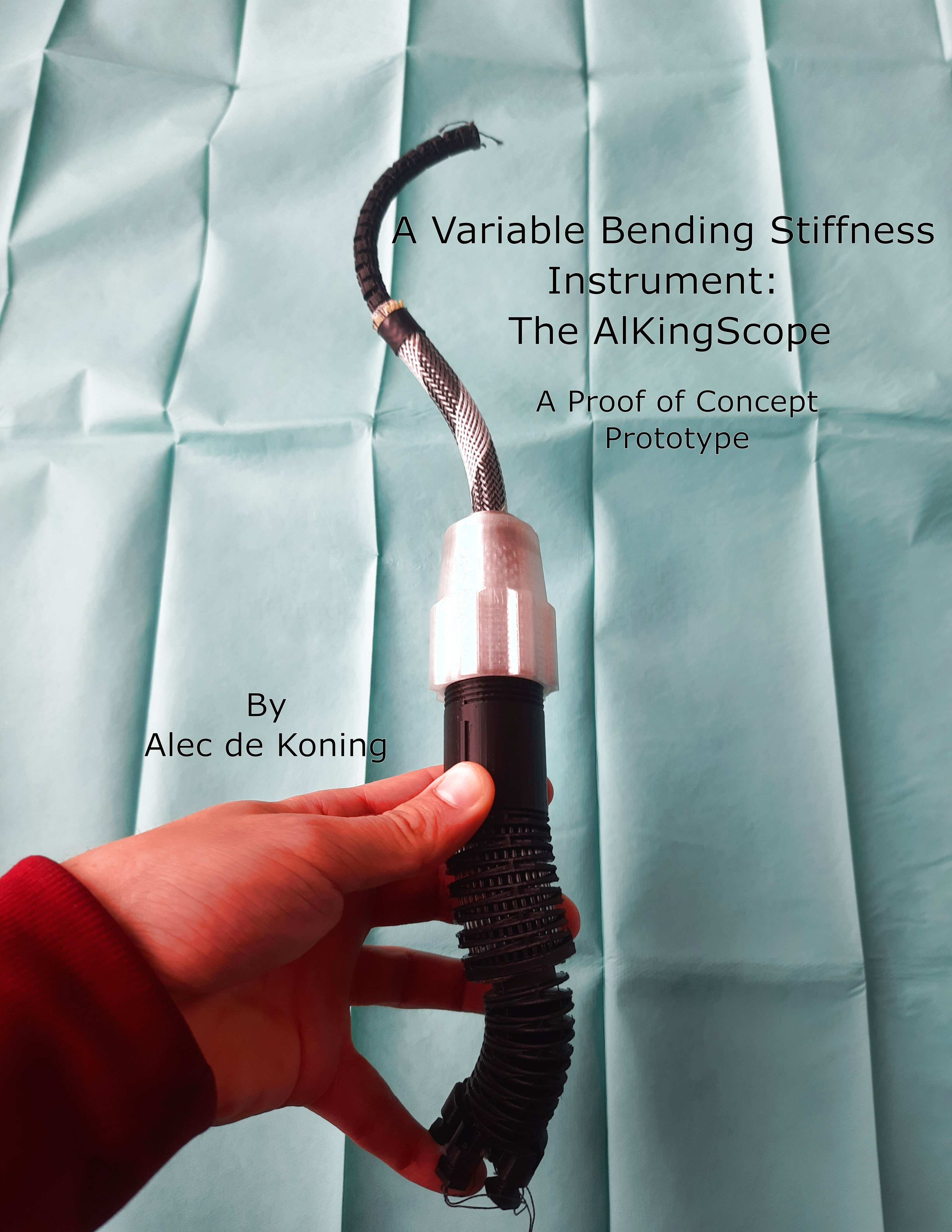
# A Variable Bending Stiffness Instrument: The AlKingScope

## A Proof of Concept Prototype

By
Alec de Koning



# A Variable Bending Stiffness Instrument: The AlKingScope

by

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*This thesis is confidential and cannot be made public until 1 July 2022.*



TU Delft

# Preface

After a long period of studying and experimenting, my master thesis has come to an end. Because of corona, I was obliged to work at home during my Master's. I had many online conversations which sometimes made it difficult to show and discuss my new designs. Luckily the university is open again and my thesis is finally finished! This research was performed at the TU Delft within the BITE (Bio-Inspired Technology Engineering) research group. Variable stiffness mechanisms were already investigated in the past. I hope that my thesis brings new perspective to this topic and more research will be performed in this field.

During my project, I received help from many people. First, I want to thank Fabian Trauzettel and Di Wu for supporting me. I had close contact with them and I could always ask my questions when needed. They guided me through this project which resulted in this thesis. Johan Bennet, a cardioligist from UZ Leuven explained his difficulties with cardiovascular procedures which helped me to gain more insight in these type of applications. I also want to thank Jos van Driel and Bradly But, who helped me with the setup for the experiment to test the variable stiffness ability.

Alec de Koning
Delft, July 2022

# Contents

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## Abstract

When treating a Chronic Total Occlusion (CTO) via Percutaneous Coronary Intervention (PCI), a guidewire first needs to be passed through or around the occlusion, a task requiring considerable skill and clinician experience. Proper backup support for the guidewire being used by the clinician is a prerequisite to prevent buckling or uncontrolled movement. Three different concepts that can vary their stiffness were generated, prototyped and evaluated against each other. Finally, a mechanism was designed that can vary its stiffness drastically by radially jamming wires together between a braided sheath and a radially rigid core that is also flexible in bending. Friction between the wires and the steerable segment generates the stiff configuration. If the braided sheath is released the wires can move along each other and the mechanism is flexible. The variable stiffness ability was tested by clamping the mechanism into a frame while applying a load to the distal tip. This resulted in a force-displacement curve that was 20 times stiffer in the stiff state than in the flexible state. The use of a braided sheath in a Variable Stiffness Mechanism (VSM) is an effective and simple way to obtain variable stiffness. The proposed design is a step forward in the developing process for VSM for cardiovascular applications.



## Keywords

Variable bending stiffness, coronary intervention, additive manufacturing, mechanically steered, axial stiffness, central channel.


## 1 Introduction

### 1.1 Background

Coronary Artery Disease (CAD) is a narrowing or blockage of the coronary arteries. It is caused by the buildup of plaques inside the arteries which is called atherosclerosis [1, 2, 3]. The build up of fatty material inside the arteries happens to everyone, however the rate of plaque growth is dependent on multiple factors, such as cholesterol level, blood pressure or diabetes [1, 4, 5]. Therefore some people experience more discomfort than others which can express itself in chest pain or a shortness of breath [4]. The effects of CAD are the leading cause of death in developed countries, which accounts for 31 % of all deaths in Europe [6] and 30.6% in the United States [5]. For patients with late-stage CAD the plaque needs to be removed and treatment is required.

Percutaneous Coronary Interventions (PCI's) are minimally invasive intervention techniques that can widen the blood vessels and restore the blood flow to the heart. Depending on the type and location of the stenosis or occlusion, different techniques are used to reach the site and widen the blood vessel. The lesion is accessed by a guidewire technique. A sheath is placed in the radial or femoral artery and a guidewire is guided through the sheath into the blood vessel and advanced to the site of the lesion. A balloon catheter is then placed over the guidewire and advanced to the blockage. At the site it will inflate and deflate multiple times to compress the fat tissue against the inner wall of the artery. This procedure is called angioplasty. However, if the balloon treatment is not enough to keep the blood vessel open, a stent is placed over the balloon which holds the plaque compressed against the artery wall after the balloon is removed.

In PCI's a guidewire is always required that is passed over or through the lesion in order to perform the procedure. These crossings can become complex due to the calcified, tortuous or totally occluded vessels [7]. A heavily calcified occlusion means that the cap of the occlusion has become hard and therefore it is difficult to puncture a guidewire through. Reaching the lesion site can also be difficult due to the tortuosity of the vessel. When there is a Chronic Total Occlusion (CTO) the whole artery is blocked and therefore a guidewire needs to puncture through the occlusion, which can lead to uncontrolled movement or buckling of the guidewire. To achieve these difficult PCI's procedures successfully, strong backup support is required [8, 9]. This means that the guiding catheter remains in the same fixed position while PCI hardware is advanced over the guidewire without backing off [9].

## 1.2 State of the art

The required back-up support is the main problem for this application. A guide catheter is placed at the ostium in front of the coronary artery to provide as much backup support as possible, see Figure 1. Guide catheters are too thick to reach in the coronary arteries and therefore micro catheters or guidewires are placed through the guide catheter in order to perform the PCI.

The backup support can be increased in a number of ways, each with its pros and cons. The most obvious solution is increasing the diameter of the guiding catheter [8]. The guide catheter is then retracted over the guidewire and a thicker guide catheter is than placed over the guidewire into the ostium. However the risks of local vascular complications, bleeding and coronary pressure damping, will be increased using a thicker guiding catheter [8, 10]. Coronary pressure damping is an abrupt decline in the mean coronary pressure, caused by the guide catheter blocking the coronary artery [11]. The terminal shape of the guiding catheter can also increase the back-up support. There are many different shaped guide catheters all suitable for a certain application, which makes it difficult to choose the right guide [9]. However, when a guiding catheter is changed, the risk increases that also the guidewire is inadvertently retracted from the lesion [12]. These are examples of passive support of the guiding catheter.

The backup support of the guide catheter can also be actively controlled by multiple techniques. An additional wire can be inserted in the coronary sinus, called a deep-seating technique [10, 13]. One or two buddy wires can be inserted into the artery to increase the friction between the guidewire and the vessel wall [10, 13]. A balloon anchoring technique uses a balloon to increase the support. An extra guidewire is placed into a side branch or along the exiting guidewire and a balloon catheter is pushed over that extra guidewire. When the balloon is inflated the guidewire is fixed in the vessel and provide support [10, 13]. The Mother-Child catheter Technique is a technique in which a large, "mother" catheter is placed into the target vessel to obtain passive support. A smaller "child" catheter is then placed trough the larger catheter to act as active support [10, 13].

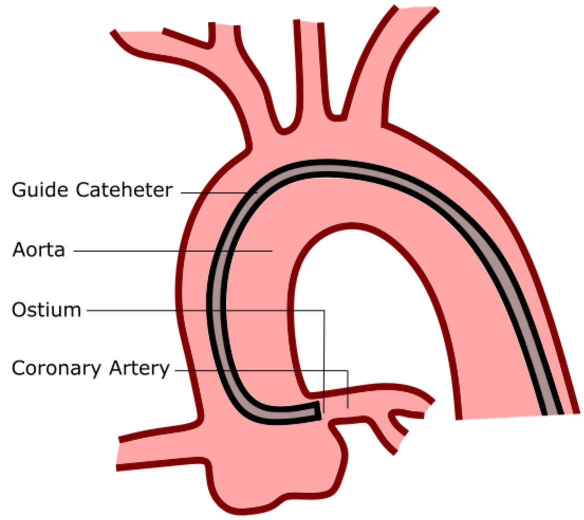


Figure 1: Schematic drawing of the placement of the guiding catheter in front of the ostium.

## 1.3 The 3Flex

The 3Flex is a mechanism that is developed in the BITE group. The steerable segment consists of a helical surface that is wound over a small beam in the middle to gain axial stiffness. It possesses a steerable segment that is 12 $mm$ in diameter and has four channels to pass hardware through which are located around the centre. Additionally, there are four channels in which the steering cables are located. Four cables are required for steering the mechanism. However for stiffening the instrument more wires are required. For holding shape there 4 clockwise helical tendons and 4 anticlockwise helical tendons are required. This becomes impractical very soon because there are 12 tendons required for every steerable segment. This mechanism is fully 3D-printed and therefore it is a quick an affordable way to make catheters.

## 1.4 Variable bending stiffness

Variable Bending Stiffness (VBS) can be explained as a mechanism that is able to regulate its own bending stiffness. It has a stiff and a flexible state which can be switched reversibly and on command. This property is widely applied in the research field of steerable instruments. In the rigid state the stiffness should be as high as possible to maintain its shape when performing the intervention. The highest possible flexibility is required in the flexible state to easily follow the tortuous path [14]. This principle is already applied in colonoscopy to prevent the formation of loops during the procedure, which caused pain in 90 % of the procedures [15]. The VBS colonoscope was made by Olympus Corporation and due to this ability, stiffening wires or an overtube were not necessary anymore to change the stiffness [15]. Variable stiffness can provide advantages for a number of surgical applications and therefore much research is done in this field. Multiple review papers about mechanisms with VBS refer to the medical field as an application [14, 16, 17].

### 1.5 Problem statement

Actively supported techniques are difficult to perform and require considerable skill and experience on part of the surgeon. Therefore it is often tried to change the passive support first, at the risk of losing guidewire position. It would therefore be desirable to create a system that can employ Variable Bending Stiffness to provide strong backup support while still being easy to guide to its target position. The 3Flex is a quick and affordable way to make catheters but lacks Variable Bending Stiffness, and has small channels to pass hardware through. Because of the helical tendons that run through the mechanism much inner space is already occupied by the wires. To solve this problem a new kind of Variable Bending Stiffness mechanism needs to be designed.

### 1.6 Goal

The goal of this study is:

To design and create a proof of concept variable stiffness mechanism that can create catheter backup support to help clinicians accurately control intravascular instruments during PCI procedures, and that can be implemented in 3D printed catheter structures possessing a central lumen.

### 1.7 Structure of the report

The first part of the paper, Section 2, describes the requirements that are obtained from the goal of this research. Section 3 shows the design process which results in the proof of concepts in Section 4. Section 5 presents the final design of the mechanism, and in Section 6 the prototype is described. In Section 7 the prototype is evaluated experimentally and is discussed in Section 8. Section 8.1 describes the limitations of this research which is concluded in Section 9.

## 2 Requirements

### 2.1 Design requirements

The goal of this research was defined in Section 1.6. To achieve this goal a design space must be defined to come up with solutions for the problem. The following design requirements have been established on the basis of the described application. Because this is a proof of concept prototype some design requirements are relaxed.

1) *Steerable segment at the distal tip.* The steerable segment is placed at the distal tip and can reach a bending angle of 90 *degrees*.

2) *Variable bending stiffness.* The mechanism is able to change its stiffness, and can alternate between a rigid and a flexible state on command.

3) *Constant Curvature.* A constant curvature is required for predictable steering and to determine the shape of the mechanism. To accomplish that the mechanism needs to have high axial stiffness. This property also contributes to the pushability of the instrument.

4) *Manufacturability.* The mechanism has to be manufacturable within the time frame and resources available in an MSc project.

5) *Outer diameter 12 mm.* An outer diameter of 3 *mm* is required to fit the application however this is relaxed to 12 *mm* which is the same diameter as the 3Flex, see Section 1.3

6) *length 10 cm.* A length of 1 meter is required to reach the ostium. For this proof of concept this length is reduced to 10 *cm*.

7) *Central channel.* The instrument must have an open central channel such that hardware can pass through, according to the obtained path.

8) *2 Degrees of Freedom (DOF).* In order to create difficult shapes the mechanism is able to steer in 2 DOF.

### 2.2 Additional requirements

In this section the additional requirements are set out. It should be noted that these are not must-have requirements for the design process but are nice-to-have as this design is further developed.

9) *Biocompatible.* The device operates in the human body and therefore it cannot exhibit toxic or carcinogenic properties.

10) *User friendly.* The mechanism should be user friendly which makes it simple and easy to use.

# 3 Concept generation

## 3.1 Morphological scheme

A design concept consists of solutions for the design requirements. To find these solution a structured overview (morphological scheme) was created from the design criteria, which consist of multiple possibilities for each criteria, see Figure 2. These possibilities can be found by brainstorming and investigate the VSMs that are already exist in this field of research. The goal is to design a two DOF VSM, therefore the principle for obtaining stiffness, the stiffening activation, the way to obtain two degrees of freedom, and steering mechanisms were explored. VSMs can modulate their stiffness by changing material properties or reconfiguring their structure. Therefore, the stiffening principles can be divided in two main categories; structural stiffening and material stiffening. The stiffness activation mechanism makes use of the structural or the material properties to stiffen a VSMs. For obtaining two degrees of freedom this can be obtained by rotations. The steering mechanisms can be divided into two categories; direct and indirect steering. Indirect steering the steering mechanism is directly attached to the instrument and for indirect steering an outer source is required to steer the mechanism. This resulted in a schematic overview of solutions for these principles, see Figure 2.

## 3.2 Component structure

### 3.2.1 Stiffness principle

The stiffness principles in the scheme all define a manner to obtain VBS. The friction between segments, particles, wires and layers can be controlled, Phase Change Materials (PCMs) utilise their material properties, other mechanisms are able to change the effective length to increasse stiffness. Structures can lock together or change the second moment of area which enhances the stiffness. Rheological fluids are able to change the viscosity to vary their rigidity.

***1) Segment Jamming:*** The rigidity of a VSM can be controlled by increasing the normal force between segments. This results in an increase of the friction force and the segments lock together. This creates the rigid state of the mechanism. For this stiffening principle it is important to use a material that has a high coefficient of friction, which cause a high friction force and therefore a stiff state.

***2) Granular Jamming:*** This type of stiffening principle is based on increasing the friction between particles. Designs that use granular jamming, typically consist of granulates within a fluid chamber that is supplied with negative gauge pressure. The vacuum compresses the particles together which increase the stiffness. The type, size and shape of the granulates influence the stiffening capability of the mechanism.

***3) Wire Jamming:*** Wire jamming mechanisms also use the principle of increasing the normal force to generate friction. A single fiber is flexible, but when multiple fibers are pushed against each other it can act as a beam, which has more stiffness than the single wire. Mechanisms that use wire jamming use a fluid chamber to compress the wires against each other.

***4) Layer Jamming:*** The last principle of jamming is called layer jamming. In this principle multiple layers are compressed together which increase friction between the layers and therefore the stiffness changes. As with the other jamming principles, this mechanism can be integrated with a fluid chamber which compresses the layers together.

***5) Changing effective length:*** The principle of varying the effective length to create a VSM is based on a load that is applied to the tip of a beam. A longer beam will deflect significantly more under the same load, all else being equal. As the beam's stiffness, $k$, (see eqn. 1) is dependent on the relationship between the load applied to the beam and the displacement due to that load, modulating the beam's length allows control over $k$. This creates a VBS system without needing to change any other parameters about the beam. This can be expressed using the following formulas:

$$F = k * \delta \tag{1}$$

$$\delta = \frac{FL^3}{CEI} \tag{2}$$

Where $F$ is the applied force, $k$ the beam stiffness, $\delta$ the displacement, $L$ the effective length, $E$ the elastic modulus, $I$ the second moment of area and $C$ is a constant which is dependent on how a beam is fixed and where the force is applied. According to this formula, $\delta$ increases with the cube of $L$, i.e. doubling $L$ will multiply $\delta$ by eight, and $k$ will be divided by the same amount.

***6) Interlocking Structures:*** Mechanisms based on interlocking structures have a flexible state in which two toothed structures are disconnected. By controlling the pressure of a fluid chamber, the teeth can connect or disconnect. The rigid state is obtained when the structures lock into each other. There are a number of ways to ingrate a locking structure in a VSM, however most commonly they are activated by fluid pressure.

