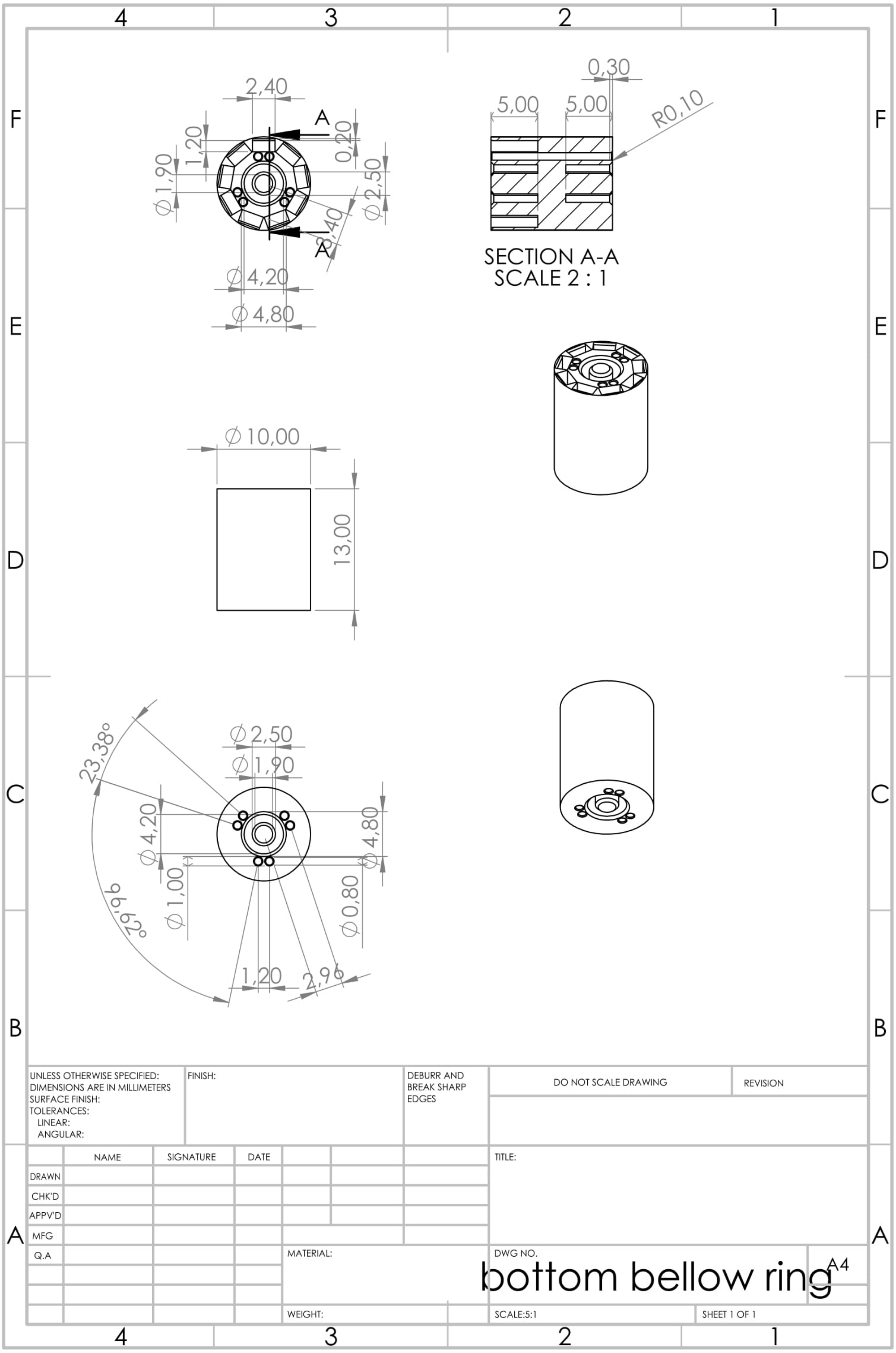
SCALE:5:1

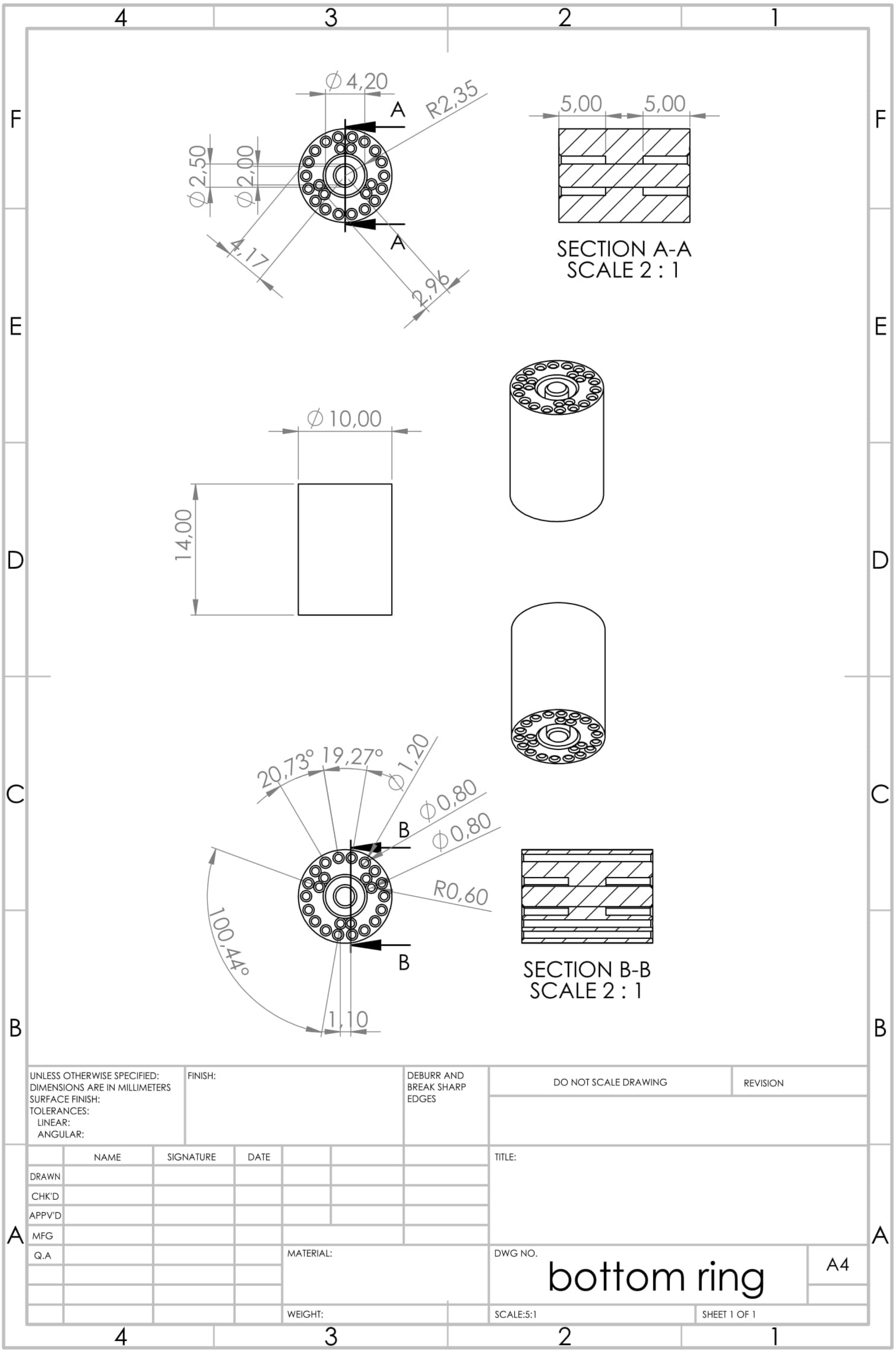
SHEET 1 OF 1



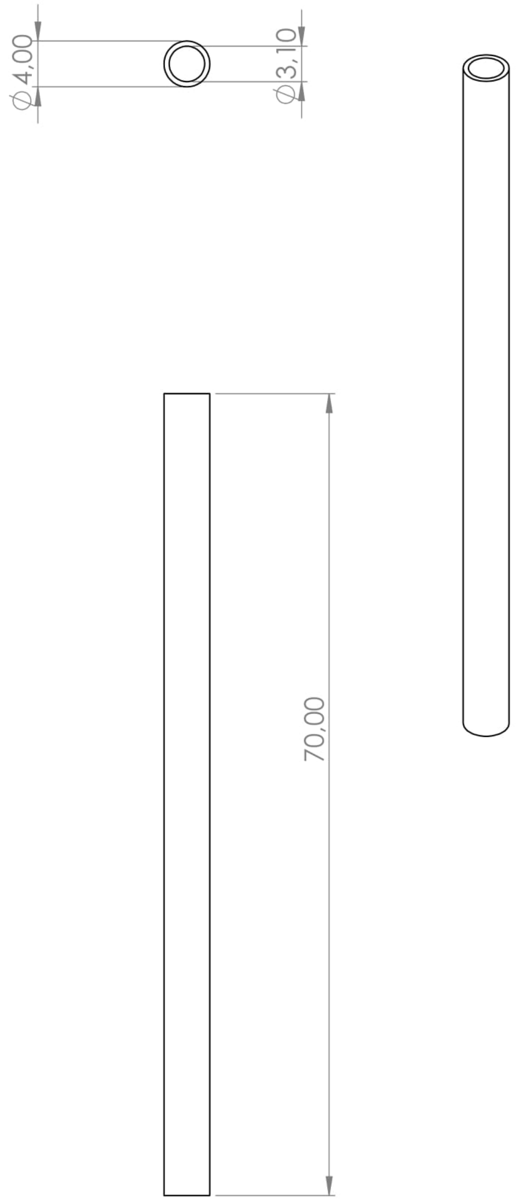
B
B
⌀4,80
⌀4,20
⌀1,90
⌀2,50
5,00
5,00
SECTION B-B
SCALE 2 : 1
⌀8,00
13,00
R0,50
⌀2,50
⌀1,90
19,56°
⌀4,80
⌀4,20
100,44°
R0,50
⌀0,80
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
constraint ring
A4
WEIGHT:
SCALE:5:1
SHEET 1 OF 1


2,40
40°
0,20
1,20
∅10,00
A
8,00
A
5,00
SECTION A-A
SCALE 2 : 1
100,44°
19,56°
R2,45
∅4,30
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
top bellow ring
A4
WEIGHT:
SCALE:5:1
SHEET 1 OF 1


4
3
2
1
F
E
D
C
B
A
2,40
A
1,20
0,20
⌀1,90
⌀2,50
8,40
A
⌀4,20
⌀4,80
0,30
5,00
5,00
R0,10
SECTION A-A
SCALE 2 : 1
⌀10,00
13,00
23,38°
⌀2,50
⌀1,90
⌀4,20
⌀4,80
⌀1,00
⌀0,80
96,62°
1,20
2,96