***7) Second Moment of Area:*** The bending stiffness is also dependent on the Second Moment of Area (SMOA) $I$ according to Equations 1 and 2. The

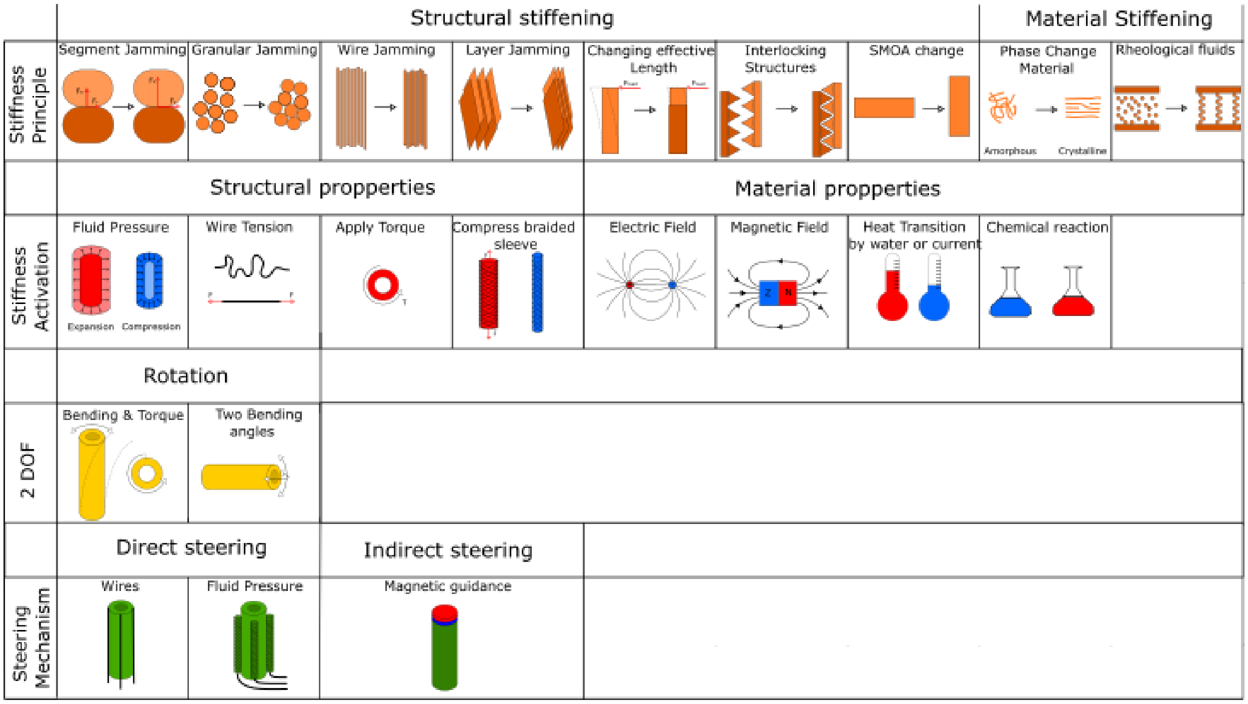


Figure 2: A morphological scheme which shows the design space of this project, based on the stiffing mechanism, stiffening activation, 2 Degrees of Freedom (DOF) and the steering mechanism.

SMOA is a measure of a cross-section's resistance to bending due to an applied moment. By changing the cross-section of a manipulator the SMOA can be changed which results in a stiffness change.

*8) **Phase Change Material:*** PCMs are materials that can change stiffness based on their material properties. There are two different types of PCMs, polymer and alloys. Polymers have a Glass Transition Temperature (GTT), which is the temperature when the material's crystal structure changes from crystalline to an amorphous state. The crystalline structure has more stiffness than the amorphous structure which causes the variation in material stiffness. In PCMs the heat transition is caused by resistive heating or water circulation.

*9) **Rheological Fluids:*** Fluids with rheological properties can change their viscosity, elasticity and plasticity in milliseconds when a magnetic or electric field is applied. Without this field the fluids are in liquid state, when the field is applied the viscosity increases and the fluid becomes a viscoelastic solid. This is a reversible process, if the applied field is removed the viscosity decreases and it act like a fluid again.

### 3.2.2 Stiffness activation

VSMs need to have something that triggers the transition from a soft to rigid state or reverse. There are a number of approaches found in the literature to activate the stiffness change in a mechanism. The stiffness activation is also dependent on the type of principle for obtaining variable stiffness, i.e. not all activation mechanisms are suitable for each stiffness principle.

*1) **Fluid Pressure:*** Fluid pressure can be used as activation mechanism by supplying positive or negative gauge pressure to a fluid chamber. This generates a compression or extending force to a structure. Stiffening mechanisms that utilise fluid chambers to stiffen the mechanism are based on jamming or interlocking structures.

*2) **Wire Tension:*** Stiffness can be activated by tensioning a wire. Wires are often used to steer a mechanism, whereby they are fixed at the tip of a bendable segment. If the shape of the bendable structure can be locked and the tension in the wires can be increased, the friction between the bendable segments will increase. In this way the stiffness can be activated by wire tension.

*3) **Torque Application:*** The activation mechanism of applying torque means that a rotation can cause a change in bending stiffness. Stiffening mechanisms based on SMOA can change stiffness by changing the cross-section which can be accomplished by a rotation.

*4) **Compressive braided Sleeve:*** The sleeve can act as a mechanical alternative to the fluid chamber. Radial expansion of the braided structure results in axial contraction and vice versa. This can cause a compressive force which can be compared with pressurising a fluid chamber. This activation mechanism can be used to for a number of stiffening principles such as jamming and interlocking structures.

***5* & *6) Electric* & *Magnetic Field:*** Rheological fluids are the only stiffening principles that can be activated by a magnetic or electric field. The particles in the fluid will arrange according to the direction of the field. Changing the field in different orientations also influence the stiffness.

***7) Heat Transition:*** The activation principle of heat transition is inextricably linked to PCM, as these materials require the heat transition to create their flexible state. This can be achieved via fluid circulation or electric current. Fluid channels are placed along the mechanism in which a hot or cold fluid flows. Due to the convection of heat, the material is heated up or cooled down. Another way to heat up materials is by using electricity. The mechanism is connected to an electric circuit and when the power turns on current is passed through the mechanism which heats up the material.

***8) Chemical Reaction:*** A chemical reaction can also activate the stiffness of a mechanism. However it is important that the reaction is reversible otherwise the VSM can not change between the different states.

#### 3.2.3 Degrees of Freedom

The steerable instrument needs to have at least two DOF. This means that the manipulator should be able to bend in two perpendicular planes. This can be accomplished with two different methods. The first principle uses a bending and a torque and the second one uses two bending angles.

***1) Bending* & *Torque:*** This system has one bending angle and when this bending is obtained a rotation of the shaft is added or reverse. If the shaft is rotated 90 Degrees the system has two bending planes that are perpendicular to each other, hence two DOF. For this system at least one tendon is required to steer the mechanism.

***2) Two Bending Angles:*** The mechanism has two bending angles which are perpendicular to each other, which results in two perpendicular bending planes. For this system at least three tendons are required to steer the mechanism.

#### 3.2.4 Steering mechanism

Three different steering mechanisms can be obtained from the morphological scheme, see Figure 2 The first mechanism is based on steering with wires. The second one on fluid pressure and the third one is based on steering using magnetic guidance in a magnetic field.

***1) Wires:*** Steering with wires can be accomplished to secure the end of a tendon that run through the bendable segment at the distal end. In the initial position, the wires that run through the manipulator are as long as the segment itself, which means that the mechanism is straight. By pulling a tendon the length of the wire is decreased which creates an inner curvature and the manipulator is steered in a certain direction. When using multiple wires to steer the mechanism, it is important that the tendons have the same initial length. Because the length decrease of the inner curvature is the same as the length increase of the outer curvature if the wires are at the same distance from the neutral axis of the bendable segment.

***2) Fluid Pressure:*** Steering with fluid pressure can be done by artificial muscles that acts as McKibben actuators. The operation principle is as follows, by increasing the pressure in the fluid chamber, the length will decrease and the width increases. A contraction is generated by this motion which can be used to steer the instrument. If both ends of the fluid chamber are connected to the manipulator it bends. The use of this type of actuator will increase the diameter because the actuators need to be placed at the outside of the instrument and expand in radial direction.

***3) Magnetic Guidance:*** A magnetically steered instrument works as follows. A permanent magnet is placed at the tip of the manipulator, which is placed in a magnetic field. By changing the direction of the magnetic field the tip of the instrument will also change its direction. In this way the manipulator can navigate through space. However changing the magnetic field in order to steer such an instrument is a complex task in which high precision is required.

### 3.3 Proof of concepts

#### 3.3.1 Concept creation

Concepts can be created by adding multiple partial solutions together. Out of the morphological scheme a total of 378 different combinations can be found, but not every one is valid. Based on design requirement 4 the mechanism must be manufacturable within the constraints of an MSc project, in which time, cost and availability play a role. Fused Deposition Modelling (FDM) printing is a convenient manufacturing technique that ensures low-cost and rapid prototyping. This technique was used to build and validate prototypes, however not every stiffness principle explained in Section 3.2.1 could be made with off-the-shelf parts and 3D printing. These principles were not investigated further.

While concepts can be validated theoretically based on a set of criteria, testing a physical proof of concept will highlight any issues that may be otherwise overlooked when setting criteria for concept evaluation. Therefore, for this concept evaluation the chosen concepts were built as proof-of-concept prototypes to validate their mechanisms. Three different proof of concepts were made to investigate the stiffening principles.

The following three mechanisms were chosen for proof-of-concept prototyping: segment jamming, wire jamming and phase change material. These are concepts that can be manufactured by an FDM printer, and/or require low cost materials. The stiffening principles will be combined to the principles for activation and steering to create a viable concept.

#### 3.3.2 AlSegJam: segment jamming

The AlSegJam concept consisted of the following principles. A segment jamming mechanism activated by wire tension was designed. Four wires running through the segment, allowing it to have two DOF and be steerable. The same wires were used for tensioning and stiffening the mechanism. For a proof of concept, multiple segments were made and tested. in addition to the printed segments, the whole frame, steering, and stiffening mechanism were also made with by additive manufacturing.

#### 3.3.3 AlPhaChange: phase change material

PCMs can be expensive if they need to have a predefined glass transition temperature or a certain amount of stiffness. Certain 3D printed materials, such as Polyactic Acid (PLA) are also PCMs and can become flexible when heating up. Because this material can be 3D printed, multiple structures can be made to change the stiffness of the mechanism that is printed. It is also possible to print other materials, such as Polyethylene Terephthalate Glycol (PETG), which has a higher GTT. Due to the difference in GTT a mechanism which consists of both PLA and PETG can have flexible and stiff parts the same time when it is heated up to a specific temperature. Therefore a full concept can be printed that works on the stiffening principle of a PCM. For the proof of concept the mechanism was exposed to hot water which heats up the material and the mechanism can become flexible. Four tendons run through this mechanism to gain the required DOF and steer the mechanism.

#### 3.3.4 AlWiJam: wire jamming

The final proof of concept consisted of a wire jamming mechanism. These mechanisms require a sheath that is radially and axially stiff to jam the wires against the sheath without causing a deformation. A tube or printed structure can act as a sheath. The wires were jammed together with a braided sleeve by using the sleeve's ability to contract when lengthened to compress the wires against the sheath. For the proof of concept a mechanism was made which possessed two bending DOF and was controlled by tendons.

# 4 Proof of Concepts

## 4.1 AlSegJam

### 4.1.1 Segment jamming

The proof of concept for the segment jamming mechanism consisted of a steerable tip that can change it stiffness by tensioning the steering cables, as well as a steering mechanism and a passive shaft. This proof of concept was the end result of other designed concepts which are described in Appendix A.1. Defects in a concept design resulted in a new concept resulting in an iterative process by which a final proof of concept was created.

### 4.1.2 Type of joints

The joints in a segment jamming mechanism need to provide two DOF. Multiple joints exist that have two DOF, such as rolling, sliding and bending joints [18]. Three types of joints structures were investigated and manufactured; revolved sliding joints, rolling friction joints and rolling toothed joints [18], see Figure 3.

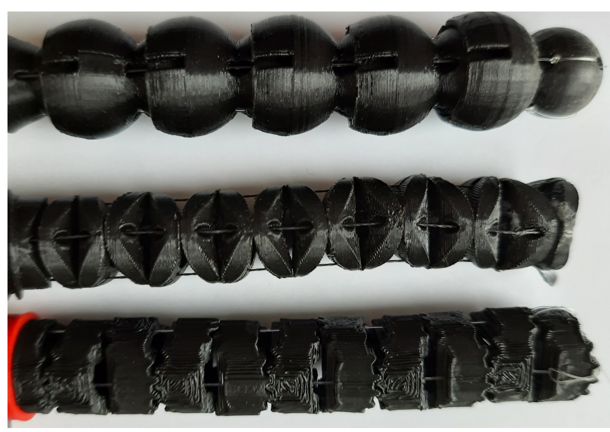

Figure 3: Three manipulators with different type of joints. The top joints are ball-and-socket joints, in the middle rolling friction joints and at the bottom rolling toothed joints [18].

Ball-and-socket joints initially have three DOF, two bending angles and a rotation about its own axis, which can be constrained by guiding wires through the joints, resulting in a two DOF steerable manipulator. The second type of joint consists of two curved surfaces which are mirrored and rotated 90 degrees with respect to each other. Placing at least three joints in series creates a manipulator that has two degrees of freedom. The toothed joints use the same principle as the rolling joints but have small teeth on their surface which restrict the joints to roll without slipping.

The concepts in Appendix A.1 that use the revolved sliding and the rolling joints, had some defects. The friction between the revolved sliding joints was not enough to create a significant difference between the rigid and flexible states. The combination of these joints in a manipulator results in a relatively high wall thickness because a ball is rotated in a socket. The wall thickness is dependent on the size of the ball and the socket, in comparison to the rolling joint in which the wall thickness is dependent on the wires. Therefore it is hard to scale down the revolved sliding joints.

The maximum bending angle between the revolved sliding joints was less than the rolling joints which were 18 and 30 degrees respectively. The rolling joints generate more friction between the joints than the spherical ones, but did slide along each other and could not create a constant curvature. A constant curvature is important for predictable steering, especially under externally applied loads, but also determining the shape in robotic applications. The final proof of concept consists of the rolling joints with teeth. The teeth ensure that the joints can rotate along the predefined path and create a constant curvature.

#### 4.1.3 Steering and stiffening mechanism

The steering mechanism is based on the antagonistic principle. The joints explained in Section 4.1.2 have four tendons running through each side of the joint with a 90 degree spacing. This creates two antagonistic pairs of tendons. The manipulator is curved by pulling on a tendon in one direction, and the opposite tendon needs to be released in order to create the curvature. This means by shortening a wire, the antagonistic wire needs to extend. If the antagonistic wires are placed at the same distance from the central channel of the manipulator the length increase and decrease is exactly the same. Therefore antagonistic pair of wires can be connected to the same wheel. Turning the wheel will lengthen a tendon in one direction and shorten a tendon in the other direction. In a two DOF manipulator two wheels can make it steer in two directions, see Figure 4.

Besides steering, a stiffening mechanism is required that stiffens the manipulator by wire tension. In this case it is important to stiffen the wires all at the same time, otherwise the shape of the manipulator changes.

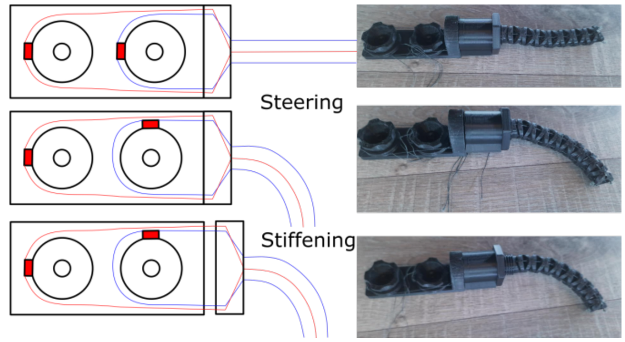


Figure 4: Steering mechanism of the manipulator. On the left a schematic drawing of the steering and stiffening mechanism. On the right the same movement executed by Concept 3.

Therefore, a shape locking mechanism was designed. Pins were placed on the frame on which the wheel could be locked. In order to steer, the wheel lifts up and rotates to achieve the desired curvature. The wheel can then lock on the pins and the curvature is fixed.

Next, the tension in the wires needed to increase evenly. The tension can be increased uniformly on the four tendons if the distance between the proximal end of the manipulator and the frame becomes larger, see Figure 4. This was accomplished by a screw mechanism between the frame and the steerable segment. The screw can slide into the frame back and forward, by rotating a screw. The forward motion of the screw moves the steerable segment away from the frame, which cause a tension increase in the cables. The high tension in the cables increases the friction between the joints and the stiff state is obtained.

#### 4.1.4 Wire length adjustment

In wire steered manipulators where all the wires are at the same distance from the central channel it is important that the length of the antagonistic wires are the same. If this is not the case, the steering input will not result in the desired movement output of the mechanism. Another reason for the wires to be equal in length is because of the stiffening mechanism used. The tension in the wires is increased such that the friction force becomes larger. If the antagonistic wires are not equal in length there will be a difference in tension in each wire, which cause an unintended deflection. To prevent this problem a pulley system was designed in which the wires can be adjusted in length, see Figure 5.

This system can adjust the wires in each direction to obtain the desired length of the wires. The tendons that run through steerable segments end in a loop, another wire runs from the steering wheel through the loop and is attached to a nut. This nut is threaded

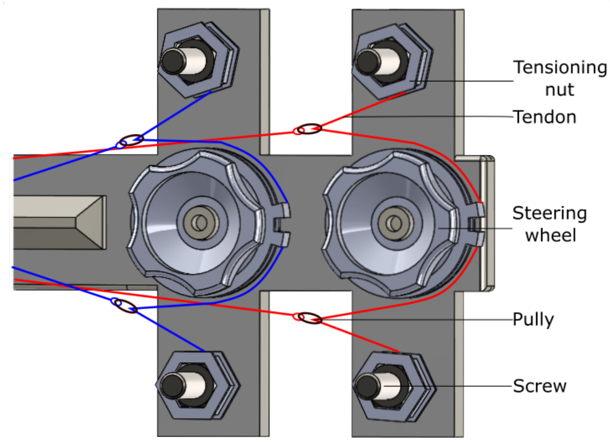


Figure 5: System that can adjust the tendons in each direction. Two antagonistic pairs of wires (blue & red) end in a loop. Another wire is connected from the wheel through the loop to the nut.

on to a screw which shortens or lengthen the cables, depending on the direction it is turned. This pulley system will affect the relation of motion between the steering wheel and the steerable segment. The displacement of the wire along the wheel is double that of the wire which steers the sheath.

#### 4.1.5 Passive shaft

Besides the steerable part of the mechanism the whole manipulator needs to be longer to be applicable for the proposed application. Therefore Concept 5 in Appendix A.1.5 was created, to find out how the passive shaft influences the stiffening and steering ability of the mechanism.

A tube needs to be placed between the proximal side of the manipulator and the frame. This tube must have two properties: firstly, it must be flexible to follow the path of the artery and secondly, it requires high axial stiffness. The axial stiffness will increase the pushability of the mechanism. This property is also required due to the stiffing mechanism which uses wire tension to increase the stiffness. If the tube compresses, the tension in the wire also decreases and the stiffening mechanism can no longer stiffen the manipulator. To be able to steer the mechanism without a deformation of the passive shaft, bowden cables are required. These cables prevent a force acting on the shaft which cause a deformation. Bowden cables are tubes that are axial stiff and flexible, which are also used for bicycle brakes.