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
bottom bellow ring
A4
WEIGHT:
SCALE:5:1
SHEET 1 OF 1



Ø 4,20
R2,35
A
Ø 2,50
Ø 2,00
4,17
2,96
5,00
5,00
SECTION A-A
SCALE 2 : 1
Ø 10,00
14,00
20,73°
19,27°
Ø 1,20
Ø 0,80
Ø 0,80
B
R0,60
100,44°
1,10
SECTION B-B
SCALE 2 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
bottom ring
A4
WEIGHT:
SCALE:5:1
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

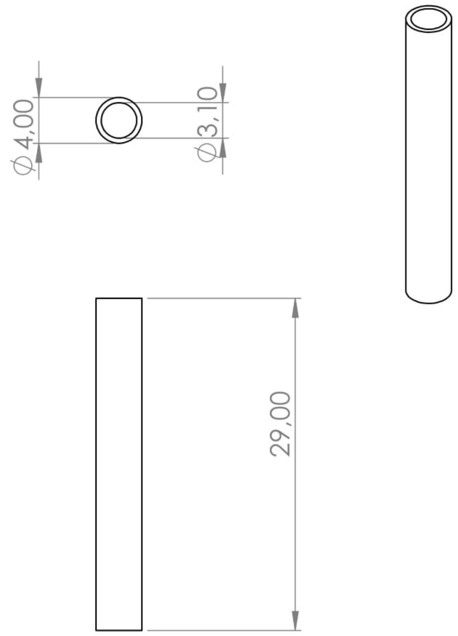
spine 1

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

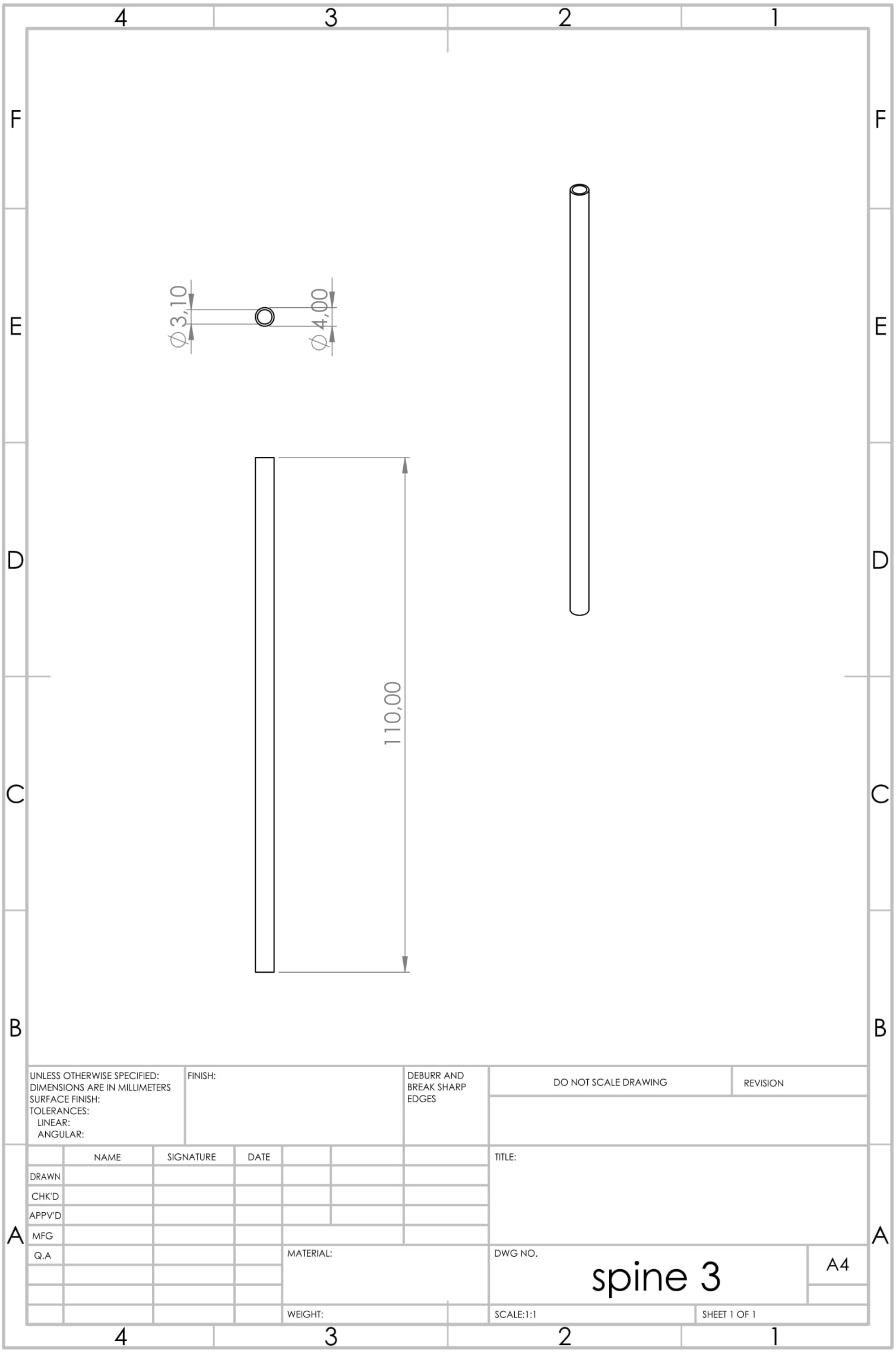
spine 2

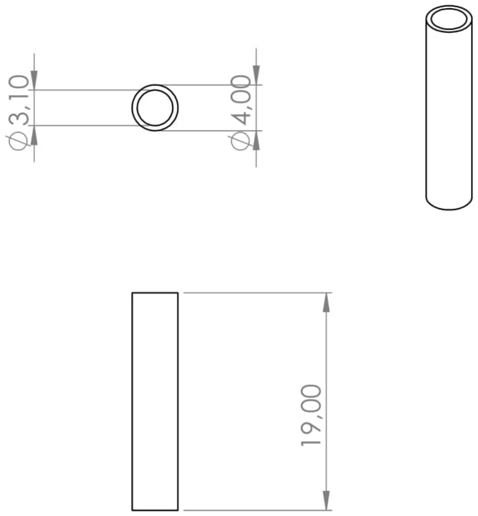
A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1


Ø3,10
Ø4,00
110,00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
spine 3
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

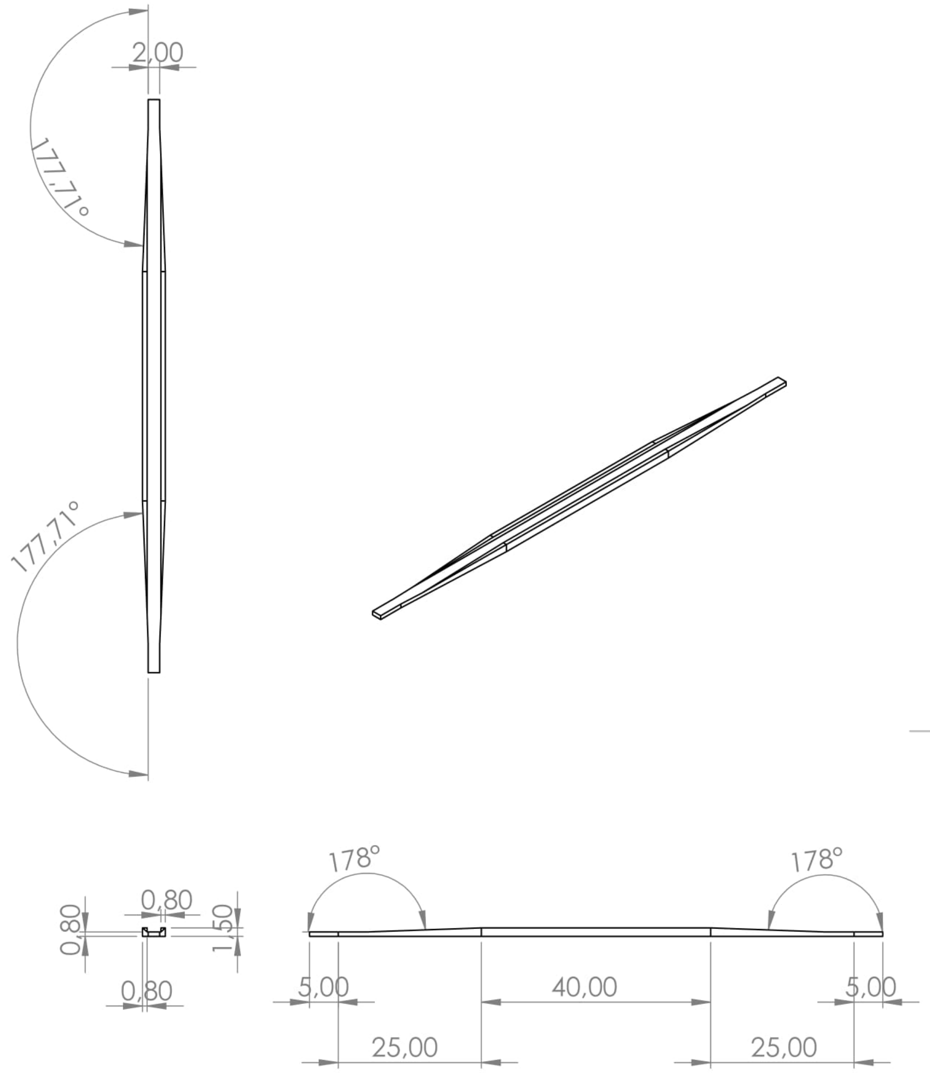
spine 4

A4

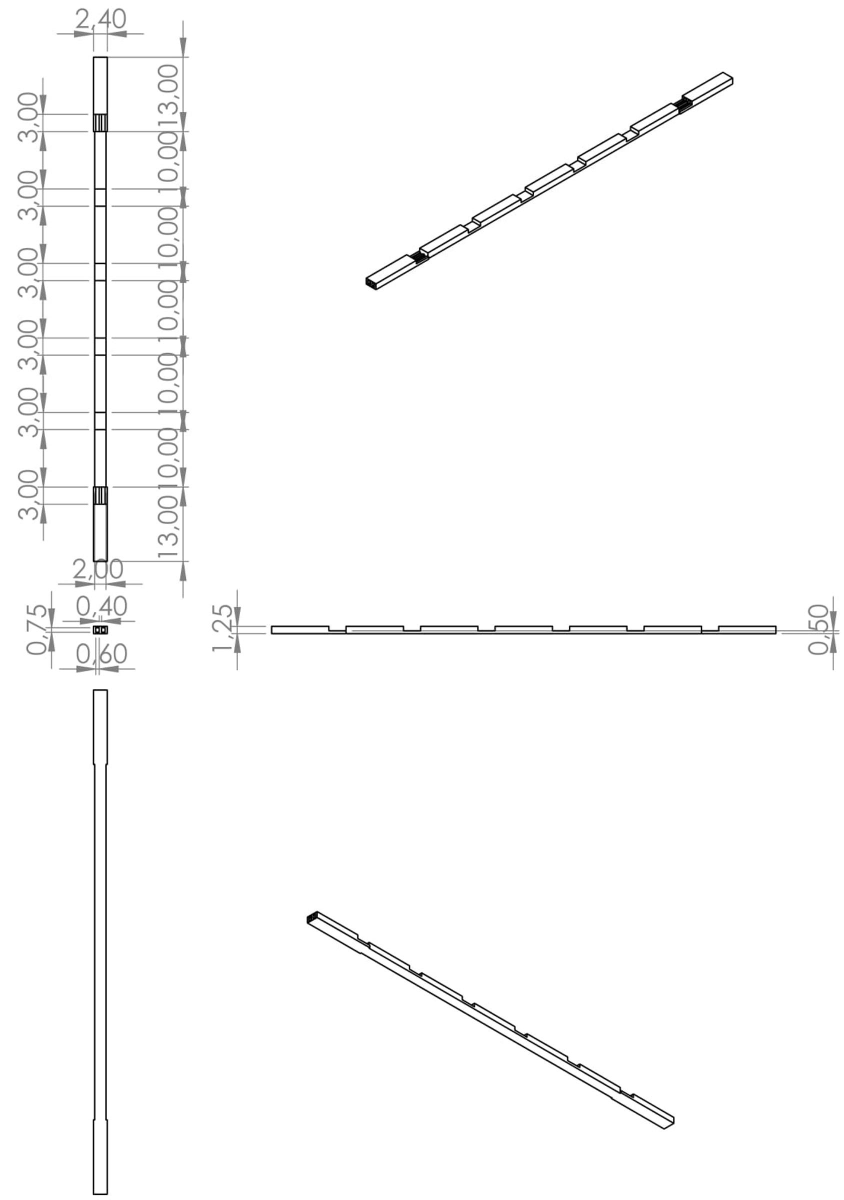
WEIGHT:

SCALE:5:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL:	DWG NO. radial expansion beam	A4
				WEIGHT:	SCALE:1:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