Concept 5 consists of tubes with high axial stiffness which was able to steer, however the passive shaft could not easily bend. In the final proof of concept flexible rubber tubes were for the passive shaft. The steering mechanism did still work, however the stiffening part did not. This is because the rubber wires were compressed and didn't gave enough support to the rest of the structure. The flexibility of the cables did show that it could easily bend and can be adjusted to curved spaces. Bowden cables have the high axial stiffness of the PTFE tube and the flexibility of the rubber tubes. The bowden cables need to consist of a endless extension spring with tubing around it that prevent that the winding's of the spring will be pressed over each other. With the right bowden cables the VSM based on segment jamming can be created.

#### 4.1.6 Result

The final proof of concept is designed by an iterative process of adjusting concepts explained in Appendix A.1, see Figure 6. The steerable tip consists of toothed rolling joints that can create a constant curvature when the mechanism is steered. The passive shaft increases the length of the mechanism but influences the stiffness. The steering wires that run through the steerable part, the rubber tubes and the stiffening mechanism are connected to a pulley to increase or decrease the length of the steering wire. However the stiffening capabilities for this prototype did not work well, therefore Concept 5 will be compared to the other proof of concepts to find out which mechanism works the best.

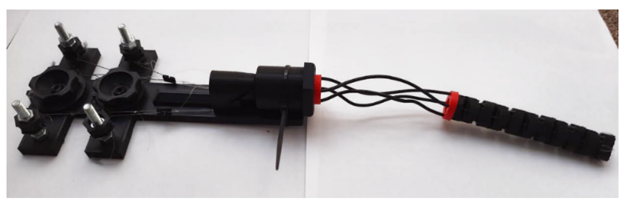

Figure 6: AlSegJam concept as segment jamming mechanism.

### 4.2 AlPhaChange

#### 4.2.1 Phase change material

The second mechanism that was prototyped was a phase change mechanism. This principle is based on heating a material to become soft and cool it down to increase the rigidity. PLA is a plastic that can act as a phase change material. PLA becomes rubbery when reaching the GTT of around 70 $°C$. Because of this property a phase change material can be printed with a FDM printer using PLA. Temperature control can be accomplished by water circulation across the whole length of the mechanism or by applying electrical current to the material to heat it up. For the proof of concept, no heating channels were implemented, but the mechanism was exposed to a bowl of water of 70 $°C$ to reach the GTT of the material.

#### 4.2.2 Bending structures

Three different tubes were designed and tested on bending, Appendix A.2, differing in structure and thickness. A solid tube structure buckles when it is bent, therefore a braided structure was made. This structure is able to bend and due to its structure also holds its shape.

The proof of concept consists of three braided bending segments, these are attached to each other by a PETG frame, see Figure 7. The braided bending structures can slide into the PETG frames and lock into position. Four tendons steer the mechanism which are connected to the PETG structures. PETG has a higher GTT than PLA, this means that the PETG structures will stay rigid when the mechanism is exposed to 70 $°C$, which is the GTT of PLA.

The steering mechanism that is used in this design is the same as described in Section 4.1.3 which consists of two wheels each steering the antagonistic tendons. Figure 8 shows an increase in diameter when it was attempted to bend the mechanism. This is due to the structure that was used for this design. If the tendons were to be attached to the PLA and the GTT is reached the wires will cut into the PLA and the mechanism is not able to steer.

Figure 7: Phase change mechanism consisting of multiple steering segments (black braided structures) and steered by two wheels.

#### 4.2.3 Result

The mechanism described in Section 4.2.2, was tested on bending by exposing the concept to hot water. While in the water, the wheels were turned and the structure bent easily. The structure was then cooled down with cold water and the rigid state was obtained. The rigidity of this mechanism is dependent on the type of bending structure that is used. In the deformed shape the stiffness was the same as in the initial shape. The printed structure of PLA acts as a shape memory polymer. After the structure was bent and became solid, the structure could return to its original shape by exposing it to the hot water once more. This property is used in the prototype the recover the original shape of the mechanism.

The curved configuration of the concept shows some interesting aspects about the phase change mechanism, see Figure 8. The mechanism does not have a constant curvature. The tendons are fixed at the top, which caused an increased deformation at the top related to the rest of the mechanism. The diameter of the bending structures expanded, which was a result of the compression force caused by the tension in the wire. Steering in the opposite direction the mechanism will not behave smoothly and cannot return to its original shape. Therefore the tension in the tendons needs to be released and the shape memory property is used. However this takes some time and still cannot totally stretch the mechanism enough to reach the original state.

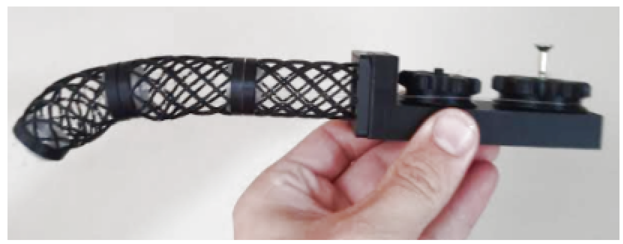

Figure 8: Phase change mechanism in its curved configuration.

### 4.3 AlWiJam

#### 4.3.1 Wire jamming

The wire jamming mechanism is based on the principle of increasing the friction between wires, such that they can act as a solid beam. The components needed for a wire jamming mechanism are a shaft, wires and a braided sheath. This design is developed by an iterative process of improving multiple concepts, described in Appendix A.3. The whole concept was made with FDM printing, besides the wires and the braied sleeve.

#### 4.3.2 Shaft selection

The shaft of the mechanism needs to have high radial and axial stiffness. The radial stiffness ensures that the wires can be jammed against the shaft without causing a deformation of the shaft. Otherwise the jamming mechanism can fail because the friction force cannot reach the desired value. The axial stiffness is required to limit the change in the length of the shaft, as due to the steering forces there will be a compressive force acting in the longitudinal direction of the sheath. The constant length and curvature of a sheath is important for determining the shape and predictable steering. However these stiffness properties will also affect the steerability of sheath. Therefore a compromise must be found between these properties.

In the concepts for this design two different tubes were tried, a silicone tube which is flexible and a high pressure air tube, which was axially stiff. Neither tube had the desired properties for the jamming mechanism. Therefore a new type of shaft was made using an FDM printer. The shaft is based on the segments of the segment jamming mechanism in combination with flexures between the segments, described in Appendix B. The shaft has all the desired properties for this mechanism, axially and radially stiff, yet flexible in bending. The sheath is steerable and consists of only one part; no assembly is required, see Figure 9.

Figure 9: Improved Sheath design that consists of 20 joints connected by a compliant flexure.

### 4.3.3 Wire placement

The wires that are used in this mechanism need to be evenly distributed along the shaft as close as possible against each other. All wires make contact to each other and to the frame, which optimises the contact area. The number of wires that is required for a certain diameter of the shaft can be calculated by the following formula 3.

$$n = \pi * (D_{shaft} + d_{wire}) \tag{3}$$

In which $n$ is the number of wires, $D_{shaft}$ the diameter of the shaft and $d_{wire}$ the diameter of the wires. This amount of wires is equally distributed around the shaft. The wires are fixed at the distal end of the mechanism and can move at the other end. At the proximal end the wires are connected to a flexible structure that allows the movement of the wires as a result of steering. The flexible structure consists of two rings in which the wires are evenly distributed with a spring in between.

### 4.3.4 Jamming mechanism

The jamming part of the mechanism is a braided sheath that needs to be elongated to obtain a compression force acting on the wires. The braided sheath is attached to a ring on both ends. If the rings are pulled away from each other the length of the braided sheath will increase and its diameter decreases. Conversely, if the braid is shortened, its diameter increases again. The ring at the distal end is fixed at the tip of the instrument to fasten the wires and the braided sheath at this point. Therefore, only the ring at the proximal end needs to be able to move back and forward along the sheath. With this movement the system will be able to vary its stiffness, see Figure 10. To apply tension on the braid from the proximal side, a screw is placed in the frame. By turning this screw, the ring attached to the braided sheath is moved in the proximal direction the braid becomes narrower, applying radial pressure on the wires, and the stiffness is changed.

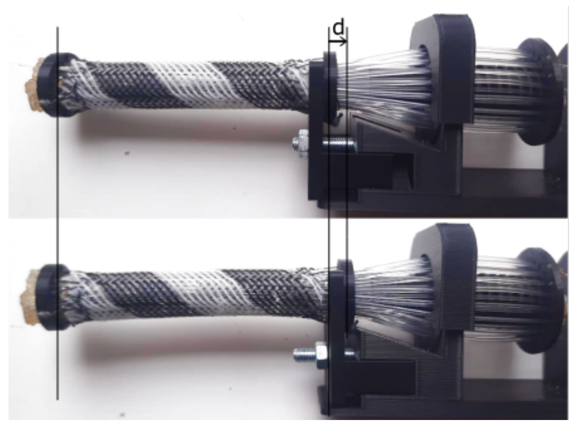


Figure 10: Jamming mechanism in flexible (A) and rigid (B) state. The braided sleeve is attached to two rings, the distal ring is fixed and the proximal ring can move. Travelling a distance d by the proximal ring stiffens the mechanism.

### 4.3.5 Result

The proof of concept of the wire jamming mechanism, see Figure 11. At the distal end the wires were glued around the shaft and a ring was placed around the wires and glued on them. The braided sheath was connected to two rings to compress and decompress the sheath on the wires. The wires run through the frame and were evenly distributed by a flexible ring structure. The structure allows shortening and lengthening of the wires when the mechanism is steered. Four wires are extended and run to two wheels, which is the same steering principle as described in Section 4.1.3. However the stiffening mechanism is a bit different. An M4 screw is placed into the the frame and by rotating a nut the ring is pulled at the proximal side which lengthens the braided sheath.

A simple test was conducted to try out the stiffening mechanism. The wheel was rotated to steer the manipulator in a certain direction. Than the stiffening mechanism was activated by rotating the nut to lengthen the braided sheath. If the stiffening mechanism worked properly the shape remains the same while lifting the wheel from the pins, which did occur, demonstrating the prototype's variable stiffness.

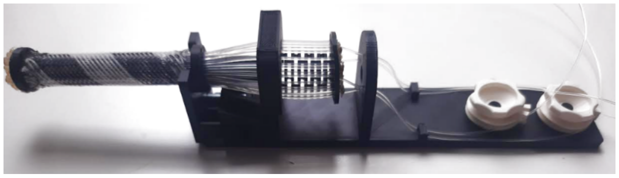

Figure 11: Proof of concept of the wire jamming mechanism.

### 4.4 Comparison

Three different proof of concepts were built and compared to decide which concept would be brought forward to a final design. The concepts were evaluated based on the design requirements. Each requirement has a weight factor rating from one to three that represents the importance of the requirement. The concepts can score a one to five based on the performance for each requirement. The product of the weight and the performance provides a total score for each concept, See Table 1.

All the concepts have a steerable distal tip which can reach a 90 *degree* bending angle. Therefore, they receive the same score for performance. The variable stiffness ability of the three mechanisms was tested by applying small weight on the distal end. The AlSegJam was still able to move after stiffening, the AlWiJam barely moved, and the AlPhaChange mechanism did not move at all.

Based on the constant curvature the AlPhaChange concept scores the lowest. When the manipulator was exposed to hot water the whole mechanism became soft and lost its axial stiffness. Therefore the phase change concept was only bent at the distal dip where the tendons were attached. The AlWiJam had more axial stiffness than the AlSegJam, which resulted in a better curvature.

The manufacturability of the concepts differ in the number of components they consist of. The AlPhaChange comprised the fewest parts and all could be printed, which made this concept the easiest to manufacture. The AlSegJam and AlWiJam consisted of many segments or wires which made them more difficult to manufacture.

The three concepts differ in size, and were scaled up for easier prototyping, the AlSegJam and AlWiJam have a diameter of 15 *mm* while the AlPhaChange have a diameter of 22 *mm*. The AlSegJam and the AlPhaChange reach the length of 10 *cm* while the AlWiJam is a aprroximately 9 *cm* shorter but can be easily lengthened by adding more segments to the shaft. All concepts meet the requirement for a central channel which resulted in the same score. This also counts for the 2 DOF requirement.

Low cost, biocompatibility, and user friendliness have the lowest weight factor because these are additional design requirements. The segment jamming and phase change mechanism consists of the same materials, PLA parts and Polypropylene (PP) wires for steering. The additional material that is required for the wire jamming mechanism are the nylon fishing lines used for the wire jamming part. The materials used in the concepts are biocompatible, however the phase change mechanism requires a heat transition system to become flexible. The average body temperature of $37°C$ is much lower than the GTT of PLA. If the mechanism is not insulated, the heat transition system is harmful for the human body.

The phase change concept is the least user friendly, because for every motion the mechanism needed to be held in hot water first to be able to steer. The segment jamming mechanism could not be steered well which makes the wire jamming concept the most user friendly.

In the end each concept is validated and based on the performance a total score was obtained. The wire jamming mechanism had the highest score and therefore this concept was further developed into a prototype.

## 5 AlKingScope

### 5.1 Steerable segment

The steerable segment comprises smaller segments that can bend with respect to each other, which are connected by a flexure, see Figure 12. The flexure provides the motion for the steerable segment. Underneath the flexure there is a small air gap, which is required to let the flexure move. The steerable segment can be made by FDM printing and consists of one part. The air gap will prevent that the flexure bonds to the segment during printing. If the air gap becomes too small the flexure is almost directly printed on the segments, which fixates the flexure and the mechanism is not able to move.

Another important feature of the mechanism is the contact point between the segments. This is the point of rotation and is always in contact with the next segment. Because of this point the steerable segment becomes axially stiff, which means that the mechanism keeps its length when it is compressed in the longitudinal direction. Five channels are located along the whole steerable segment. The outer four channels are used to pass the steering wires through, which are

Table 1: Rating table for the the three different concepts based on the design requirements.

| Requirement | Weight (1-3) | Concept score (1-5) | | |
|---|---|---|---|---|
| | | **Segment Jamming** | **Phase Change** | **Wire Jamming** |
| Steerable segment | 3 | 5 | 5 | 5 |
| Variable stiffness | 3 | 2 | 5 | 4 |
| Constant curvature | 3 | 4 | 1 | 5 |
| Manufacturability | 2 | 4 | 5 | 4 |
| Outer diameter | 2 | 4 | 2 | 4 |
| Length | 2 | 5 | 5 | 4 |
| Central channel | 2 | 5 | 5 | 5 |
| 2 DOF | 3 | 5 | 5 | 5 |
| Biocompatible | 1 | 5 | 2 | 5 |
| User Friendly | 1 | 3 | 2 | 4 |
| **Total** | | 92 | 86 | 100 |

fixed at the tip of the steerable segment. By changing the length of the wires, the mechanism can create a curvature. The length change is dependent on the radius and the curvature of the mechanism and can be expressed as:

$$D_t = -\pi r_{axial} \frac{\theta}{180} \tag{4}$$

In which $D_t$ is the displacement of the thread, $r_{axial}$ the distance from the wires to the neutral axis and $\theta$ the bending angle of the manipulator in degrees.

Besides the steering channels there is a channel located at the center of the steerable segment. This channel can be used to push hardware through which is dependent on the procedure that is performed.

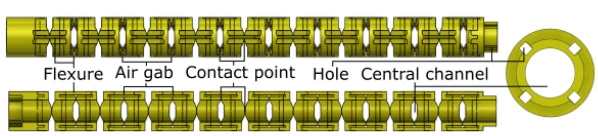


Figure 12: Schematic overview of the steerable segment. The flexure connects two segments together which have a single point of contact over which it can bend. There are four steering channels and a central channel.

## 5.2 Stiffening mechanism

### 5.2.1 Design

The stiffening mechanism as described in the wire jamming proof of concept is used for this design. The steerable segment is surrounded by monofilament wires and a braided sheath. In order to create the variable stiffness, the braided sheath should be fixed at the tip of the steerable segment and be able to move back and forward along the segment at the proximal end. In this way the braided sheath can widen and narrow to determine the stiffness, see Figure 13. In the flexible state, Figure 13 (A) the braided sheath is not compressed which makes it easy for the wires to move along each other. When the segment is steered the relative length of the wires will change as the curvature is created, i.e. the lines on the outside of the curvature become longer and on the inside of the curvature they become shorter. If the desired steering angle is obtained, the braided sheath can be compressed against the steering mechanism, the wires remain in the same position and the steerable segment is locked, see Figure 13 (B).

### 5.2.2 Force analysis

A number of assumptions were made to find a relationship between the friction and the applied moment. First, the mechanism becomes stiff due to friction between the wires and the steerable segment, the wires and the braided sheath, and between the wires themselves. To simplify the model, these friction forces are lumped together to a single friction force for each wire. Secondly, the system is in static equilibrium when the load is applied. Thirdly, the friction forces are assumed to be symmetrical around the neutral plane. Finally, the friction force is assumed to be constant along the whole length of the shaft, and the wires are assumed to be evenly distributed.

In order to understand the friction force acting on the mechanism it is necessary to understand the movement of the wires, because friction forces always act to oppose movement. For this analysis an external force is acting on the tip of the mechanism, which generates a moment, see Figure 14 A. If there is no friction between the wires and the segment, the tip will move downwards. This movement cause a length change of the wires, see Figure 14 B. This example shows that for an applied moment the top and bottom wire want to displace the most in order to create the curvature. When the braided sheath is compressed,

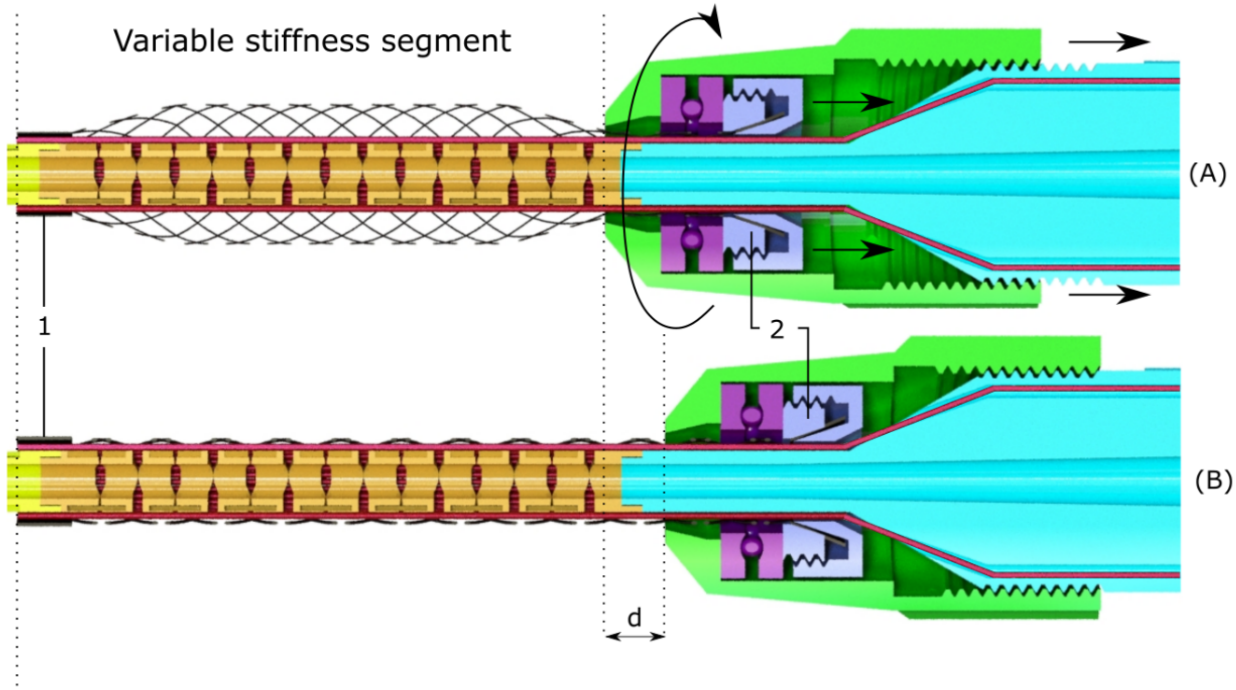


Figure 13: Schematic overview of the variable stiffness mechanism in which the numbers represent the fixation points of the braided sheath. The tip is fixed by a shrinking tube (1), proximal end is fixed by a screw mechanism (2). (A) Is the flexible state, by rotation in the given direction a displacement of (d) is obtained and result in the stiff state (B).

a normal force will act on the fibers which cause a friction force, see Equation 5

$$F_n = \mu F_r \tag{5}$$

In which $F_n$ is the normal force caused by the braided sheath, $\mu$ the coefficient of friction and $F_r$ the friction force. The friction force is acting against the movement and in order to stay stiff when the moment is applied, this defines the direction of the friction forces, see Figure 14 C.