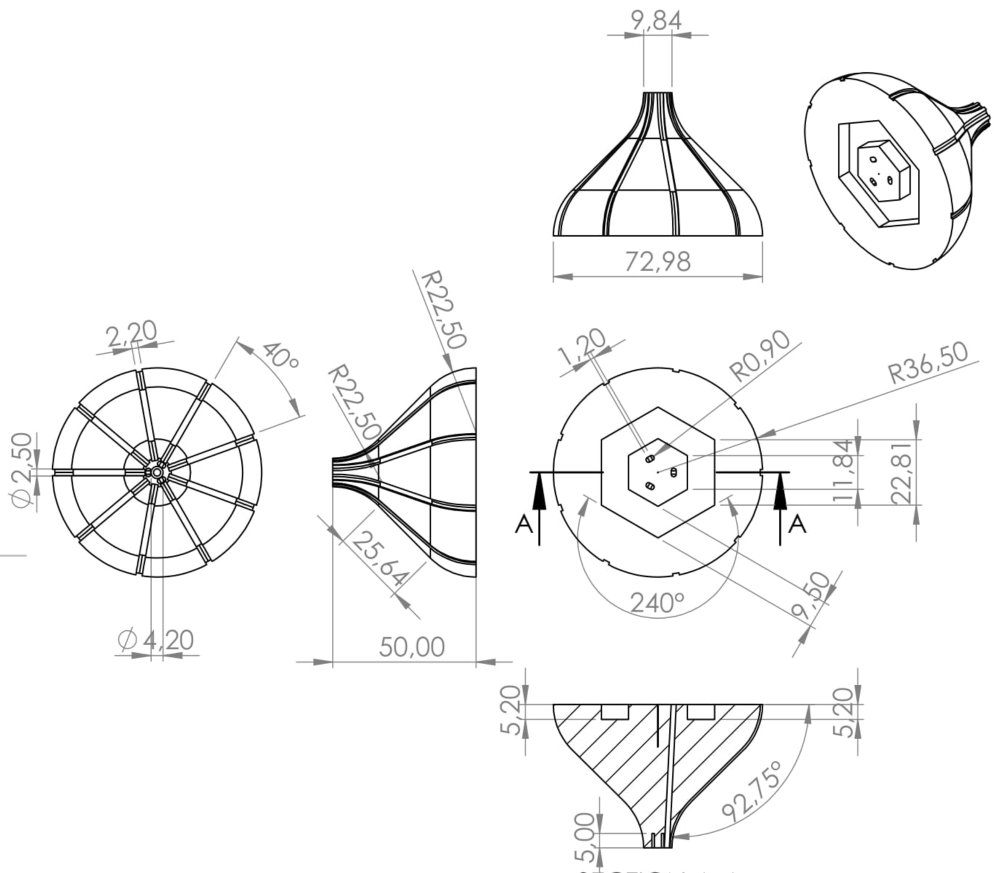
slider

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



SECTION A-A

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

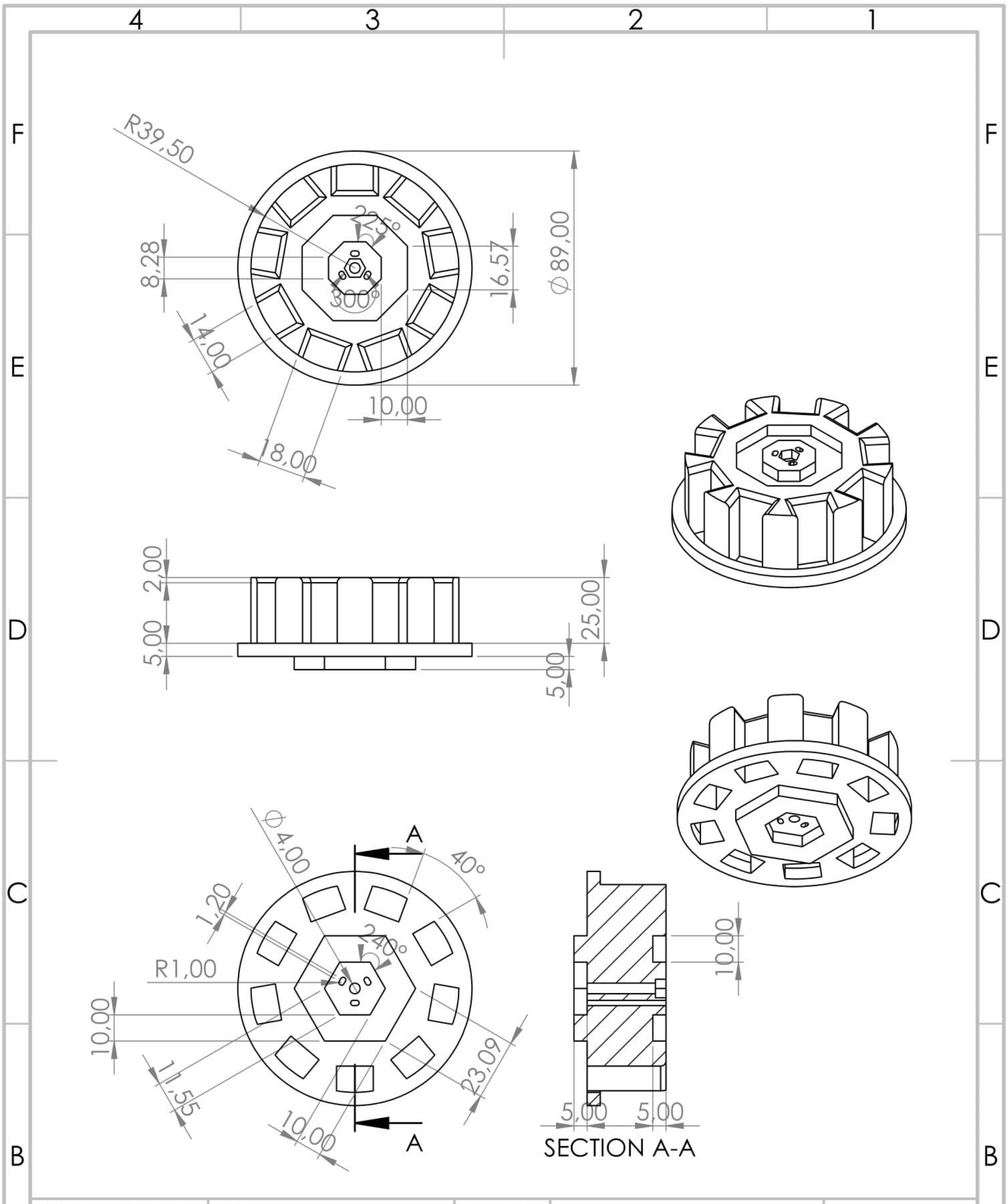
wire guide

A4

WEIGHT:

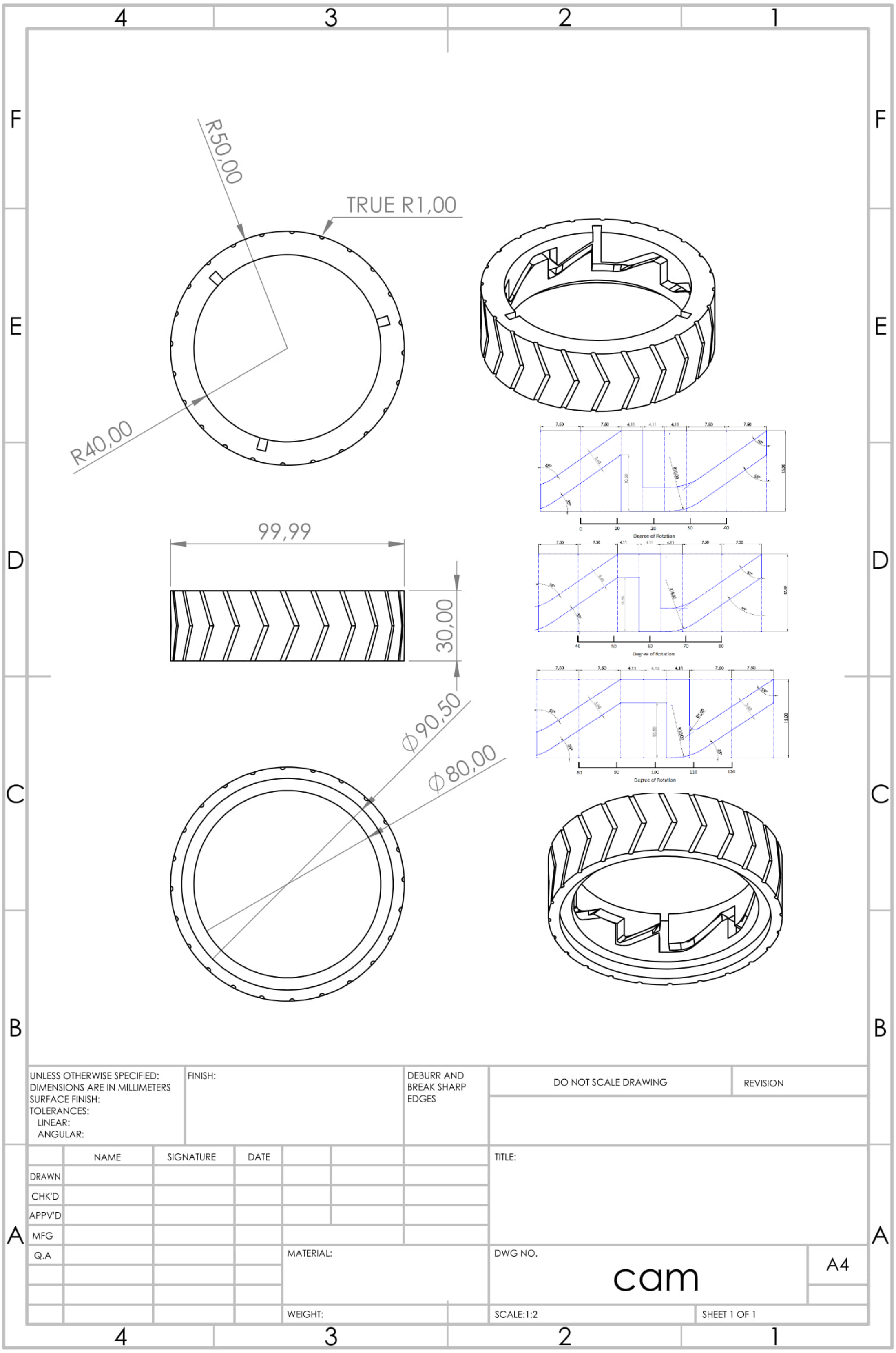
SCALE:1:2

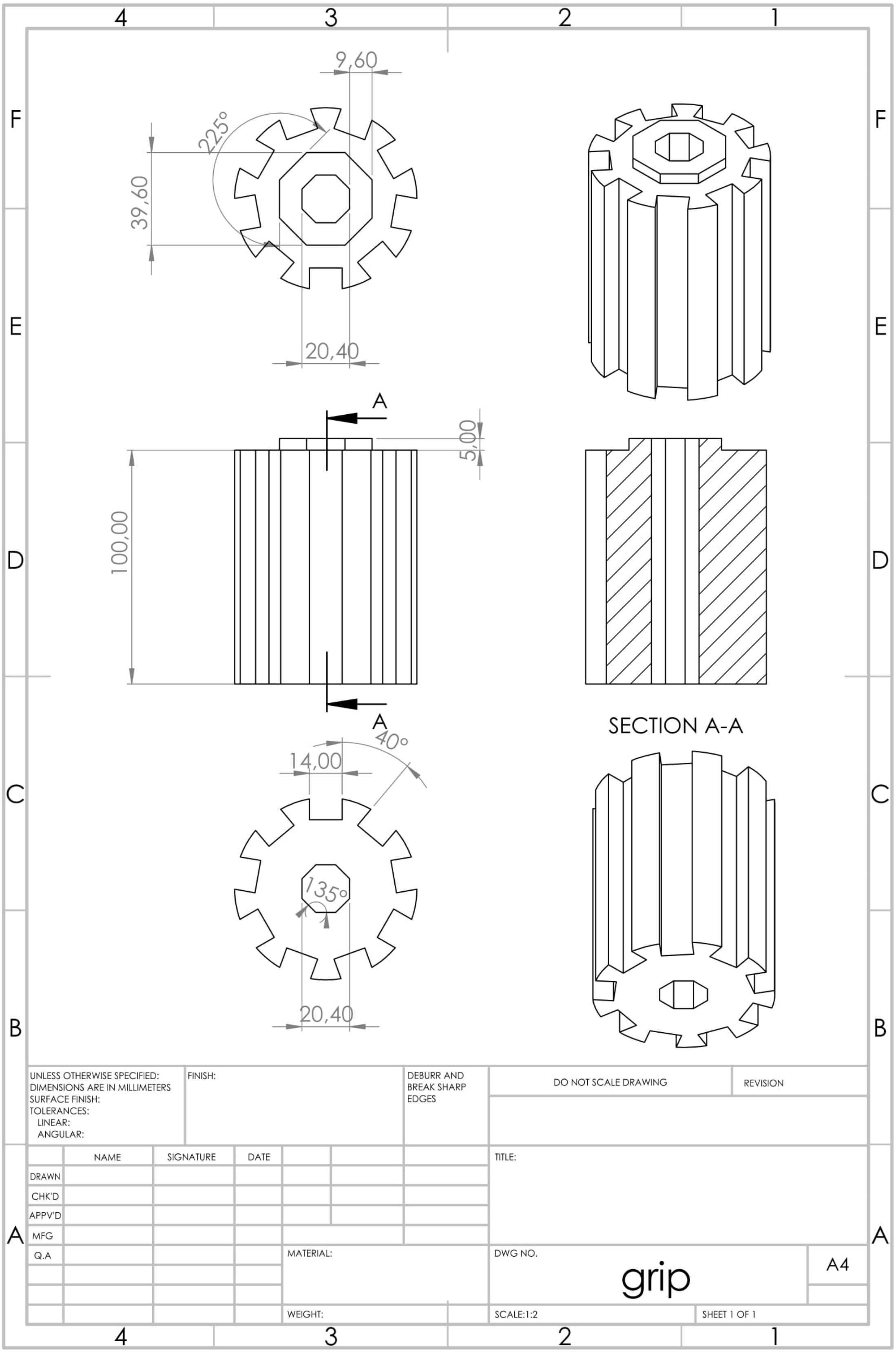
SHEET 1 OF 1

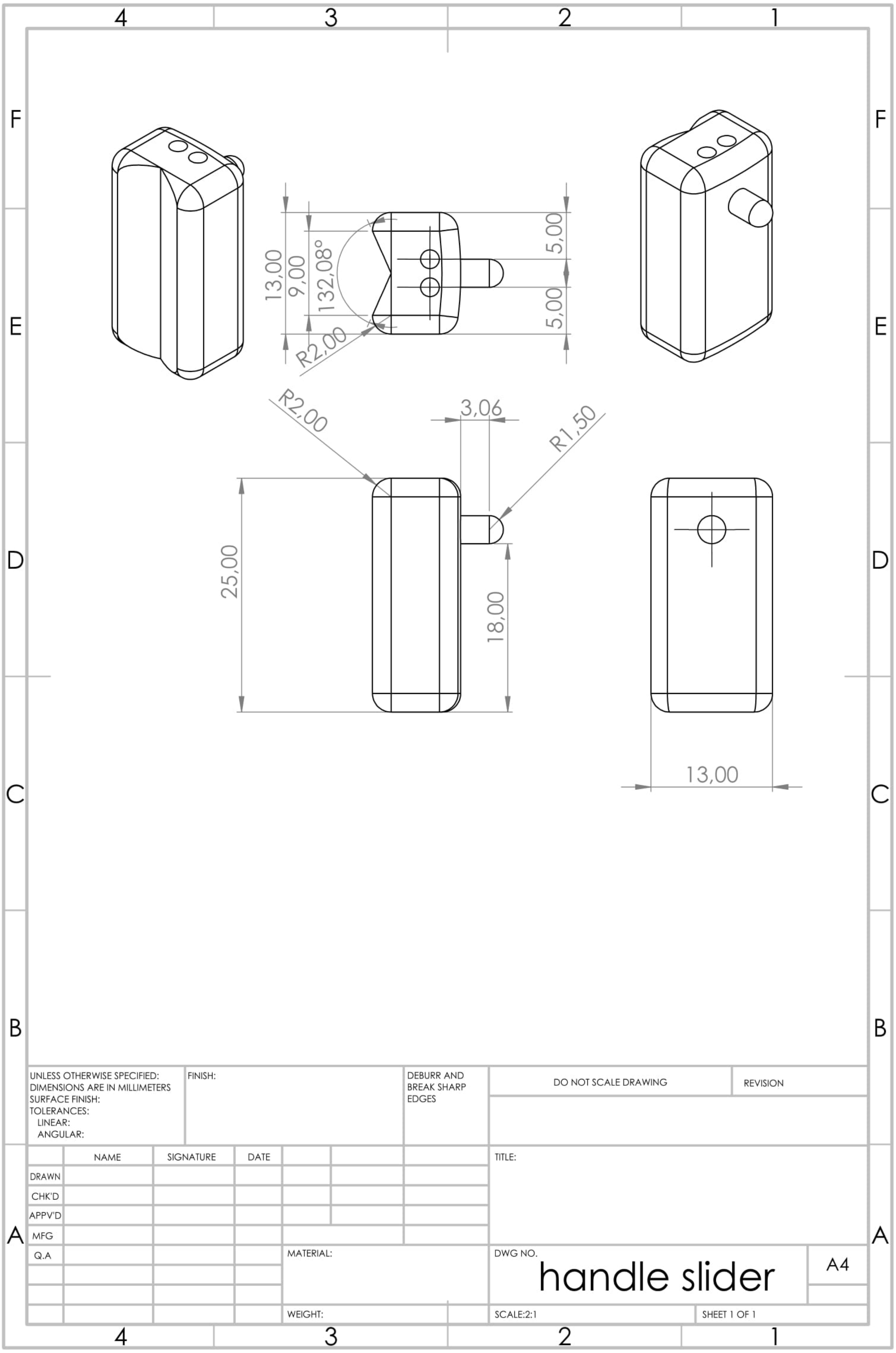


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

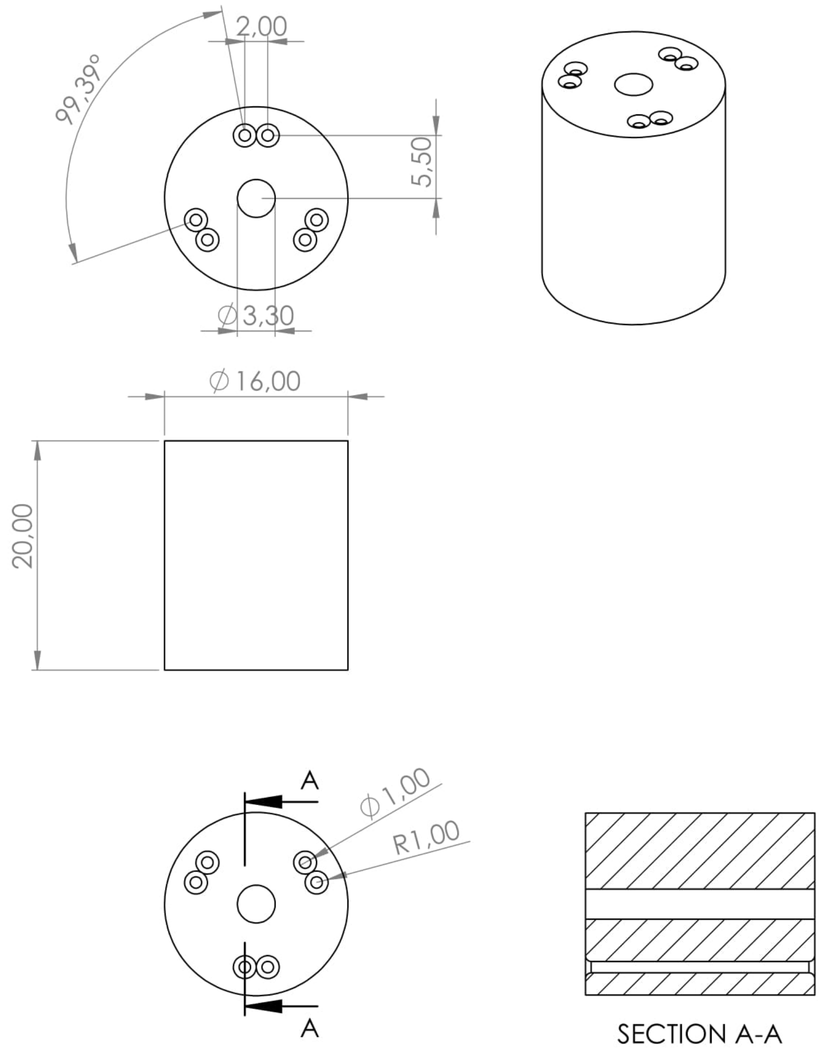
	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL:	DWG NO. cam holder — A4
				WEIGHT:	SCALE:1:2 — SHEET 1 OF 1