The friction force of each wire creates a moment around the neutral plane. The magnitude of this moment is dependent on the perpendicular distance between the neutral plane and the wire. The moment generated by a single friction force can be expressed as:

$$M = F_r r sin(\alpha) \tag{6}$$

In which $F_r$ is the friction force, $r$ is the radius of the mechanism and $\alpha$ is the location of the wire in radians relative to the neutral plane.

The total moment created by the friction force can be calculated by summing each individual moment created by each wire. First the total amount of wires is required, see Equation 3. The neutral plane is in the center of the mechanism. Therefore, both halves have the same contribution to the total moment caused by the friction force. The wires are equally distributed and therefore the angular spacing between the wires can be defined:

$$\alpha = \frac{2\pi}{N} \tag{7}$$

In which $N$ is the total amount of wires used in the mechanism. A sum function can be obtained by substitution of Equation 7 in 6 and add up all the different positions of the wires, see Equation 8.

$$M_{total} = F_r r \sum_{i=0}^{N} sin(\frac{2\pi}{N} i) \tag{8}$$

The relation between the friction force and the applied load can be found by the static equilibrium of the system.

$$\begin{gathered} \sum M = 0 \\ F_r r \sum_{i=0}^{N} sin(\frac{2\pi}{N} i) = F_{external} L \end{gathered} \tag{9}$$

## 5.3 Steering unit

### 5.3.1 Design

The steerable mechanism is based on the on the teleoperation design of a hyper-redundant surgical instrument [19] In the teleoperation design the steerable segment is connected to the steering unit via a

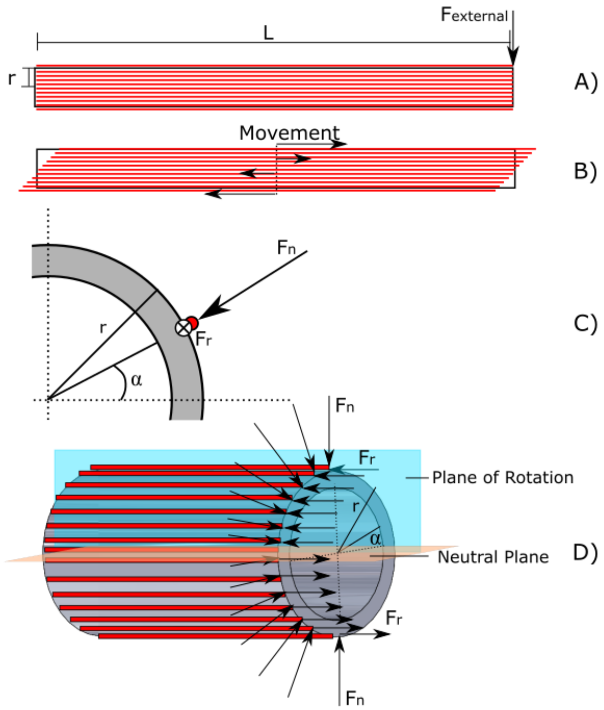


Figure 14: Schematic figure of the friction force acting on the mechanism, the wires (red) and the frame (grey). (A) The proposed configuration, a force is applied at the tip, which cause movement of the wires (B). The forces acting on a single wire when the mechanism is in rigid state and load is applied (C). 3D view of the forces acting on a segment when a load is applied in the predefined direction (D).

rigid shaft. Cables run from through the teleoperation system which connects the steerable segment to the steering unit. The diameter of the steering unit is four times larger than the steerable segment which results in a amplification factor in the range of motion. A 5 degrees bending angle of the steering unit results in a 20 degrees bending angle of the steerable segment. Because the steering unit and steerable segment are connected by cables, the tip moves in the opposite direction compared to the steering unit. However the mechanism that is used as a steering unit device consists of many components which all have to be assembled [19]. To overcome this downside an FDM manufacturing technique is used to obtain a steering device that consists of only one part. The proposed mechanism consists of two steerable segments, the most proximal one is able to change its stiffness. Cables that run through the segments need to be connected to the steering unit. As long a wire jamming mechanism is used as a VSM, the wire can also be used to steer the mechanism. Therefore there are only four internal cables required to steer the mechanism. Because of the difference in steering two different steering mechanisms were designed. One is able to steer the wires of the wire jamming mechanism and the other is able to steer the cables that are fixed at the distal segment. The steering mechanism must have the same restrictions as the steerable segment. Two rings with a triangle surface are connected by a flexure. The top edge of the triangle is against the upper ring, which ensures axial stiffness. Because it is only an edge, the joint can bent along this line. This also determines the placement of the flexures which are perpendicular to this line. The next ring is turned with an angle of 90 *degrees* with respect to the previous one which makes sure that the system can move in two DOF. Together they form a two DOF joint, see Figure 15. A long steerable unit can be made if multiple joints are placed in series, but to know the amount of joints that are required, the desired bending angle of the distal tip is necessary.

#### 5.3.2 Geometric displacement

The maximum displacement of the wires by a single steering joint can be calculated by its geometric relationship, see Figure15. The relation between the bending angle and the wire displacement in the steerable shaft is explained in Section 5.1. The wire displacement for a specific bending angle in the steerable segment, can be linked to the number of joints that are required in the steering mechanism to reach that bending angle.

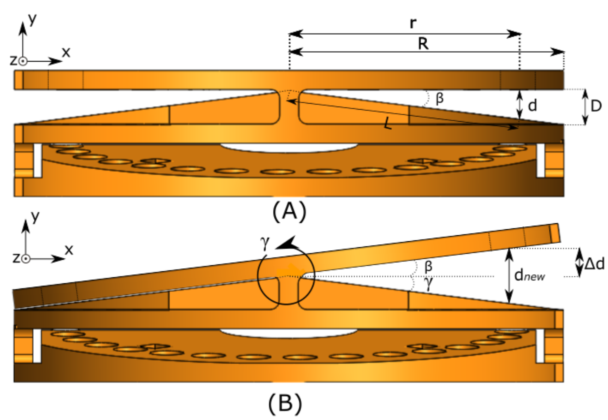


Figure 15: Geometric terminology steering joint. (A) Joint is straight configuration. (B) Joint is bent by $\gamma$ around the z-axis.

Based on the maximum bending angle of the joint, the displacement of the tendons can be obtained and this will be compared to the $D_t$ from Equation 4 . The length between the center of rotation (COR) and the wires is defined by $L$ and can be expressed with the following formula:

$$L = \frac{d}{sin(\beta)} \tag{10}$$

In which $d$ is the distance between two joint at the place where the wires run, and $\beta$ is the max bending angle of the joint. Based on the geometric terminology the following equations can be derived to obtain $d$.

$$\frac{d}{r} = \frac{D}{R} \tag{11}$$

In which $D$ is the distance between two joints, $R$ the outer radius of the steering part and $r$ the distance from the neutral axis to the tendons. When the joint is bent around the z-axis by $\phi$, $d$ will become larger and can be expressed in the following formula:

$$d_{new} = L(sin(\beta) + sin(\gamma)) \tag{12}$$

Since the structural relations remain the same the maximum bending angle $\phi_{max}$ is equal to $\theta$. The maximum length change of a wire by the angle $\phi$ can be expressed as:

$$\begin{aligned} \Delta d &= d_{new} - d \\ \Delta d &= Lsin(2\beta) - \frac{Dr}{R} \end{aligned} \tag{13}$$

Substituting Eqn. 10, 11 and 12 into Eqn. 13 allows to simplify Eqn 13 to:

$$\Delta d = \frac{rD}{R} \tag{14}$$

Now the number of joints can be determined required for the desired bending angle:

$$N_{joints} = \frac{D_t R}{rD} \tag{15}$$

With the number of joints the steering unit can be set. The two steering units are different, see Figure 16. Figure 16 A consists of the steering unit used to steer the VBS part of the mechanism. The cross-section consists of 30 equally distributed holes which are used to guide the lines of the wire jamming mechanism. These wires are fixed at the end of the steerable segment. In order to leave space for the fixation of these wires a small cylindrical surface is place on top of the second steerable segment, see Figure 16 B. This mechanism only consists of a central channel and square holes to guide the internal cables, that run from the tip of the mechanism to the end of the steering mechanism. This steering mechanism has the same properties as the teleoperation system developed by Henselmans [19] and does not require any assembly.

## 5.4 Complete design

The complete design consists of two steerable segments (Fig.17 A, Part 1 & 2). Both parts are steerable and Part 2 can lock its shape. The combination

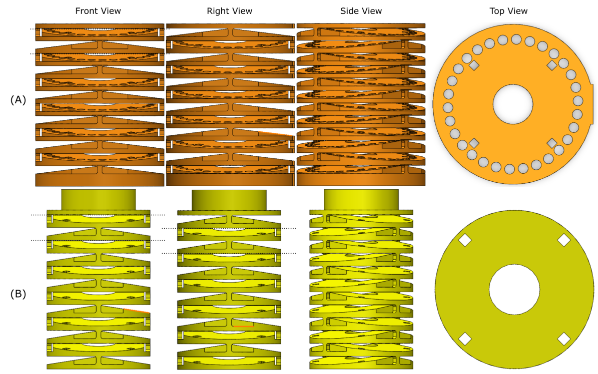


Figure 16: Schematic view of the steering unit, front, right, side and top view. (A) Steering unit for Variable Bending Stiffness (VBS) segment. (B) Steering unit for the tip segment

of these two steerable segments can create complex shapes and provide backup support due to their VS ability. The fibres around the VBS segment are fixed at the tip and run through the frame and are attached to the right side of the first steering unit (Fig.17 A, Part 10). Due to this the VBS segment is able to steer. The stiffening cone (Fig.17 A, Part 5) can be screwed onto the thread of the frame. This movement ensures that the proximal end of the braided sheath will be pulled backwards and forwards to change the stiffness of the mechanism. Rotation is converted to translation and therefore there is a thrust bearing (Fig.17 A, Part 6) placed between the stiffening cone and the parts that lock the braided sheath (Fig.17 A, Parts 7 & 8). Without the bearing a torque would be applied to the braided sheath, which cause a rotation of the braided sheath, the fibres and the steerable segment. The segment can be damaged by this because it can not resist such high torques.

The braided sheath is fixed between two segments that are screwed into each other and is placed in between these segments. When these parts are screwed together a high friction force occurs between the braided sheath and the fixation segments. This force prevents the braided sheath from moving when the stiffening cone is screwed on the frame. The frame (Fig.17 Part 9) starts with a cylindrical part which has the same diameter as the steering segments. This is the rigid section over which the stiffening cone can slide. The reason for this is that the stiffening motion does not affect the shape of the steerable segment. In this section channels are made that guide the steering wires that run from the front to the back of the mechanism.

The second part of the frame is cone shaped which ends in a cylinder with an external screw thread. Because of the increased diameter the wires used for the stiffening mechanism are equally distributed in

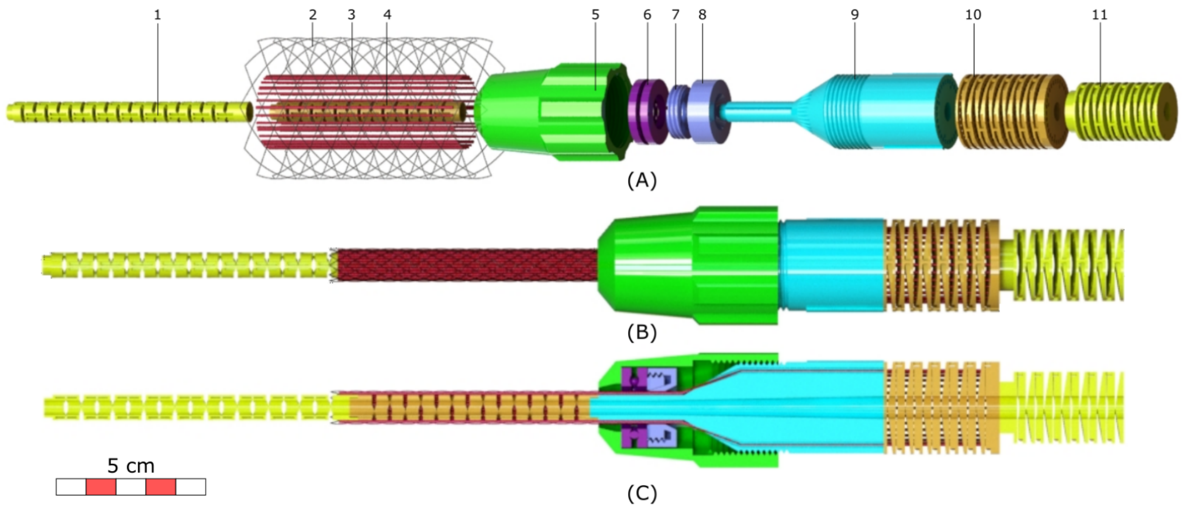


Figure 17: Schematic figure of the AlKingScope, (A) Exploded view of the steerable variable stiffness mechanism, which consists of top steerable segment (1), braided sheath (2), nylon wires (3), variable bending stiffness (VBS) steerable segment (4), stiffening cone (5), thrust bearing (6), fixation of the braided sheath (7) & (8), frame (9), steering segment for the VBS segment (10) and top segment (11). (B) Side view of the total assembly fitted together, indicating dimensions. (C) Cross section of the steerable VBS mechanism.

the frame. The steering units are connected at the end of the mechanism (Fig.17 Parts 10 & 11). The colour of the mechanism represents which steerable segment is steered by which steering unit. According to design requirement 6 the mechanism needs to have an inner lumen, otherwise the mechanism cannot act as a sheath. Therefore, there is a central channel running from the top to the end of the mechanism, see Figure 17 C.

# 6 The AlKingScope prototype

## 6.1 Materials

The prototype consists of a number of FDM printed parts, see Figure 18. These are the parts consisting of PLA and PETG. The stiffening cone needs to withstand the highest forces, because this part stiffens the braided sheath. Therefore it was printed with PETG which has a higher tensile strength than PLA [20, 21]. The thrust bearing prevents the torque that is created by the stiffening cone from being applied directly to the braided sheath and with that also the steerable segment. The bearing is made of chrome steel which has a low coefficient of friction and rolls fluently to compensate for the torque created by the stiffening cone.

The braided sheath consist of multiple Polyethylene Terephthalate (PET) wires that are woven into each other to create the braided structure. The stiffening wires are made of monofilament nylon wires, which are flexible and available in many different sizes. For the stiffening wires it is important that the shape remains the same when they are jammed and therefore the wires consist of monofilament line, rather than braided line. The steering wires are made of braided PP wires, the advantage of these wires compared with regular nylon fishing wire is that these wire barely change length when they are under tension. This feature is essential for a steering mechanism described in Section 5.3, otherwise the maximum angle of the steerable segment is reduced while the angle of the steering unit remains the same. Therefore an elastic wire influence the steering capabilities in a negative way.

A phenomenon known as creep can occur over time in braided wires. However this process takes a long time to occur and for this MSc project it will not influence the behaviour of the mechanism. The materials used in the steering part of the prototype all are biocompatible, such as PLA, PET and nylon or can be changed to a biocompatible form of that material.

## 6.2 Manufacturing

Figure 18 provides an exploded view of the components used in the prototype that needs to be assembled. First the steering wires are fixed at the top and advanced through the steerable segments, the frame and the steerable units. These parts were also glued together. The stiffening fibres were inserted in through the frame and fixed at the steerable unit. The wires have a predefined curvature, which can lead to a curvature in the mechanism. Therefore the wires were inserted in a way that the curvature is always

Figure 18: Overview of the components, black and white parts are produced with additive manufacturing technique. The material of the black parts are Polyactic Acid (PLA) and the white part is Polyethylene Terephthalate Glycol (PETG). The transparent wires are monofilament nylon fishing wire and the black wires are braided Polypropylene (PP) fishing wire. The grey ring is made of chrome steel.

directed outwards. If all the fibres were inserted the curvatures of each wire cancel each other out, and do not effect the shape of the mechanism. At the distal end of the wires, glue was added to attach them to the steerable segment. The braided sheath was fixed between the appropriate segments and pushed over the wires. When the sheath was in place a heatshrink tube was added to fix the braided sheath at the distal end. The thrust bearing and stiffening cone were attached, completing the variable stiffness section. In the end only the steering wires had to be attached at the proximal end. For the steering mechanism it is important that all the wires have the same length. To accomplish this, a small screw mechanism was made to change the length of the wires. The manufacturing process resulted in the final prototype, see Figure 19, which could be validated.

# 7 Evaluation

## 7.1 Goal of the experiment

An experiment was conducted to validate the VBS ability of the Prototype. The goal of the experiment was to find the stiffness ratio between the flexible and rigid state of the mechanism and obtain a force displacement relation of both states.

## 7.2 Experimental setup

Figure 20 shows the experimental setup to test the stiffness of the prototype. For this experiment multiple pieces of equipment are required. A physical instrument (PI) stage, which is a linear stage with a resolution of 0.1 $\mu m$, is used to track the displacement. A load sensor measures the force applied to the VBS segment. A computer to regulate the movement of the PI stage and obtain the data from it. Profiles to create a frame in which the mechanism can be fixed. The frame was built in front of the PI stage perpendicular to the linear stage. The prototype is positioned downwards, so that the gravity does not affect the bending of the VBS segment.