R50,00
TRUE R1,00
R40,00
99,99
30,00
ϕ90,50
ϕ80,00
Degree of Rotation
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
cam
A4
WEIGHT:
SCALE:1:2
SHEET 1 OF 1


9,60
225°
39,60
20,40
A
5,00
100,00
A
SECTION A-A
40°
14,00
135°
20,40
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
grip
A4
WEIGHT:
SCALE:1:2
SHEET 1 OF 1



13,00
9,00
132,08°
5,00
5,00
R2,00
R2,00
3,06
R1,50
25,00
18,00
13,00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
handle slider
A4
WEIGHT:
SCALE:2:1
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

pull ring

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1

Appendix B: Experimental Data

15mm Diameter Tube						
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.825	0.952	0.825	0.825	0.889	0.889
Test 2	0.793	0.809	0.794	0.730	0.810	0.762
Test 3	0.761	0.778	0.762	0.730	0.762	0.794
16mm Diameter Tube						
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.762	0.762	0.762	0.762	0.778	0.841
Test 2	0.698	0.778	0.762	0.778	0.698	0.794
Test 3	0.698	0.746	0.746	0.730	0.714	0.841
17mm Diameter Tube						
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.667	0.635	0.667	0.635	0.603	0.667
Test 2	0.587	0.603	0.603	0.698	0.635	0.698
Test 3	0.587	0.603	0.635	0.667	0.651	0.825
18mm Diameter Tube						
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.524	0.508	0.603	0.635	0.571	0.651
Test 2	0.651	0.508	0.587	0.667	0.619	0.571
Test 3	0.603	0.524	0.587	0.683	0.635	0.651
19mm Diameter Tube						
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.540	0.587	0.571	0.508	0.667	0.603
Test 2	0.603	0.587	0.603	0.635	0.683	0.635
Test 3	0.508	0.571	0.571	0.587	0.667	0.746
20mm Diameter Tube						
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.508	0.667	0.603	0.698	0.698	0.635
Test 2	0.698	0.667	0.667	0.651	0.635	0.603
Test 3	0.556	0.603	0.651	0.667	0.667	0.381

	17mm Diameter Tube Second Experiment					
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.413	0.667	0.683	0.603	0.524	0.635
Test 2	0.667	0.571	0.603	0.540	0.603	0.635
Test 3	0.651	0.587	0.667	0.571	0.444	0.667
	18mm Diameter Tube Second Experiment					
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.667	0.683	0.667	0.651	0.683	0.587
Test 2	0.651	0.651	0.635	0.603	0.762	0.587
Test 3	0.667	0.651	0.603	0.635	0.635	0.571
	19mm Diameter Tube Second Experiment					
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.794	0.762	0.683	0.667	0.698	0.698
Test 2	0.698	0.698	0.683	0.651	0.714	0.683
Test 3	0.730	0.762	0.698	0.667	0.667	0.714
	20mm Diameter Tube Second Experiment					
	0 rotations	**3 rotations**	**6 rotations**	**9 rotations**	**12 rotations**	**15 rotations**
Test 1	0.778	0.730	0.746	0.667	0.698	0.603
Test 2	0.762	0.714	0.667	0.714	0.698	0.587
Test 3	0.651	0.698	0.667	0.651	0.667	0.587

Conical Tube	
Test 1	0.857
Test 2	0.889
Test 3	0.857
Irregular shaped tube	
Test 1	0.857
Test 2	0.825
Test 3	0.698
Conical Tube Lubricated	
Test 1	0.825
Test 2	0.794
Test 3	0.730