The load cell is attached to the PI stage, therefore the distance travelled by the PI stage is the same as for the load cell and the relation can be found between the force and displacement. For this experiment two different load cells were used, a 100$gram$ and a 9$N$ load cell. The 100 $gram$ load cell was used to measure the force displacement in the flexible state and the other was used for the stiff state. The load cells were tuned to measure a maximum force of 0,8$N$ and 6$N$ respectively, otherwise the load cells can be damaged

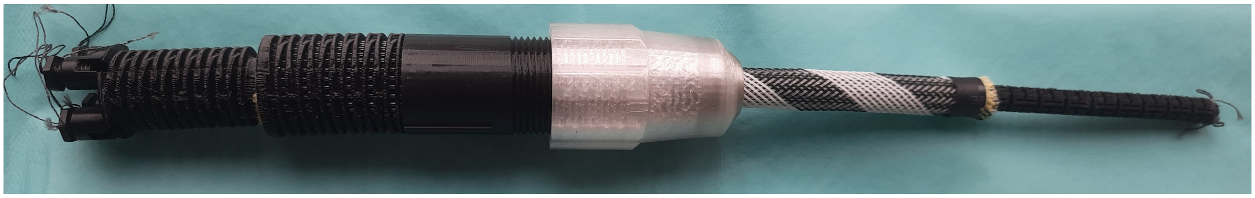

Figure 19: Final prototype AlKingScope.

if too much force is applied. Two different load cells were used to increase the resolution of the measurement. The smaller load cell measures smaller force variations which is required in the flexible state, because a small force can already cause a displacement.

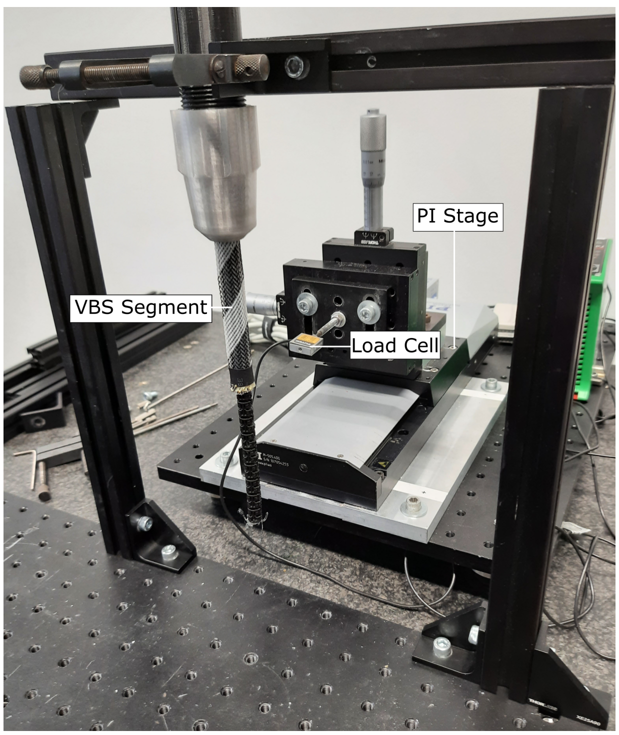


Figure 20: Experimental setup in which the variable bending stiffness (VBS) segment is fixed at the frame. The physical instrument (PI) stage (linear stage) can move forward which measures the displacement and the load cell measures the force exerted on VBS segment.

## 7.3 Experimental procedure

The experimental procedure to measure the force displacement of the VBS segment was as follows:

1. The prototype is fixed in the frame pointing downwards and perpendicular to the the motion of the PI stage. The load cell is connected to the PI stage.

2. For the measurement of the flexible state the stiffening cone is at the first thread, which means that the mechanism is flexible. If the measurement for the stiff state is performed the cone is fully threaded around the frame.

3. The PI stage is moved forward to find the distance where the load cell almost hits the prototype in order to set the point of contact between the load cell and the VBS segment. The position of the load cell with respect to the PI stage can be manually adjusted by two linear stages, to find the right point of contact.

4. The PI stage is moving forward by small increments to find the displacement at the maximum force of the load cell. This location is stored in the computer.

5. The PI stage is moved back to the position from Step 3 which is just ahead of the VBS segment.

6. The PI stage is moved to the position explained in Step 4 and back to the initial position. The data from this measurement was exported and the VSM was set in the its straight configuration. This measurement was performed 5 times.

7. After these measurements were performed, the prototype was rotated 60 *degrees* about its long axis to find the force displacement relation in that configuration and Steps 3-6 were repeated.

The measurement was performed in three different configurations each with a 60 *degrees* rotation. This gave a total of 15 force displacement curves for the flexible and stiff state respectively. The measurement was repeated to obtain a better estimation of the experimental error.

## 7.4 Experimental results

The experiment was conducted to find the relation between the stiffness in flexible and rigid state. The results, see Figures 21 & 22, can not be validated as the force displacement of the bending stiffness, as to calculating the bending stiffness the force must always be perpendicular to the VBS segment. In this setup the force is applied in the same direction while the segment was bent and therefore the measured force had two components, one parallel to the VBS segment and one perpendicular to it. The component of the force that is perpendicular to the VBS segment can be obtained if the angle and the length of the VBS segment is known. In this setup only the displacement of the PI stage is measured and not the angle. Therefore only an estimation can be made of the bending force in this setup. This limitation is further explained in Section 8.4. The measurement is the same for both stages and therefore it is assumed that it the error created by the component of the force will cancel each other out. Because of this the stiffness ratio can be retracted from this measurement.

Figure 21 & 22 show the obtained data from the measurement. Figure 21 represents the data from the flexible state. The Figure starts with a quick increment to $0.08N$ and from that point it increases steadily over the course of its displacement. This is expected, the slope is constant because the mechanism is not plastically deformed and the dynamic friction force that occurs stays constant. The quick increment at the beginning can be explained by the force that is required to move the VBS segment. The segment has some stiffness from its structure and when the load cell hits the segment, the static friction must be overcome to move the mechanism. The static friction is higher than the dynamic fiction which causes the rapid increases of the force at the beginning.

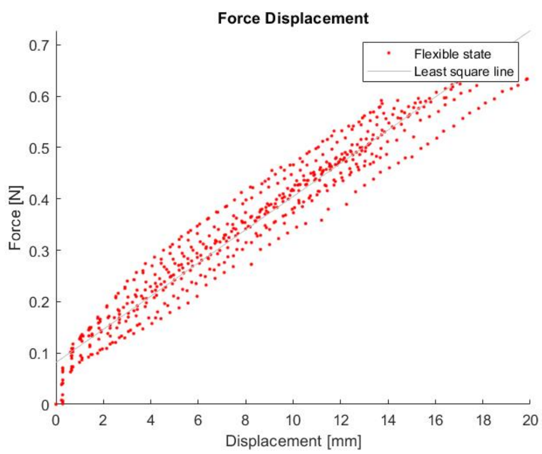


Figure 21: Experimental result of the force displacement of the flexible state.

Figure 22 shows the data of the stiff state. In contrast to the flexible state there is no rapidly increase of force for the first microns but a constant slope till around 2 $mm$. The reason for this is that the due to the high friction that is created in the mechanism, the dynamic friction is almost the same as the static friction force which results in a constant slope. After 2 $mm$ there is an increase in the variability between measurements. In Figure 22 it seems that three different lines were plotted. However these three combinations of data points do not represent the three different configurations, because the number of data points in each line is not the same.

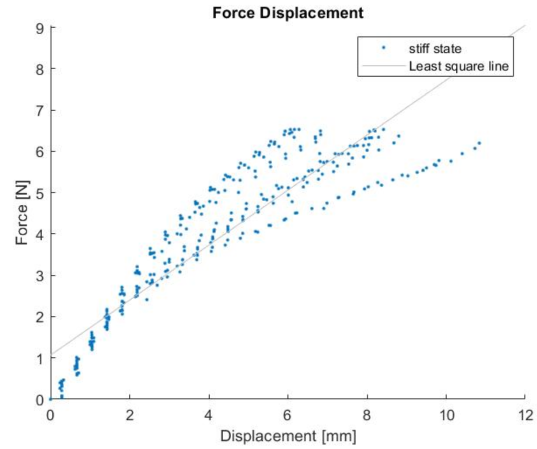


Figure 22: Experimental result of the force displacement of the stiff state.

In the end a the least square function was plotted in Figures 21 & 22 which averages all the data points. If the slope of both lines were compared, a ratio between the flexible and stiff state could be found which is stated in Equation 16.

$$\eta_{EI} = \frac{EI_{stiff}}{EI_{flexible}} \approx 20 \tag{16}$$

This is the mean stiffness ratio based on this experiment. This means that the stiff state has 20 times more bending stiffness than the flexible state.

# 8 Discussion

## 8.1 Limitations

This research project was largely performed during the Covid pandemic, therefore for prototyping I used my own FDM printer, a Creality Ender 3 (Shenzhen Creality 3D Technology Co, Ltd., Shenzhen, P.R.C.). The campus was closed and therefore the machines at the University could not be utilised. This is the reason why FDM printing is important for this research. Maybe with other materials or manufacturing techniques the prototype would be different in shape or performance. The FDM manufacturing technique also led to the choice of the proof of concepts because these concepts consisted of partially or totally of FDM printed materials. Other proof of concepts could be chosen if also other manufacturing techniques were available.

Furthermore the stiffening mechanism is tested with only one sort of wires. These are mono-filament nylon fishing wires of 1 *mm*. Other wires may have a higher coefficient of friction which lead to a higher stiffness. A thorough material selection study would have to be performed to determine the best material.

Another limitation of this research is the design of the steerable segment. The steerable segments are two round surfaces that can bend along each other. The steering units have a triangle shape between the joints and the edge of the triangle is the line of rotation between the segments. These are two different type of joints which has both axial stiffness. To find out which one works better more models could be made and tested to use the best working steerable segment or unit.

## 8.2 Constant curvature

The mechanism can create a constant curvature if each flexure has the same stiffness. The flexures have the exact same dimensions, however after a period of time some flexures became more fatigued than others. If that happens it is more easy to bend around that flexure than over others and the curvature is no longer constant. The mechanism will only bend around that flexure and in the end it will break due to fatigue. Further research needs to be done in order to find the right configuration of the flexures, such that they will not wear as easily.

## 8.3 Size

The size of the mechanism plays an important role for this application. This prototype is built at a larger size for simplicity and to still be able to manufacture most parts via FDM printer. The wires used for the braided sheath have a diameter of 0.25 *mm*. These are woven into each other which results in a thickness of 0.5 *mm*. The wires that use friction to stiffen the mechanism have a diameter of 1 *mm*. This can be scaled down to tiny wires of 0.1 *mm* or even smaller, however it is important to think what influence this can have on the stiffening ability. Fiber jamming mechanism are mostly unrestrained by size [22]. This means that the stiffening mechanism will still work with smaller wires, however the stiffness of the wires itself and the resting moment created by the wires will change . Therefore the mechanism will be less stiff when smaller wires are used.

Besides the wires and braided sheath also the steerable segment needs to be scaled down. The thickness of these segments is dependent on the flexure that connects the two joints, the space between the flexure and the joint (air gap), and the point were two joints need to be connected in order to be axially stiff, see Figure 12. Other manufacturing techniques can be used to miniaturise the design and reduce the size of the steerable segment. It remains to be seen if a miniaturised design will be manufacturable. Furthermore, detailed finite element analysis and destructive testing will be required to determine the design's strength and fatigue life at that scale.

## 8.4 Measurement

In the measurement the force measured with the load cell did not consist of only the bending force. When the variable stiffness segment is moved the direction of the bending force starts to change. In another setup or by making a number of assumptions a better estimation of the bending force can be made.

In the first place a measurement can be set up that applies a moment to the mechanism instead of a force. The tip of the segment is attached to the edge of a disk with the same radius as the length of the variable stiffness segment. When the disk starts to rotate a moment is applied to the segment which starts to bend. In this setup a relation between the moment and bending angle can be obtained. This can be translated to a force displacement relation which only consist of a bending force.

Another way to provide a better estimation for the bending force in this setup, is to find the maximum bending angle at the maximum displacement. When a grid is placed behind the variable stiffness segment the bending angle can be determined by geometric relations. If it is assumed that the bending angle scales linearly with the displacement, the bending angle is known for each displacement. When this is known the component of the bending force can be calculated for every displacement and an estimation of the bending force displacement relation is obtained.

Besides the measurement setup the results can also be discussed. The data curves from the flexible state behave as expected, which is a linear curve. The curves from the data of the stiff state do not behave as expected. The first thing that stands out is that it seems that there are three main lines in Figure 22. These lines of measured data points do not represent the three different orientations, because there are fewer data points in the lower line than the others. This was caused by the stiffening cone not being threaded to the same position each time a measurement was performed. Because this motion has to be applied manually, there are some human errors involved in it. A mechanism in which this stiffening cone can be moved automatically, or tightening with a torque wrench will resolve this error. Another reason for this can be the mechanism was fixed differently during the measurements, this can be the cause of the staggered data points.

The second thing to notice is that the curvature starts out linear and gets curved after about two millimetres. It is expected that the relation is linear and the reason for the curvature needs to find out. A reason for this can be the fixation of the mechanism, see Figure 23. The mechanism is fixed by two

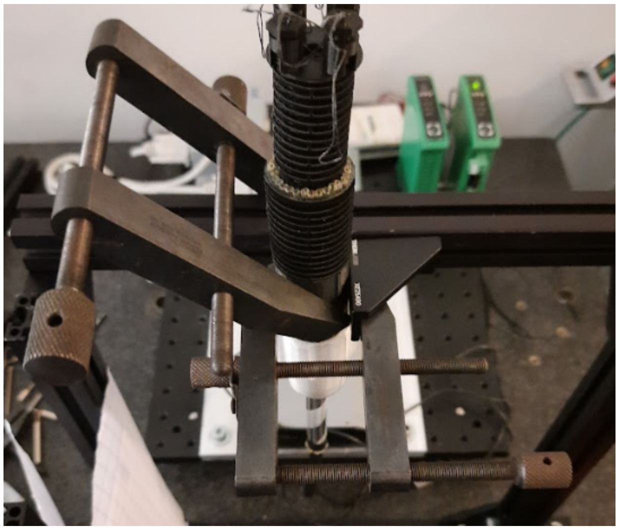

Figure 23: Fixation of the prototype with two claps around the mechanism.

clamps that have to be manually screwed to fixate the prototype to the frame. When load is applied at the tip of the mechanism, a moment is applied to the frame. Increasing the load at the tip, also increases the torque on the frame and it can start to move when it is not properly fastened, see Figure 24. Figure 24 (A) shows the initial position of the prototype with respect to the frame. In the magnified image two reference lines were drawn to show the orientation of the prototype. In Figure 24 (B) the same reference lines were used and placed on the same spot, but now the VBS segment is at is maximum bending angle. There is some space between the reference lines and the prototype which means that the prototype has moved, which is marked in red. When this happens the load cell measures a smaller force, and therefore the measurement points are curved. For this measurement a second human error can be found by attaching the prototype to the frame to fixate it. This can also be the explanation why there are three main lines in Figure 22. Because of this error the slope of the data points should be measured for the first 2 $mm$ which results in a higher relation between the flexible and stiff state than mentioned in Section 7.4. Taking this into account, a stiffness ratio of 40 can be obtained. While more work is required to thoroughly characterise this mechanism, this early work seems to show great promise.

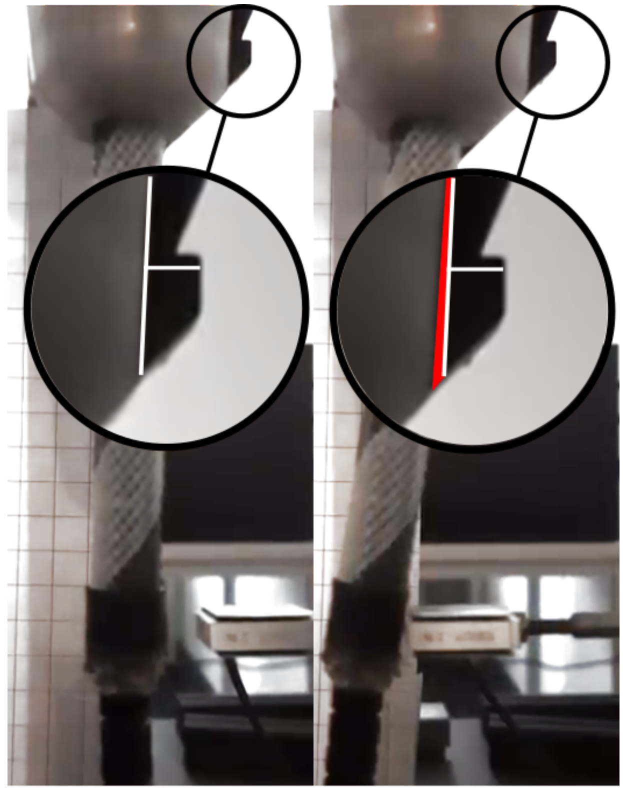


Figure 24: Deflection of AlKingScope during measurement (red). (A) Initial position position of the prototype in stiff state. The magnified image shows the reference lines (white lines) between the frame of the prototype and the frame on which the prototype is fixed. (B) Position of Variable Bending Stiffness (VBS) segment at maximum displacement. The magnified images shows the same reference lines as in A, in red the displacement of the prototype with respect to the frame.

## 8.5 Stiffness comparison

The stiffness ratio ratio can be compared to other VSMs that exist in literature. The literature review that was conducted before this thesis was also based on VSMs for medical applications in which also the stiffness ratios of different devices were presented. A comparison was made between those stiffness ratios and the stiffness ratio of this prototype. Only one mechanism has a higher stiffness ratio than 20: a phase change mechanism with a stiffness ratio of 22 [23]. The next highest stiffness ratios are around 15 which are two phase change [24, 25] and one fluid pressure mechanism [26]. These are different stiffening principles and if this mechanism is compared to other jamming mechanisms, the highest stiffness ratio is 10 [27].

While more work is required to thoroughly characterise this mechanism, this early work seems to show great promise. The prototype proposed in this work appears to have a stiffness ratio double that of existing VSMs based on granular jamming, such as the design by Lin et al [27], which was the highest found in literature as jamming mechanism.

### 8.6 Costs

The materials and parts of the prototype were described in Section 6.1. These materials influence the price of the mechanism. This proof of principle protoype consist mainly of FDM printed parts which are a low-cost material. Because this manufacturing technique was chosen, the FDM 3D printing can also be used in the future to ensure low-cost prototypes. In this cost analysis only the costs of the materials and parts itself is taken into account. The production, development, shipping and other costs were neglected, as these are extraordinarily difficult to predict in the current economic climate. Besides the parts and materials, table Appendix D provides an overview of the costs of the mechanism. The third column shows the the price per unit. The fourth column shows the amount of material or parts that are required for the mechanism which results in the final unit price. The total cost of material and parts to make this prototype is € 7,15. The design of the AlKingScope alows for a low cost prototype in the future.

### 8.7 Further research

Further research is required to investigate if this working principle can be used for surgical applications. As explained in Section 8.3 the size should be smaller and a new research can find out if it is possible to even build such a small mechanism and whether such a system would have sufficient strength to stand up to regular use.

Further research should also investigate how the length of the stiffening mechanism is related to its stiffness. If the stiffening segment becomes larger, which is required for the medical application, the braided sheath must compress the wires equally along the entire length of the mechanism which can become a problem. This is because the lengthening force on the braid will decrease along the length due to friction, which will result in less compression and therefore less friction on the wires at the distal end. However the bending moment at the distal end is smaller than at the proximal end which may compensate for the loss of friction at the distal end. The research can also investigate the use of multiple smaller stiffening segments in order to create a long variable stiffness segment.

Other research can investigate different applications for this mechanism. The VBS segment can also be used for a concentric follow the leader device, in which the path of the mechanism will stay the same. In a concentric tube system a tube is propagated into an other tube which remains stiff [28]. The tube follows the path of the stationary tube and if tube has passed the distal end of the stationary tube, the inner tube can be steered in the right direction and also become stiff. A model of such a follow the leader device was designed by a number of people [29, 30]. However these designs lack the principle of variable stiffness which can contribute to the ability of creating a rigid path. Therefore the AlKingScope can contribute to concentric tube system.