Appendix C: MATLAB Code

```
%% data

clear all
clc

d15r0=[316 315 314];
d15r3=[320 315.5 314.5];
d15r6=[316 315 314];
d15r9=[316 313 313];
d15r12=[318 315.5 314];
d15r15=[318 314 315];

d16r0=[314 312 312];
d16r3=[314 314.5 313.5];
d16r6=[314 314 313.5];
d16r9=[314 314.5 313];
d16r12=[314.5 312 312.5];
d16r15=[316.5 315 316.5];

d17r0=[311 308.5 308.5];
d17r3=[310 309 309];
d17r6=[311 309 310];
d17r9=[310 312 311];
d17r12=[309 310 310.5];
d17r15=[311 312 316];

d18r0=[306.5 310.5 309];
d18r3=[306 306 306.5];
d18r6=[309 308.5 308.5];
d18r9=[310 311 311.5];
d18r12=[308 309.5 310];
d18r15=[310.5 308 310.5];

d19r0=[307 309 306];
d19r3=[308.5 308.5 308];
d19r6=[308 309 308];
d19r9=[306 310 308.5];
d19r12=[311 311.5 311];
d19r15=[309 310 313.5];

d20r0=[306 312 307.5];
d20r3=[311 311 309];
d20r6=[309 311 310.5];
d20r9=[312 310.5 311];
d20r12=[312 310 311];
d20r15=[310 309 302];

d17r0_2=[303 311 310.5];
d17r3_2=[311 308 308.5];
d17r6_2=[311.5 309 311];
d17r9_2=[309 307 308];
d17r12_2=[306.5 309 304];
d17r15_2=[310 310 311];

d18r0_2=[311 310.5 311];
d18r3_2=[311.5 310.5 310.5];
d18r6_2=[311 310 309];
d18r9_2=[310.5 309 310];
d18r12_2=[311.5 314 310];
d18r15_2=[308.5 308.5 308];

d19r0_2=[315 312 313];
d19r3_2=[314 312 314];
d19r6_2=[311.5 311.5 312];
d19r9_2=[311 310.5 311];
d19r12_2=[312 312.5 311];
d19r15_2=[312 311.5 312.5];

d20r0_2=[314.5 314 310.5];
d20r3_2=[313 312.5 312];
d20r6_2=[313.5 311 311];
d20r9_2=[311 312.5 310.5];
d20r12_2=[312 312 311];
d20r15_2=[309 308.5 308.5];

d20g114=[311 310 311];
d20g2520=[308 310 311];

conall=[317 318 317];
irregular=[317 316 312];
connal_lub=[316 315 313];

d15r0_r=(d15r0-290)/31.5;
d15r3_r=(d15r3-290)/31.5;
d15r6_r=(d15r6-290)/31.5;
d15r9_r=(d15r9-290)/31.5;
d15r12_r=(d15r12-290)/31.5;
d15r15_r=(d15r15-290)/31.5;

d16r0_r=(d16r0-290)/31.5;
d16r3_r=(d16r3-290)/31.5;
d16r6_r=(d16r6-290)/31.5;
d16r9_r=(d16r9-290)/31.5;
d16r12_r=(d16r12-290)/31.5;
d16r15_r=(d16r15-290)/31.5;

d17r0_r=(d17r0-290)/31.5;
d17r3_r=(d17r3-290)/31.5;
d17r6_r=(d17r6-290)/31.5;
d17r9_r=(d17r9-290)/31.5;
d17r12_r=(d17r12-290)/31.5;
d17r15_r=(d17r15-290)/31.5;

d18r0_r=(d18r0-290)/31.5;
d18r3_r=(d18r3-290)/31.5;
d18r6_r=(d18r6-290)/31.5;
d18r9_r=(d18r9-290)/31.5;
d18r12_r=(d18r12-290)/31.5;
d18r15_r=(d18r15-290)/31.5;

d19r0_r=(d19r0-290)/31.5;
d19r3_r=(d19r3-290)/31.5;
d19r6_r=(d19r6-290)/31.5;
d19r9_r=(d19r9-290)/31.5;
d19r12_r=(d19r12-290)/31.5;
d19r15_r=(d19r15-290)/31.5;

d20r0_r=(d20r0-290)/31.5;
d20r3_r=(d20r3-290)/31.5;
d20r6_r=(d20r6-290)/31.5;
d20r9_r=(d20r9-290)/31.5;
d20r12_r=(d20r12-290)/31.5;
d20r15_r=(d20r15-290)/31.5;

d17r0_2_r=(d17r0_2-290)/31.5;
d17r3_2_r=(d17r3_2-290)/31.5;
d17r6_2_r=(d17r6_2-290)/31.5;
d17r9_2_r=(d17r9_2-290)/31.5;
d17r12_2_r=(d17r12_2-290)/31.5;
d17r15_2_r=(d17r15_2-290)/31.5;

d18r0_2_r=(d18r0_2-290)/31.5;
d18r3_2_r=(d18r3_2-290)/31.5;
d18r6_2_r=(d18r6_2-290)/31.5;
d18r9_2_r=(d18r9_2-290)/31.5;
d18r12_2_r=(d18r12_2-290)/31.5;
d18r15_2_r=(d18r15_2-290)/31.5;

d19r0_2_r=(d19r0_2-290)/31.5;
d19r3_2_r=(d19r3_2-290)/31.5;
d19r6_2_r=(d19r6_2-290)/31.5;
d19r9_2_r=(d19r9_2-290)/31.5;
d19r12_2_r=(d19r12_2-290)/31.5;
d19r15_2_r=(d19r15_2-290)/31.5;

d20r0_2_r=(d20r0_2-290)/31.5;
d20r3_2_r=(d20r3_2-290)/31.5;
d20r6_2_r=(d20r6_2-290)/31.5;
```

```
    d20r9_2_r=(d20r9_2-290)/31.5;
    d20r12_2_r=(d20r12_2-290)/31.5;
    d20r15_2_r=(d20r15_2-290)/31.5;

    d20g114_r=(d20g114-290)/31.5;
    d20g2520_r=(d20g2520-290)/31.5;

    conall_r=(conall-290)/31.5;
    irregular_r=(irregular-290)/31.5;
    connal_lub_r=(connal_lub-290)/31.5;
    %% plot


    hold on

    title('Experiment Results')
    ylabel('Slip Ratio')
    xlabel('Diameter Instrument')


    sd15r0=scatter([15 15 15], d15r0_r, 15,
'r', 'filled');
    sd15r3=scatter([16 16 16], d15r3_r, 15,
'r', 'filled');
    sd15r6=scatter([17 17 17], d15r6_r, 25,
'r', 'filled', 's');
    sd15r9=scatter([18 18 18], d15r9_r, 25,
'r', 'filled', 's');
    sd15r12=scatter([19 19 19], d15r12_r,
25, 'r', 'filled', 's');
    sd15r15=scatter([20 20 20], d15r15_r,
25, 'r', 'filled', 's');

    sd16r0=scatter([15.1    15.1    15.1],
d16r0_r, 15, 'g', 'filled');
    sd16r3=scatter([16.1    16.1    16.1],
d16r3_r, 15, 'g', 'filled');
    sd16r6=scatter([17.1    17.1    17.1],
d16r6_r, 15, 'g', 'filled');
    sd16r9=scatter([18.1    18.1    18.1],
d16r9_r, 25, 'g', 'filled', 's');
    sd16r12=scatter([19.1    19.1    19.1],
d16r12_r, 25, 'g', 'filled', 's');
    sd16r15=scatter([20.1    20.1    20.1],
d16r15_r, 25, 'g', 'filled', 's');

    sd17r0=scatter([15.2    15.2    15.2],
d17r0_r, 15, 'b', 'filled');
    sd17r3=scatter([16.2    16.2    16.2],
d17r3_r, 15, 'b', 'filled');
    sd17r6=scatter([17.2    17.2    17.2],
d17r6_r, 15, 'b', 'filled');
    sd17r9=scatter([18.2    18.2    18.2],
d17r9_r, 15, 'b', 'filled');
    sd17r12=scatter([19.2    19.2    19.2],
d17r12_r, 25, 'b', 'filled', 's');
    sd17r15=scatter([20.2    20.2    20.2],
d17r15_r, 25, 'b', 'filled', 's');

    sd18r0=scatter([15.3    15.3    15.3],
d18r0_r, 15, 'c', 'filled');
    sd18r3=scatter([16.3    16.3    16.3],
d18r3_r, 15, 'c', 'filled');
    sd18r6=scatter([17.3    17.3    17.3],
d18r6_r, 15, 'c', 'filled');
    sd18r9=scatter([18.3    18.3    18.3],
d18r9_r, 15, 'c', 'filled');
    sd18r12=scatter([19.3    19.3    19.3],
d18r12_r, 25, 'c', 'filled', 's');
    sd18r15=scatter([20.3    20.3    20.3],
d18r15_r, 25, 'c', 'filled', 's');

    sd19r0=scatter([15.4    15.4    15.4],
d19r0_r, 15, 'm', 'filled');
    sd19r3=scatter([16.4    16.4    16.4],
d19r3_r, 15, 'm', 'filled');
    sd19r6=scatter([17.4    17.4    17.4],
d19r6_r, 15, 'm', 'filled');
    sd19r9=scatter([18.4    18.4    18.4],
d19r9_r, 15, 'm', 'filled');
    sd19r12=scatter([19.4    19.4    19.4],
d19r12_r, 15, 'm', 'filled');
    sd19r15=scatter([20.4    20.4    20.4],
d19r15_r, 25, 'm', 'filled', 's');

    sd20r0=scatter([15.5    15.5    15.5],
d20r0_r, 15, 'k', 'filled');
    sd20r3=scatter([16.5    16.5    16.5],
d20r3_r, 15, 'k', 'filled');
    sd20r6=scatter([17.5    17.5    17.5],
d20r6_r, 15, 'k', 'filled');
    sd20r9=scatter([18.5    18.5    18.5],
d20r9_r, 15, 'k', 'filled');
    sd20r12=scatter([19.5    19.5    19.5],
d20r12_r, 15, 'k', 'filled');
    sd20r15=scatter([20.5    20.5    20.5],
d20r15_r, 25, 'k', 'filled', 's');


    axis([14.8 20.99 0 1])
    legend([sd15r0  sd16r0  sd17r0  sd18r0
sd19r0 sd20r0], '15mm Diameter Tube', '16mm
Diameter Tube', '17mm Diameter Tube', '18mm
Diameter Tube', '19mm Diameter Tube', '20mm
Diameter                              Tube',
'Location','southwest','Orientation','verti
cal')
    %% plot 2

    hold on

    title('Experiment Results')
    ylabel('Slip Ratio')
    xlabel('Diameter Instrument')

    sd17r0=scatter([15 15 15], d17r0_r, 15,
'b', 'filled');
    sd17r3=scatter([16 16 16], d17r3_r, 15,
'b', 'filled');
    sd17r6=scatter([17 17 17], d17r6_r, 15,
'b', 'filled');
    sd17r9=scatter([18 18 18], d17r9_r, 15,
'b', 'filled');
    sd17r12=scatter([19 19 19], d17r12_r,
25, 'b', 'filled', 's');
    sd17r15=scatter([20 20 20], d17r15_r,
25, 'b', 'filled', 's');

    sd18r0=scatter([15.1    15.1    15.1],
d18r0_r, 15, 'c', 'filled');
    sd18r3=scatter([16.1    16.1    16.1],
d18r3_r, 15, 'c', 'filled');
    sd18r6=scatter([17.1    17.1    17.1],
d18r6_r, 15, 'c', 'filled');
    sd18r9=scatter([18.1    18.1    18.1],
d18r9_r, 15, 'c', 'filled');
    sd18r12=scatter([19.1    19.1    19.1],
d18r12_r, 25, 'c', 'filled', 's');
    sd18r15=scatter([20.1    20.1    20.1],
d18r15_r, 25, 'c', 'filled', 's');

    sd19r0=scatter([15.2    15.2    15.2],
d19r0_r, 15, 'm', 'filled');
    sd19r3=scatter([16.2    16.2    16.2],
d19r3_r, 15, 'm', 'filled');
    sd19r6=scatter([17.2    17.2    17.2],
d19r6_r, 15, 'm', 'filled');
    sd19r9=scatter([18.2    18.2    18.2],
d19r9_r, 15, 'm', 'filled');
    sd19r12=scatter([19.2    19.2    19.2],
d19r12_r, 15, 'm', 'filled');
    sd19r15=scatter([20.2    20.2    20.2],
d19r15_r, 25, 'm', 'filled', 's');
```

```
    sd20r0=scatter([15.3    15.3    15.3],
d20r0_r, 15, 'k', 'filled');
    sd20r3=scatter([16.3    16.3    16.3],
d20r3_r, 15, 'k', 'filled');
    sd20r6=scatter([17.3    17.3    17.3],
d20r6_r, 15, 'k', 'filled');
    sd20r9=scatter([18.3    18.3    18.3],
d20r9_r, 15, 'k', 'filled');
    sd20r12=scatter([19.3    19.3    19.3],
d20r12_r, 15, 'k', 'filled');
    sd20r15=scatter([20.3    20.3    20.3],
d20r15_r, 25, 'k', 'filled', 's');

    sd17r0_2=scatter([15.5    15.5    15.5],
d17r0_2_r, 15, 'b', 'filled');
    sd17r3_2=scatter([16.5    16.5    16.5],
d17r3_2_r, 15, 'b', 'filled');
    sd17r6_2=scatter([17.5    17.5    17.5],
d17r6_2_r, 15, 'b', 'filled');
    sd17r9_2=scatter([18.5    18.5    18.5],
d17r9_2_r, 15, 'b', 'filled');
    sd17r12_2=scatter([19.5    19.5    19.5],
d17r12_2_r, 25, 'b', 'filled', 's');
    sd17r15_2=scatter([20.5    20.5    20.5],
d17r15_2_r, 25, 'b', 'filled', 's');

    sd18r0_2=scatter([15.6    15.6    15.6],
d18r0_2_r, 15, 'c', 'filled');
    sd18r3_2=scatter([16.6    16.6    16.6],
d18r3_2_r, 15, 'c', 'filled');
    sd18r6_2=scatter([17.6    17.6    17.6],
d18r6_2_r, 15, 'c', 'filled');
    sd18r9_2=scatter([18.6    18.6    18.6],
d18r9_2_r, 15, 'c', 'filled');
    sd18r12_2=scatter([19.6    19.6    19.6],
d18r12_2_r, 25, 'c', 'filled', 's');
    sd18r15_2=scatter([20.6    20.6    20.6],
d18r15_2_r, 25, 'c', 'filled', 's');

    sd19r0_2=scatter([15.7    15.7    15.7],
d19r0_2_r, 15, 'm', 'filled');
    sd19r3_2=scatter([16.7    16.7    16.7],
d19r3_2_r, 15, 'm', 'filled');
    sd19r6_2=scatter([17.7    17.7    17.7],
d19r6_2_r, 15, 'm', 'filled');
    sd19r9_2=scatter([18.7    18.7    18.7],
d19r9_2_r, 15, 'm', 'filled');
    sd19r12_2=scatter([19.7    19.7    19.7],
d19r12_2_r, 15, 'm', 'filled');
    sd19r15_2=scatter([20.7    20.7    20.7],
d19r15_2_r, 25, 'm', 'filled', 's');

    sd20r0_2=scatter([15.8    15.8    15.8],
d20r0_2_r, 15, 'k', 'filled');
    sd20r3_2=scatter([16.8    16.8    16.8],
d20r3_2_r, 15, 'k', 'filled');
    sd20r6_2=scatter([17.8    17.8    17.8],
d20r6_2_r, 15, 'k', 'filled');
    sd20r9_2=scatter([18.8    18.8    18.8],
d20r9_2_r, 15, 'k', 'filled');
    sd20r12_2=scatter([19.8    19.8    19.8],
d20r12_2_r, 15, 'k', 'filled');
    sd20r15_2=scatter([20.8    20.8    20.8],
d20r15_2_r, 25, 'k', 'filled', 's');

    axis([14.8 20.99 0 1])
    legend([sd17r0_2   sd18r0_2   sd19r0_2
sd20r0_2], '17mm Diameter Tube', '18mm
Diameter Tube', '19mm Diameter Tube', '20mm
Diameter                         Tube',
'Location','southwest','Orientation','verti
cal')
    %% plot 3

    hold on

    title('Experiment Results')
    ylabel('Slip Ratio')
    xlabel('Diameter Instrument')

    sd20g114=scatter([15 15 15], d20g114_r,
15, 'r', 'filled');
    sd20g2520=scatter([16     16     16],
d20g2520_r, 15, 'b', 'filled');
    sdconnal=scatter([17 17 17], conall_r,
15, 'g', 'filled');
    sdconnal_lub=scatter([18    18    18],
connal_lub_r, 15, 'm', 'filled');
    sdirregular=scatter([19    19    19],
irregular_r, 15, 'k', 'filled');

    axis([14.8 19.99 0 1])
    legend([sd20g114   sd20g2520   sdconnal
sdconnal_lub  sdirregular],  '20mm  Diameter
Tube',  '20mm  Diameter  Tube  with  Weight',
'Conical', 'Conical Lubracated', 'Irregular
shape',
'Location','southwest','Orientation','verti
cal')

    %% statistical analysis

    y1=[d15r0' d15r3' d15r6' d15r9' d15r12'
d15r15' d16r0' d16r3' d16r6' d16r9' d16r12'
d16r15' d17r0' d17r3' d17r6' d17r9' d17r12'
d17r15' d18r0' d18r3' d18r6' d18r9' d18r12'
d18r15' d19r0' d19r3' d19r6' d19r9' d19r12'
d19r15' d20r0' d20r3' d20r6' d20r9' d20r12'
d20r15'];

    Ano1=anova1(y1)
    si1=size(y1)


    y2=[d15r0' d15r3' d15r6' d15r9' d15r12'
d15r15' d16r0' d16r3' d16r6' d16r9' d16r12'
d16r15'];

    Ano2=anova1(y2)
    si2=size(y2)


    y3=[d17r0' d17r3' d17r6' d17r9' d17r12'
d17r15' d18r0' d18r3' d18r6' d18r9' d18r12'
d18r15' d19r0' d19r3' d19r6' d19r9' d19r12'
d19r15' d20r0' d20r3' d20r6' d20r9' d20r12'
d20r15'];

    Ano3=anova1(y1)
    si3=size(y3)

    T1_1=[d15r0  d15r3  d16r0  d16r3  d16r6
d17r0 d17r3 d17r6 d17r9 d18r0 d18r3 d18r6
d18r9 d19r0 d19r3 d19r6 d19r9 d19r12 d20r0
d20r3 d20r6 d20r9 d20r12];
    T1_2=[d15r6 d15r9 d15r12 d15r15 d16r9
d16r12 d16r15 d17r12 d17r15 d18r12 d18r15
d19r15 d20r15];


    [T1_h T1_p]=ttest2(T1_1, T1_2)
    sa1_1=size(T1_1)
    sa1_2=size(T1_2)
    n1    =    sampsizepwr('t2',[mean(T1_1)
var(T1_1)],mean(T1_2),0.9,[])

    T2_1=[d15r0  d15r3  d15r6  d15r9  d15r12
d15r15  d16r0  d16r3  d16r6  d16r9  d16r12
d16r15];
    T2_2=[d17r0  d17r3  d17r6  d17r9  d17r12
d17r15 d18r0 d18r3 d18r6 d18r9 d18r12 d18r15
d19r0 d19r3 d19r6 d19r9 d19r12 d19r15 d20r0
d20r3 d20r6 d20r9 d20r12 d20r15];
```

```
    [T2_h T2_p]=ttest2(T2_1, T2_2)
    sa2_1=size(T2_1)
    sa2_2=size(T2_2)
    n2    =    sampsizepwr('t2',[mean(T2_1)
var(T2_1)],mean(T2_2),0.9,[])


    T3_1=[d17r0  d17r3  d17r6  d17r9  d17r12
d17r15 d18r0 d18r3 d18r6 d18r9 d18r12 d18r15
d19r0 d19r3 d19r6 d19r9 d19r12 d19r15 d20r0
d20r3 d20r6 d20r9 d20r12 d20r15];
    T3_2=[d17r0_2  d17r3_2  d17r6_2  d17r9_2
d17r12_2  d17r15_2  d18r0_2  d18r3_2  d18r6_2
d18r9_2  d18r12_2  d18r15_2  d19r0_2  d19r3_2
d19r6_2  d19r9_2  d19r12_2  d19r15_2  d20r0_2
d20r3_2 d20r6_2 d20r9_2 d20r12_2 d20r15_2];

    [T3_h T3_p]=ttest2(T3_1, T3_2)
    sa3_1=size(T3_1)
    sa3_2=size(T3_2)
    n3    =    sampsizepwr('t2',[mean(T3_1)
var(T3_1)],mean(T3_2),0.9,[])


    T4_1=[d20g114];
    T4_2=[d20g2520];

    [T4_h T4_p]=ttest2(T4_1, T4_2)
    sa4_1=size(T4_1)
    sa4_2=size(T4_2)
    n4    =    sampsizepwr('t2',[mean(T4_1)
var(T4_1)],mean(T4_2),0.9,[])


    T5_1=[conall];
    T5_2=[connal_lub];

    [T5_h T5_p]=ttest2(T5_1, T5_2)
    sa5_1=size(T5_1)
    sa5_2=size(T5_2)
    n5    =    sampsizepwr('t2',[mean(T5_1)
var(T5_1)],mean(T5_2),0.9,[])
```