## 9 Conclusion

In this research a proof of concept Variable Bending Stiffness (VBS) instrument was designed and validated based on the stiffening capabilities. Three different proof of concepts were made and compared based on the design requirements. A mechanism that changes its stiffness by means of wire jamming was further developed and manufactured. The wires of this device are radially jammed together between a braided sheath and a radially rigid, yet flexible compliant core. By applying axial tension on the braided sheath, its diameter can be decreased, which compresses the wires against the core. The friction created by the jamming mechanism causes a stiff state of the mechanism. The stiffness in the stiff state is approximately 20 times higher than the flexible state which was experimentally validated. Further research investigates the size reduction and lengthening of the prototype in order to accommodate for the requirements needed to fulfil the medical application. While more work is required the proof of concept prototype shows great promise for future designs.

## Abbreviations

**CAD** Coronary Artery Disease
**CTO** Chronic Total Occlusion
**PCI** Percutaneous Coronary Intervention
**VBS** Variable Bending Stiffness
**FDM** Fused Deposition Modelling
**DOF** Degrees of Freedom
**VSM** Variable Stiffness Mechanism
**PCM** Phase Change Material
**SMOA** Second Moment of Area
**PLA** Polyactic Acid
**PETG** Polyethylene Terephthalate Glycol
**GTT** Glass Transition Temperature

**PET** Polyethylene Terephthalate

**PP** Polypropylene

**PTFE** Polytetrafluoroethylene

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# A Appendix: Design process

## A.1 Pathway to AlSegJam: segment jamming

### A.1.1 Concept 1

The first concept that was created consisted of only a frame with steerable segments. The joints used in this design are the ball and socket joints. The mechanism works as follows; the wires are placed through the joints and fixed at the distal end. When threading a screw on the frame the wire shortens which creates a curvature. When the curvature was obtained the other screws were tightened to maintain the curvature. Next, all the screws were tightened to increase the tension in all wires. This concept was not user friendly because it did not have a proper steering and stiffening mechanism. This was the next thing that had to be improved in the design.

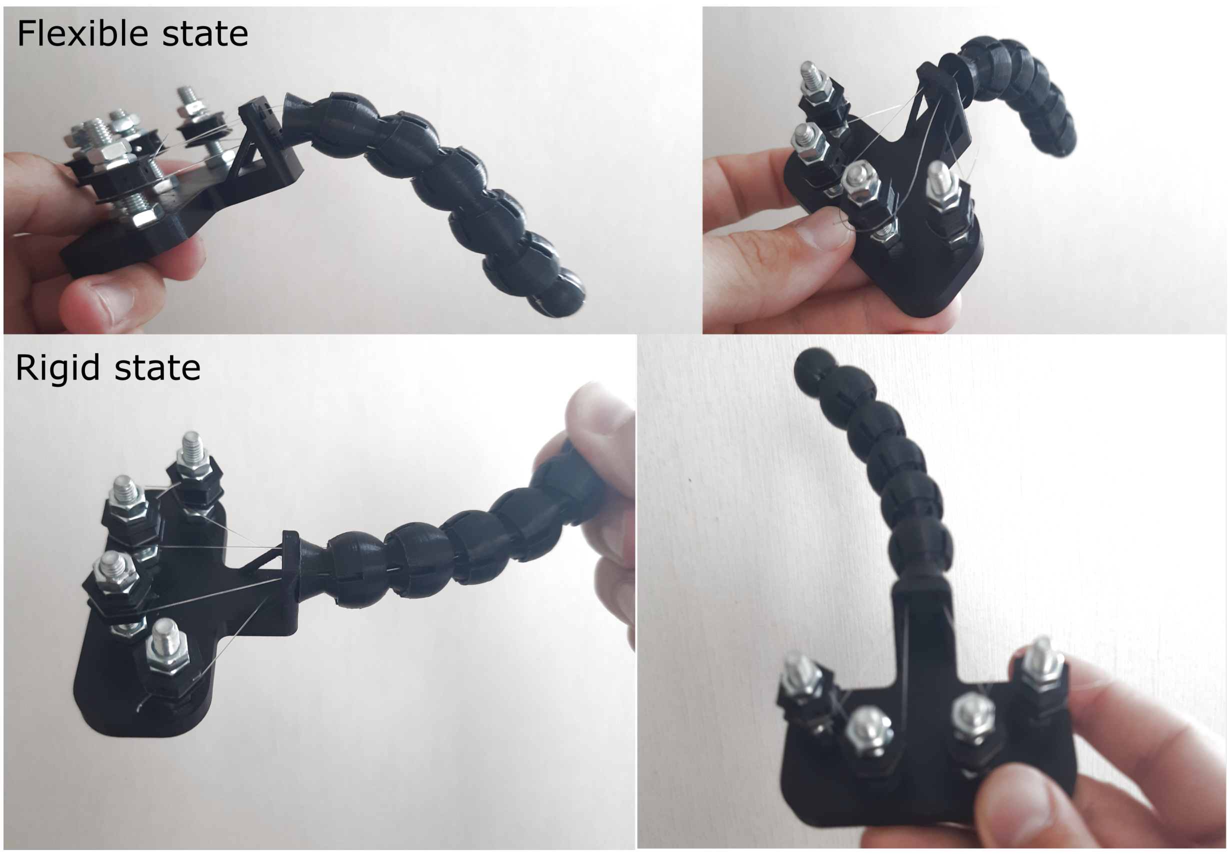



Figure 25: First concept of the segment jamming mechanism in flexible and stiff state. The ball and socket joints can be fixed to each other by tighten the screws on the frame which applies tension to the wires.

### A.1.2 Concept 2

For this type of concept a steering mechanism and stiffening mechanism needed to be designed and the same type of joints were used as for Concept 1. The mechanism is steered by two wheels, each steering an antagonistic pair of wires, see Figure 26 Steering. The wheels are locked on some pins and have to be lifted up to rotate and steer the mechanism. The pins ensure that if the desired curve is achieved the wheel can not rotate and the desired shape retains.

The stiffening mechanism uses wire tension to increase the stiffness. The first joint is fixed to a screw mechanism. The screw slides into the frame back and forward by threading a nut. Because the wheels were fixed on the pins the shape of the mechanism did not change when the tension was applied to the wires, see Figure 26 Stiffening.

This concept has a user friendly steering and stiffening mechanism. However the joints did not lock proper together and did not create a constant curvature. Therefore the next design was focused on creating other type of joints for the mechanism in order to create a constant curvature and increase the friction between the segments.

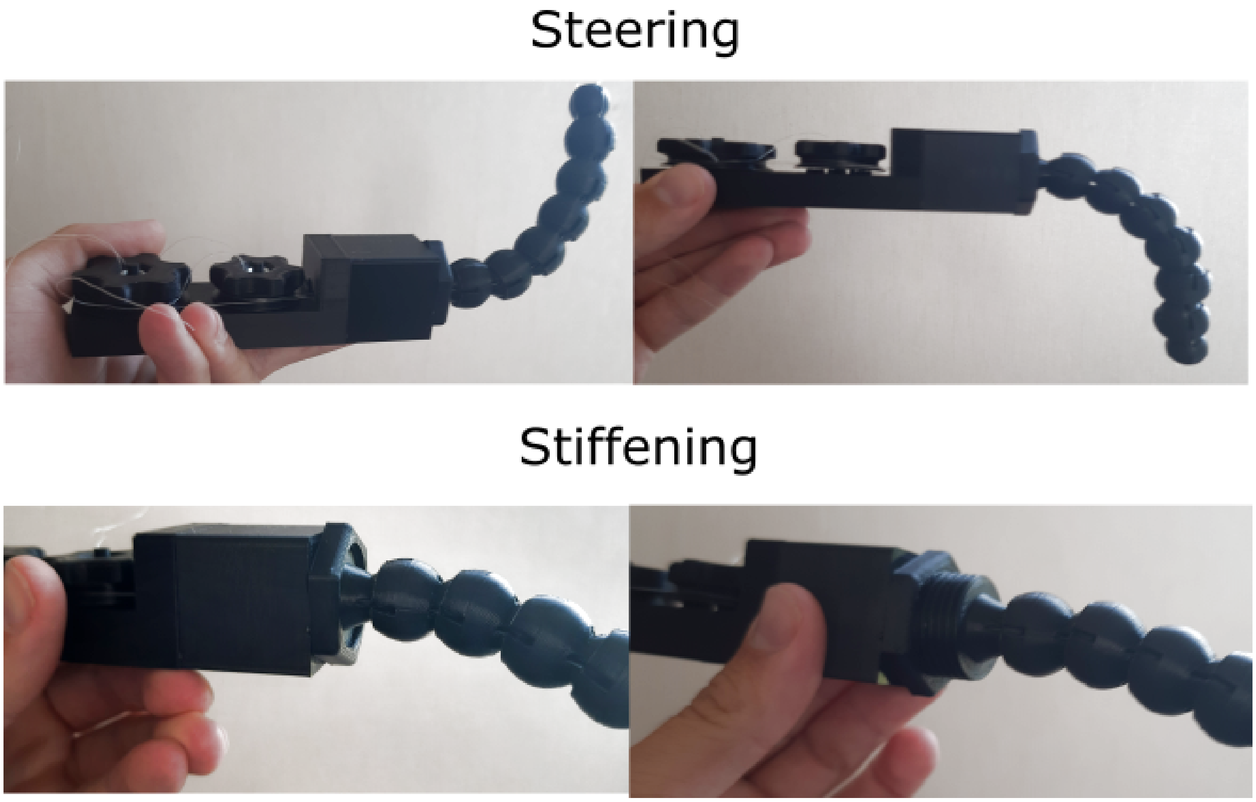



Figure 26: Second concept of segment jamming mechanism. The mechanism is steered by two wheels that lock onto pins on the frame. This retains the shape of the mechanism when the wires are tensioned by the stiffening mechanism.

#### A.1.3 Concept 3

In the third concept rolling friction joints are used for the steerable segment. These joints have a curvature on both sides which are rotated 90 *degrees* with respect to each other. By stacking these joints by 90 *degrees* on each other a 2 DOF manipulator is created, see Figure 27. The steering and stiffening mechanism is the same as for Concept 2, however the frame is minimised to save time with manufacturing.

A test was conducted to find out if the system had variable stiffness. A small weight was connected to the tip of the manipulator. The mechanism was tested while having a straight shape in the initial position without any load. When adding a weight the deflection could be observed. In the flexible state a weight of 50 *gram* was added which caused a deflection of 30 *mm*. Then the stiffening mechanism was activated. There was almost no deflection, therefore a bigger weight of 135 *gram* was added. This load caused a deflection of 20 *mm*. This test concluded that the system had variable stiffness, because in the stiff state less deflection was observed while more load was applied. In comparison to Concept 2 this mechanism had a higher stiffness, however there was still no constant curvature because the joints could slide along each other.

#### A.1.4 Concept 4

This concept was made to find out if the sliding between joints can be prevented by using another material. Rubber is a material that has a high coefficient of friction, which could easily be attached to the joints. Therefore the joints were covered with a rubber layer and the same concept was made as Concept 3, see Figure 28.


Figure 27: Third concept of segment jamming mechanism. The mechanism is steered by two wheels and stiffened by a screw mechanism. The joints used in this concept are the rolling friction joints. The bottom shows a stiffness test. On the left the deflection of the mechanism in flexible state with a load of 50 gram. On the right the deflection of the mechanism in stiff state with a load of 135 gram.

The rubber on these joints prevented the sliding effect between the segments, however it was still difficult to create a constant curvature and it took much time to add rubber to all the joints. The investigation to find the right joints was still in progress. In order to be able to easily test these things a design needed to be made on which a steerable segment could be easily placed, without printing and assemble a whole new design. Also the length of the manipulator needed to be increased to fit the design requirements. With this is mind Concept 5 was created.

### A.1.5 Concept 5

The final concept was designed to increase the length of the mechanism by adding a passive shaft between the steerable segments and the frame. The passive shaft consist of tubes that connect the frame to the steerable manipulator. To be able to steer the mechanism without changing the length of the passive shaft bowden cables are required. These cables prevent a force acting on the shaft which otherwise cause a deformation. Bowden cables are tubes that are axial stiff and flexible, which are also used for bicycle breaks.

In this design, see Figure29 Polytetrafluoroethylene (PTFE) tubes with a wall thickness of 2 *mm* were used. PTFE tubing has a relatively high stiffness compared to other plastics. With this passive shaft the concept was able to steer and change stiffness. However this concept was not as good as in the previous design. The main problem of this design was that it was still hard to bent the passive shaft which should be flexible in order to adapt to different shapes easily.

The frame was adjusted to attach different types of steerable segments more easily. The channels in which the cables run through the frame are located at the outside. This makes it more easy to fit the cables through. To compensate for the difference in tendon length from different steerable segments a line tensioner is placed in between the wires, see Figure 29 right. This way each steerable section could fit this frame.

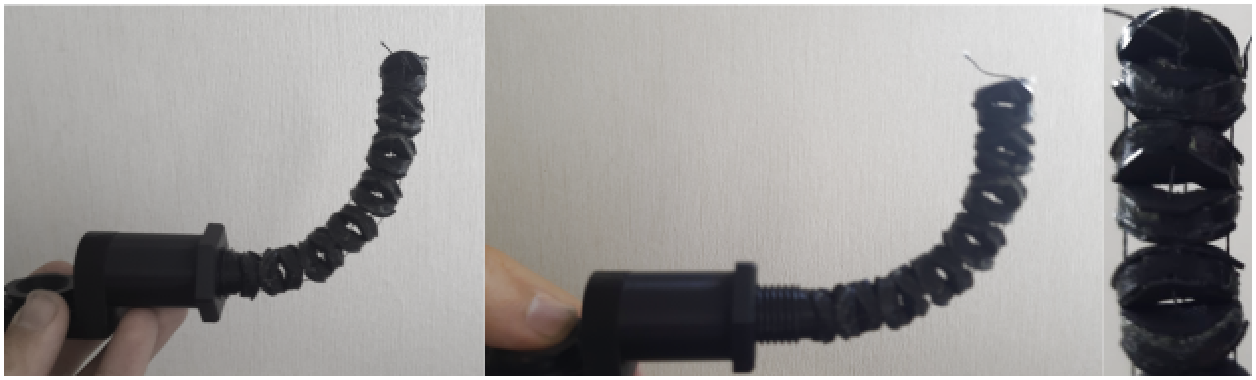


Figure 28: Fourth concept of segment jamming mechanism. The mechanism is steered by two wheels and stiffens by a screw mechanism. The joints used in this concept are the rolling friction joints with a rubber layer on it. Left shows the flexible state, the middle shows the rigid state and on the right a close up of the joints.

Multiple segments were tested in which the curvature or length was changed, however this did not create a constant curvature. In the end a toothed joint was made which did create a constant curvature, explained in Section 4.1.2.

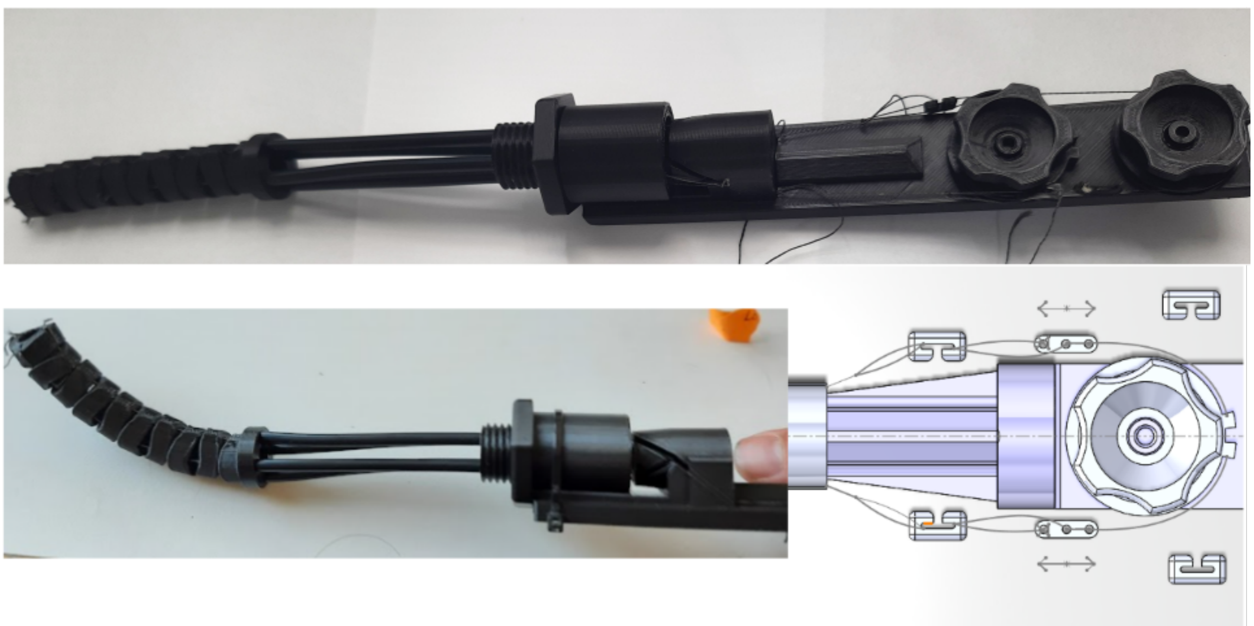


Figure 29: Fifth concept of segment jamming mechanism. The mechanism is steered by two wheels and stiffens by a screw mechanism. Between the frame and steerable segment PTFE tubes are placed. At the bottom right a schematic figure of the wire tensioning mechanism.

## A.2 Pathway to AlPhaChange: phase change material

PLA is a material that becomes flexible when it is heated above the GTT. Three different structures were made and tested on bending, see Figure 30. The relation between the bending capability and the structure was investigated. The parts consist of two helical structures and the first two structures also have rings in between, they differ from each other by thickness.

The structures were heated up by water at 70 *degrees*, the material became flexible and was bent. The first structure was the hardest to bent and the structure without the rings was the easiest. This test concluded that the structure does influence the bending capability even if the whole part becomes flexible. After the test the parts were exposed to the hot water again and the original shape was obtained. This means PLA acts as a shape memory polymer, which is a polymer that can obtain a predefined shape when it is heated. The third structure was used to implement in the proof of concept.

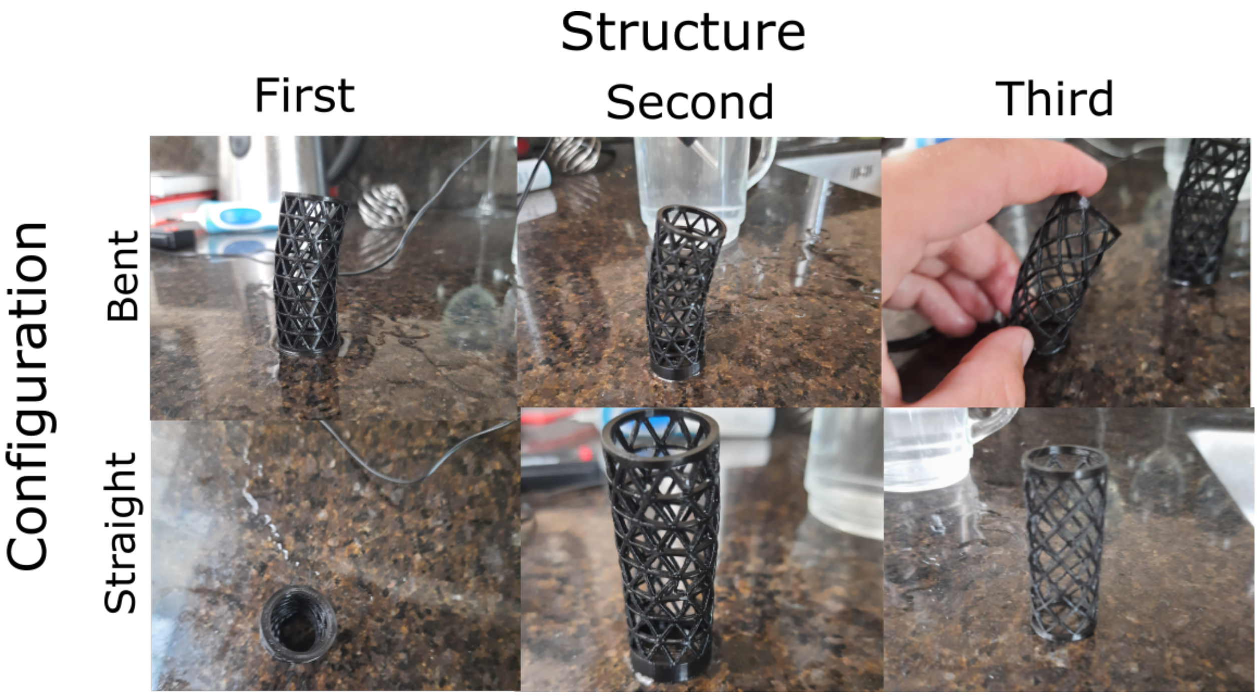



Figure 30: Curved and straight configuration of each structure. Three different structures of Polyactic Acid (PLA) that were tested on bending, when heating it till Glass Transition Temperature (GTT).

## A.3 Pathway to AlWiJam: wire jamming

### A.3.1 Concept 1

The first concept that was made of wire jamming was quite simple to find out where to focus on for the proof of concept, see Figure 31. A flexible silicone tube surrounded by fishing wires over which a braided sheath was placed. Two tendons were inserted and attached to a steering wheel. The stiffening mechanism of the segment jamming design was used to pull on the braided sheath. This concept was made to find out if the principle could work. The following test was conducted to find out if the stiffening mechanism did work. The wheel was rotated to steer the manipulator in a certain direction. Then the stiffening mechanism was activated by threading the nut that lengthens the braided sheath. At this moment the mechanism was at the stiff state, and the wheel was locked. If the stiffening mechanism did work properly the shape should remain while lifting the wheel from the pins. After lifting the wheel the tube reached its straight configuration again, which meant that the stiffening mechanism did not work properly. The flexible shaft lacks the properties of radial and axial stiffness. This hinders the jamming principle, but increases the steerability of the tube. The wires were not equally distributed along the flexible tube and did not change length when the tube was bent. Therefore a new conceptwas needed with an axial and radial stiff tube, an equal wire distribution and wires that could change length according to the bending.

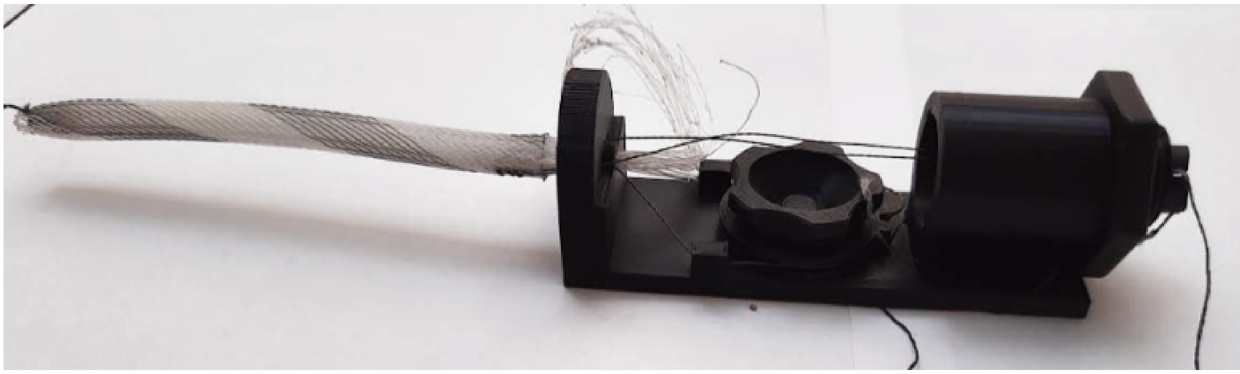


Figure 31: First concept of a wire jamming mechanism. The tube is steered by a wheel and the braided sheath is tensioned whith a screw mechanism.

#### A.3.2 Concept 2

The focus on this concept was on the wire jamming mechanism. High pressure air tubing was used in this design which has radial stiffness because it is made to handle high pressures of fluids. The wires were made of monofilament nylon fishing line of 1 *mm*. Taking into account the diameter of the tubing and the 1 mm fishing wires the exact amount of wires can be determined that are required for the mechanism. A special separation system is used to dived the wires equally, see Figure 32. A braided sheath is placed over the wires and connected to two rings. The ring at the top is fixed. By moving the other ring the sheath can compress and decompress. In this concept the same steering mechanism is used as in the segment jamming design which is described in Section 4.1.3. However the stiffening mechanism is different. A M4 screw is placed into the the frame and by rotating a nut the ring is pulled at the proximal side which lengthens the braided sheath, see Figure 33. The same test as described in Section A.3.1 was conducted with this mechanism and after lifting up the wheel the shape of the mechanism did remain the same. Which means that the stiffening mechanism worked and the manipulator had variable stiffness. The disadvantage of this design was the stiffness of the tube which made it hard to steer the mechanism. The final concept is described in 4.3

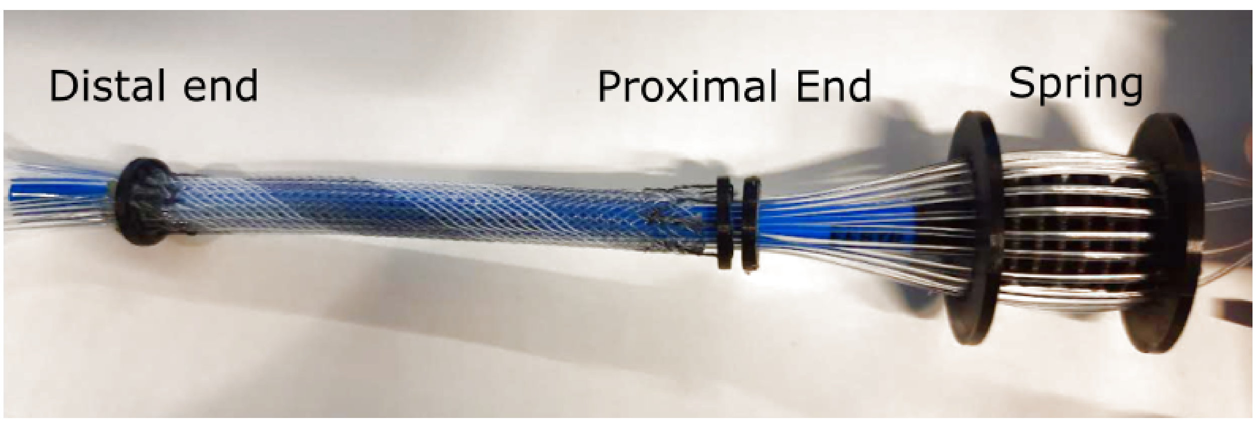



Figure 32: Wire placement of the jamming mechanism. The distal ring is fixed which attach the wires together. The spring mechanism is printed with 21 holes to equally distribute the wires over the diameter of the shaft.

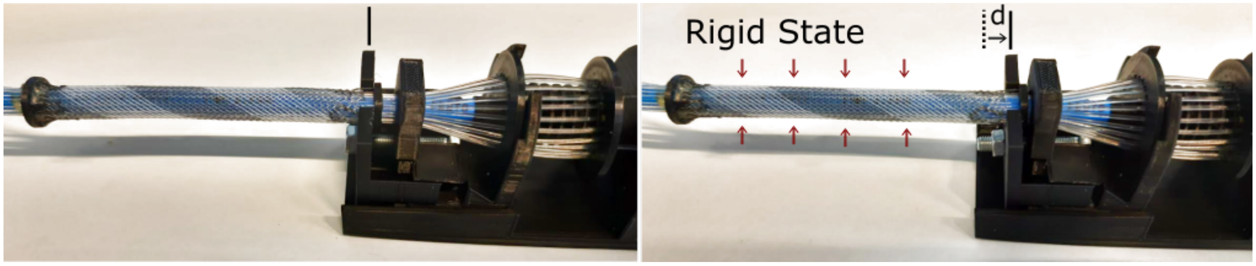



Figure 33: Jamming mechanism. The distal ring is fixed and the proximal ring can move back and forward over the mechanism. $d$ is the distance travelled by the ring which is activated by threading the nut at the stiffening mechanism.

# B Development of the steerable segment

## B.1 Concept

In the previous sections the segment jamming mechanism and the wire jamming mechanism were described. In the segment jamming mechanism it was hard to create a constant curvature, but the system had high axial stiffness because of the segments that were used. In the wire jamming mechanism the curvature was constant but because of the stiffness of the tube it was also hard to steer. The tube needed to be radial stiff otherwise there will be no central lumen anymore when the wires were pressed against the outside wall. Taking these properties of the mechanisms into account a new type of mechanism was designed.

## B.2 Type of joints

The first step was to create a way in which the segments were already attached to each other after printing. This will prevent the use of wires to attach the segments together. Also the segments are no longer able to shift along each other which generates the constant curvature. Multiple compliant joint mechanisms were investigated. Compliant joints are small flexures that elastically deform to create a bending motion. Compliant joints are classified, for this type of mechanism the interest was at primitive revolute compliant joints [18]. Because of the simplicity of these joints they can be printed and added to the segments. These flexures can be integrated in the segment jamming mechanism as long as they are connected in the same plane as the bending plane of the segments. The compliant joints that were tested were the rectangular, right-circular corner-filleted (RCCF), parabolic and cross axis joint [18], see Figure 34.

These flexures were all printed in the same direction (right side on the build plate) to find out which flexure lasted the longest against bending. The length, width and thickness of the joints are the same, besides the size of fillet that is used in the RCCF and parabolic design. The cross axis joints were hard to print and therefore they easily broke. The joint with the highest fillet broke because this had only a small point of rotation. The single beam broke because of the high stress concentrations at the corners. After testing, the RCCF joint lasted the longest under bending. Therefore these joints were used to find the best possible configuration of the joint. First the curvature of the segments was changed, with the current curvature the segments could not bend very easily. After a few iterations a curvature of 11 $mm$ was used in the design.

## B.3 Design of the manipulator

The first manipulator consisted of the joints stacked above each other with a 90 degrees rotation from the previous one, see Figure 35. This design worked as expected and could bent in the 2 DOF. However there were some improvement that could be made.

In this design the flexures can plastically deform because there is no limit of bending. In order to solve this, the shape of the joints were adjusted. The second improvement is the distance between each joint. If this is decreased more joints can be placed per length unit, which increases the flexibility. These improvements resulted in the sheath from Figure 37. The both sheaths have the same length but the second version has 8 more joints and can not plastically deform due to bending. This segment can be printed by an FDM printer without assemblage.

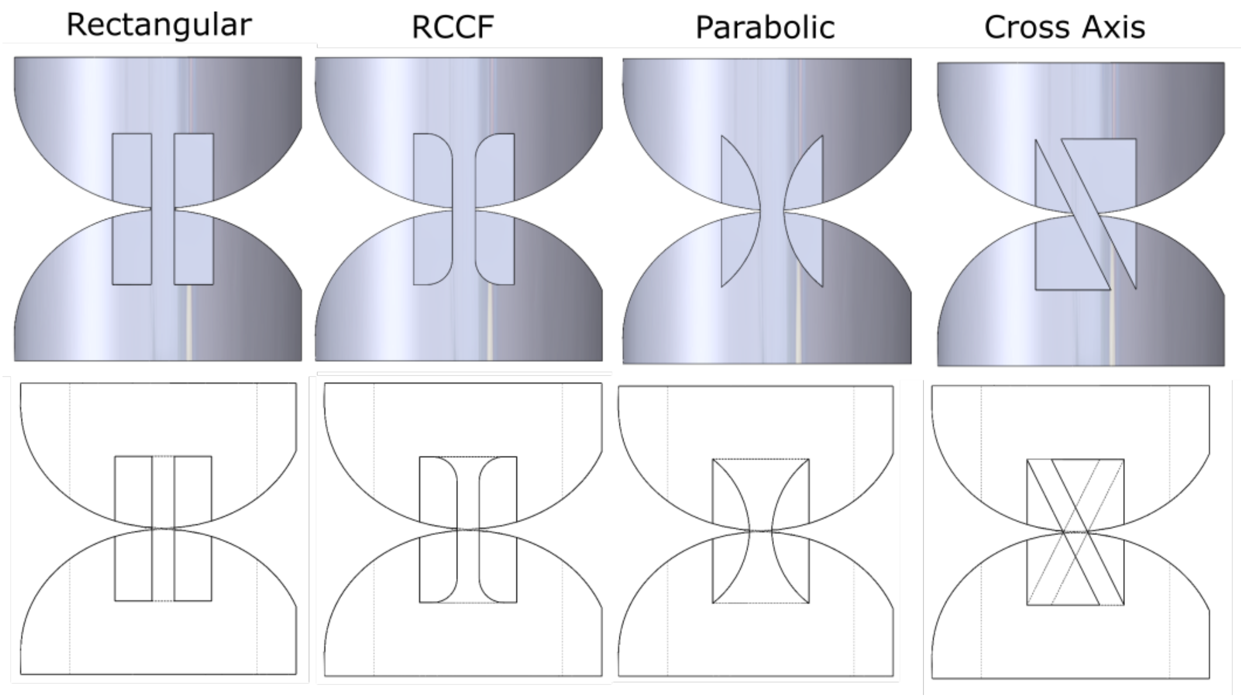



Figure 34: Four different compliant flexure designs integrated between the segments. A rectangular, right-circular corner-filleted (RCCF), Parabolic and Cross axis joint.

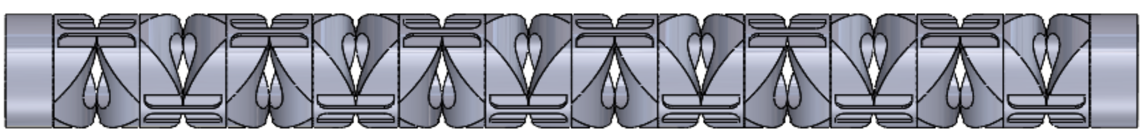


Figure 35: Sheath design that consists of multiple segments connected by a compliant flexure.

Figure 36: Improved Sheath design that consists of multiple segments connected by a compliant flexure.

# C Dimensions

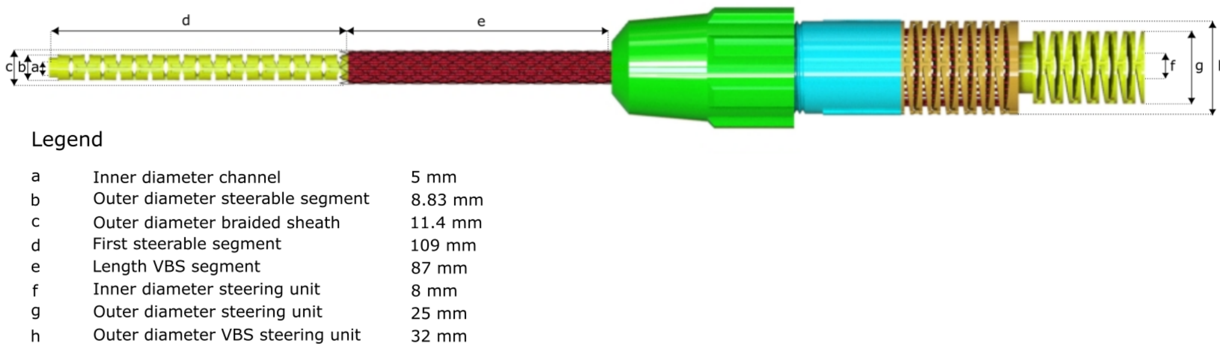



Figure 37: Schematic overview of the dimensions of the AlKingScope.

# D Costs

*Table 2: Materials and costs of the prototype.*

| Part | Material | Price per Unit | Amount | Unit Price |
|---|---|---|---|---|
| Frame (Black) | Polyactic acid (PLA) | € 34/2,2kg | 0,030 kg | € 0,46 |
| Steerable Segments and Units (Black) | Polyactic acid (PLA) | € 34/2,2kg | 0,038 kg | € 0,59 |
| Stiffening Cone (Transparant) | Polyethylene terephthalate glycol (PETG) | € 18,88/0,75kg | 0,016 kg | € 0,40 |
| Thrust Bearing | Chrome Steel | € 4,25 | 1 | € 4,25 |
| Braided Sheath | Polyethylene terephthalate (PET) | € 0,60/m | 0,11 m | € 0,07 |
| Stiffening Wires | Monofilament nylon | € 10,25/60m | 7,5 m | € 1,28 |
| Steering Wires | Polypropylene (PP) | € 15,44/300m | 2 m | € 0,10 |
| **Total Price** | | | | € 7,15 |

# E Technical drawings

The technical drawings of the components used in the AlKingScope can be found in this Appendix. First the whole assembly is shown in which the components are enumerated. The components can be found in the same order:

1 & 2) Distal and Proximal steerable segment

3) Stiffening cone

4) Frame

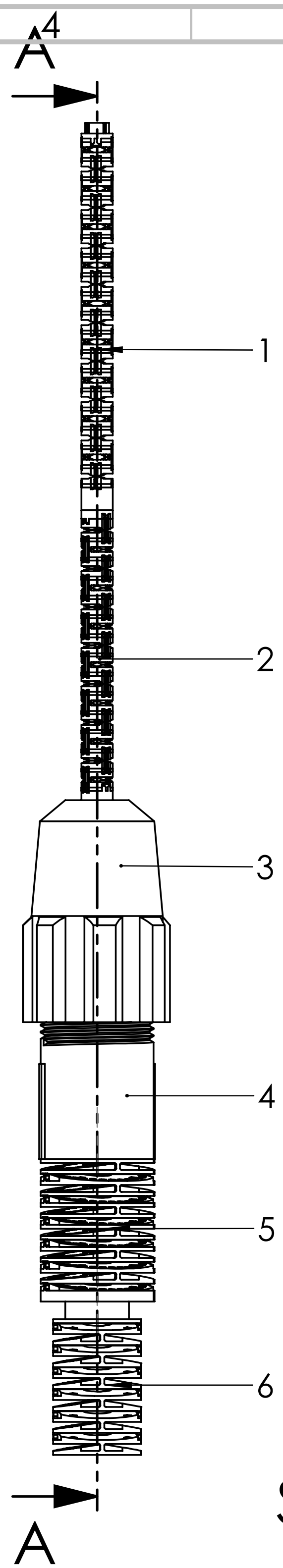
5) Distal steering unit

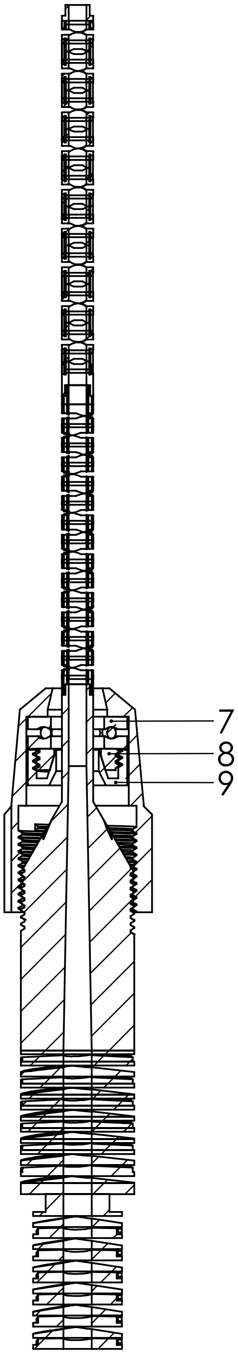
6) Proximal steering unit

7) Thrust bearing

8) Fixation screw

9) Fixation nut




SECTION A-A

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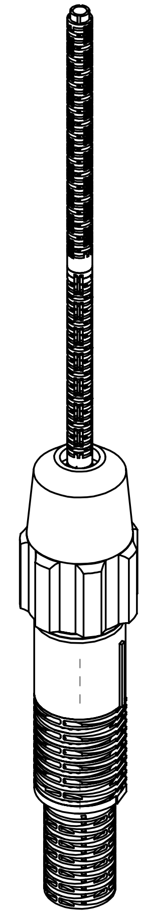

| Item No. | Description |
|---|---|
| 1 | Distal steerable segment |
| 2 | Proximal steerable segment |
| 3 | Stiffening cone |
| 4 | Frame |
| 5 | Distal steering segment |
| 6 | Proximal steering segment |
| 7 | Thrust bearing |
| 8 | Fixation screw |
| 9 | Fixation nut |

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AlKingScope

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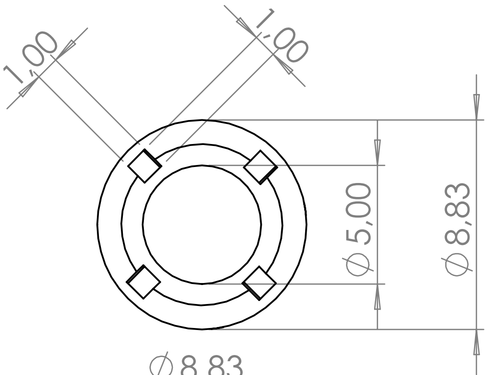


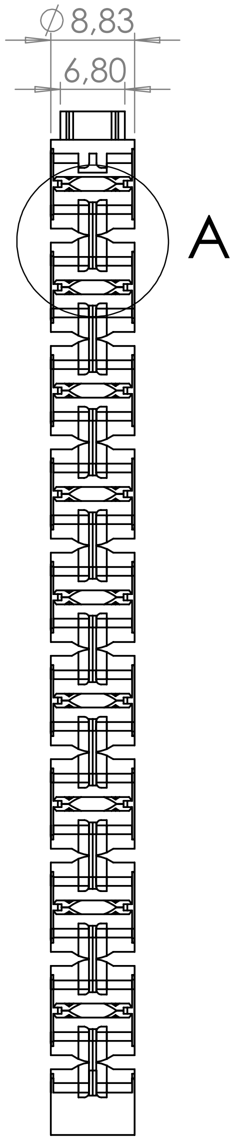


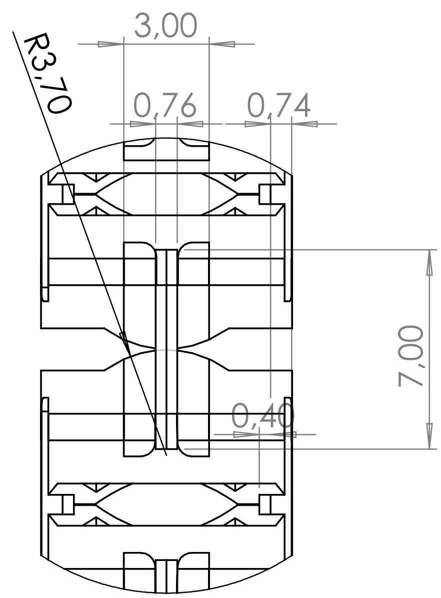


DETAIL A

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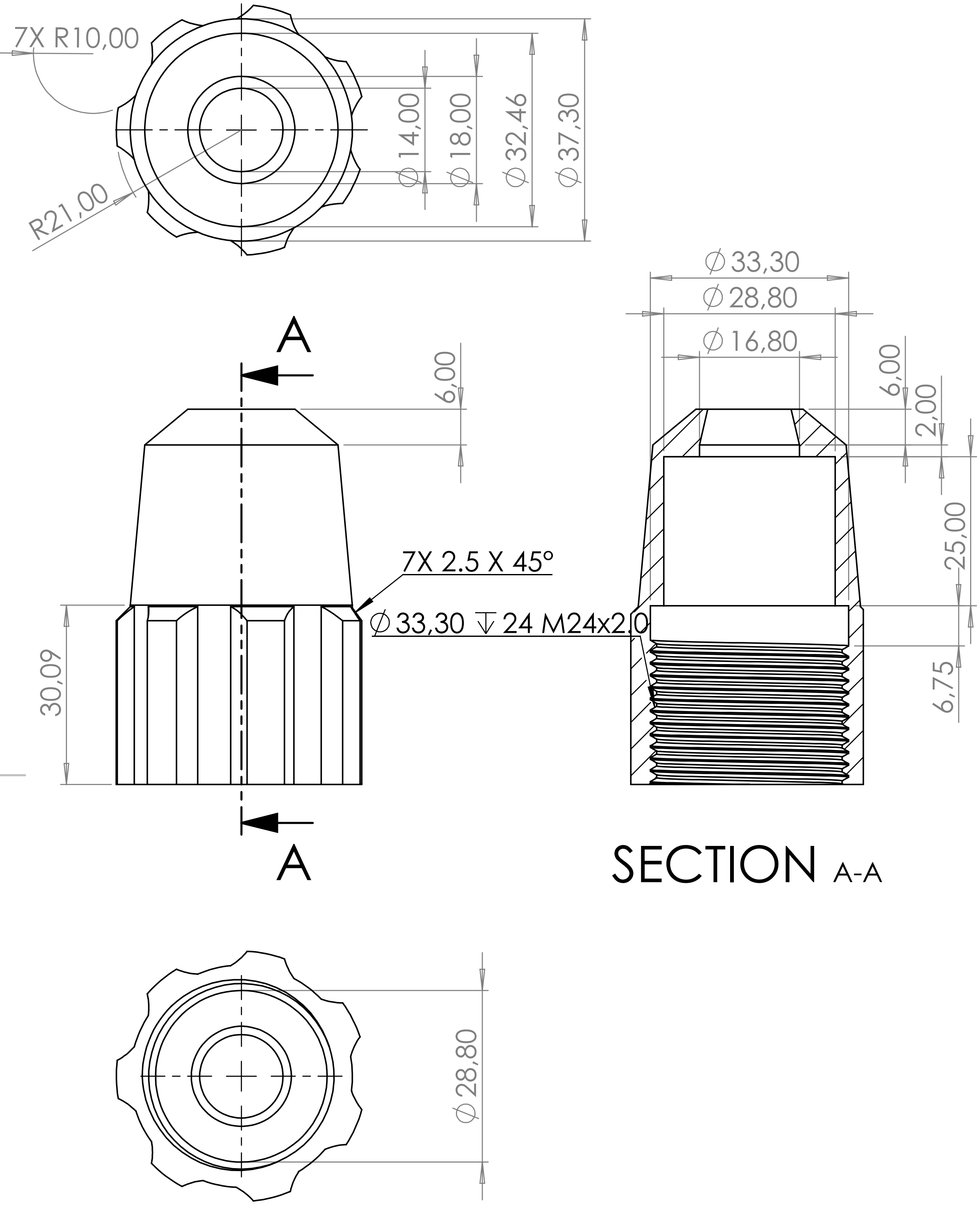


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# StiffeningCone

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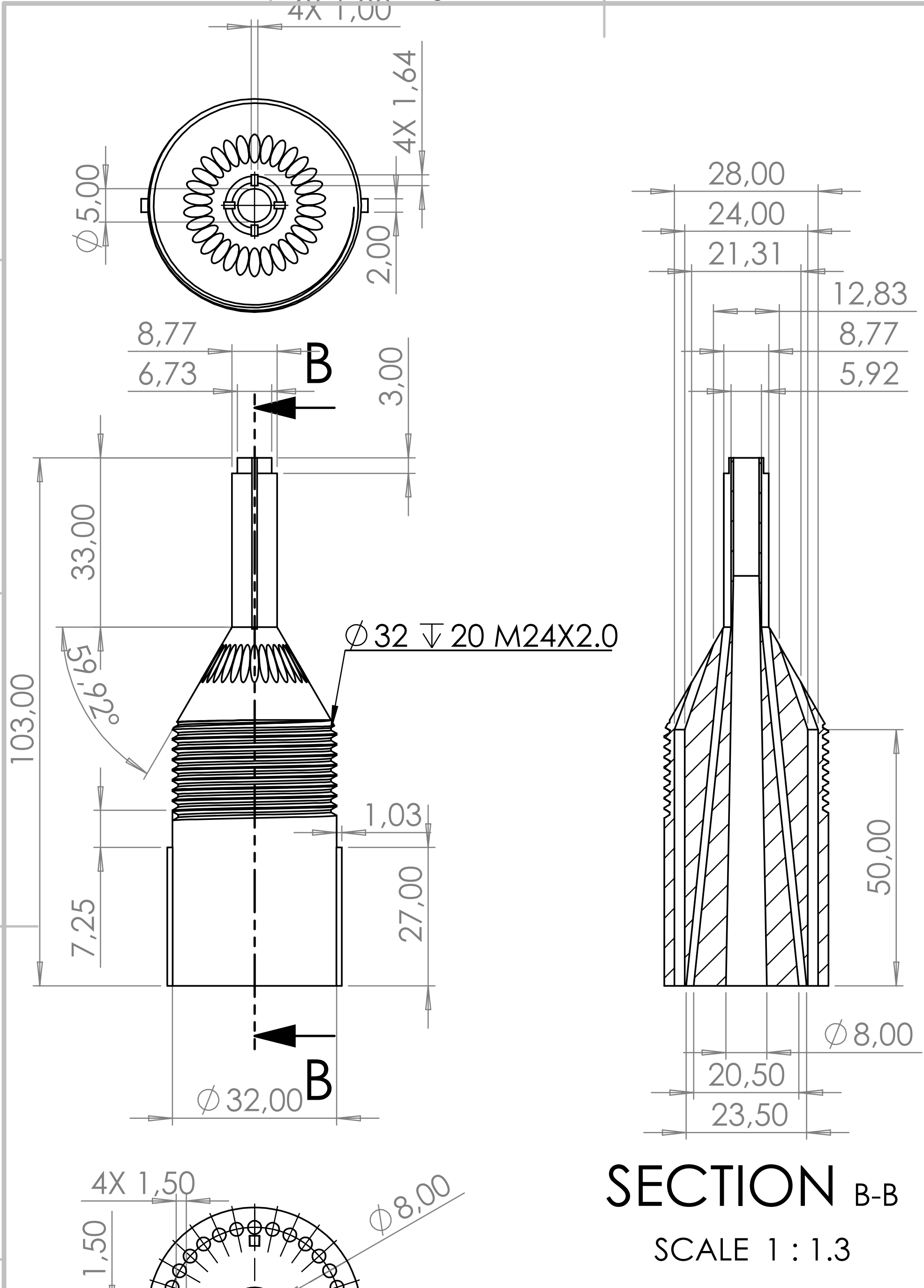


SECTION B-B

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# Frame

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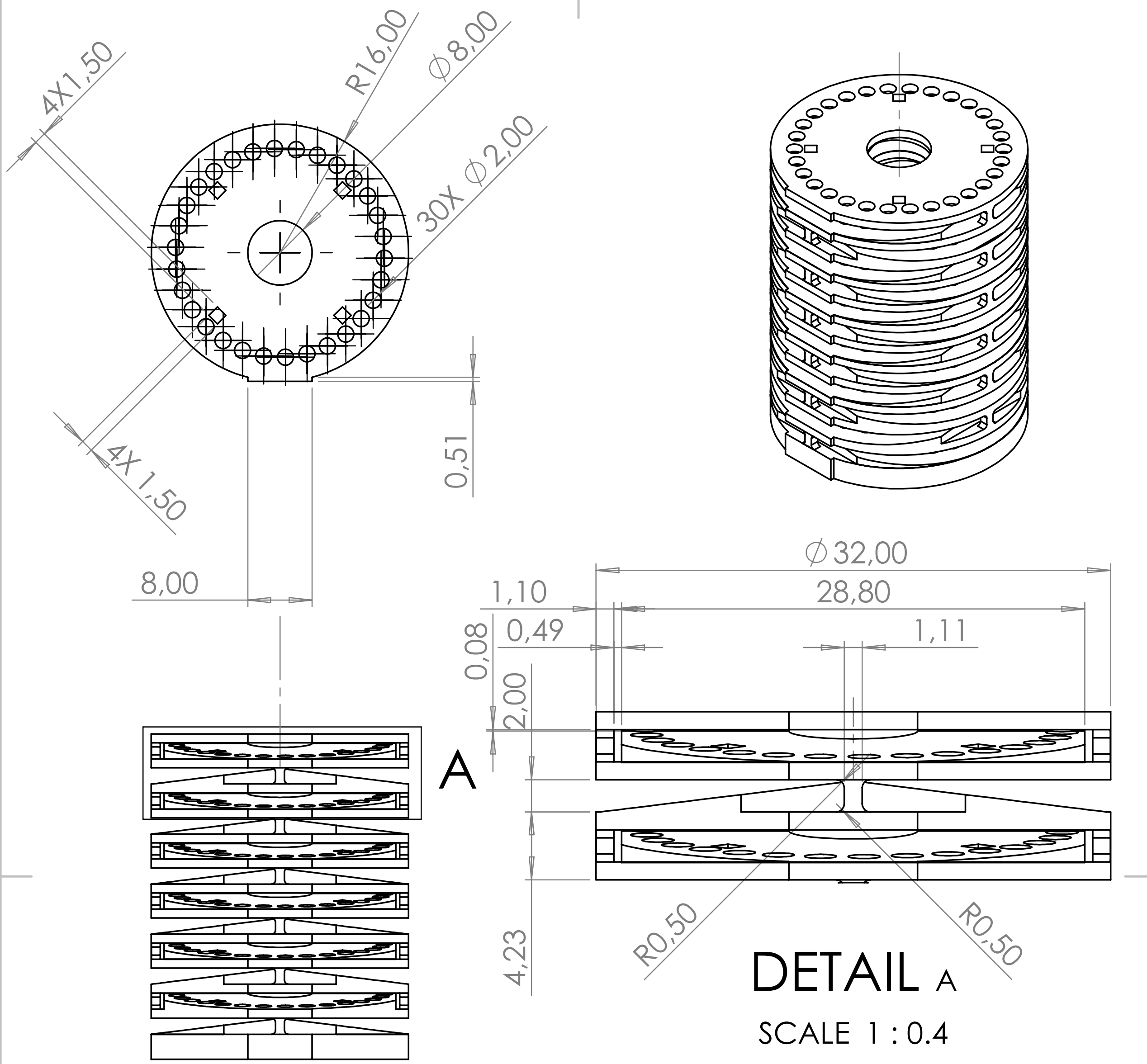


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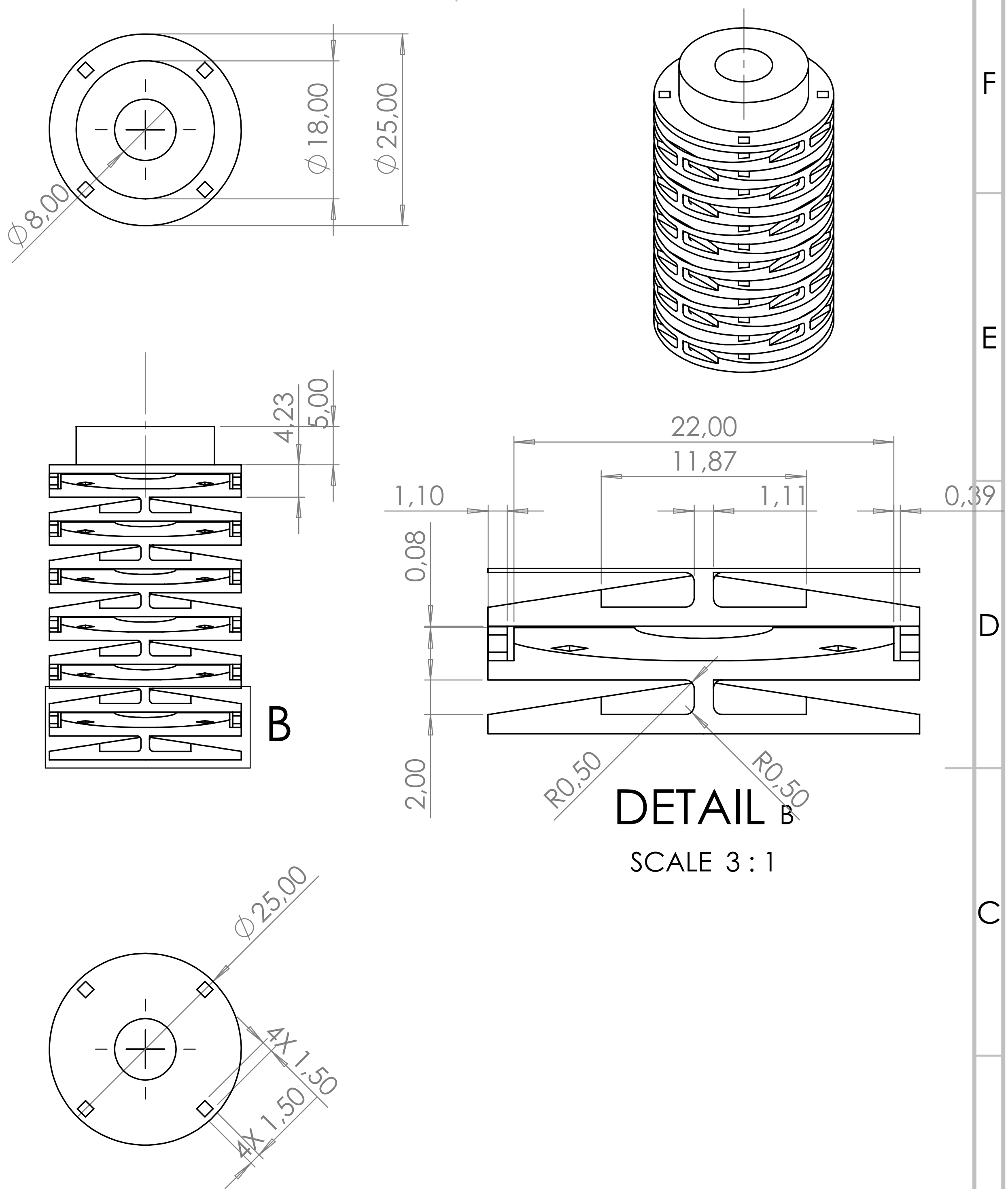


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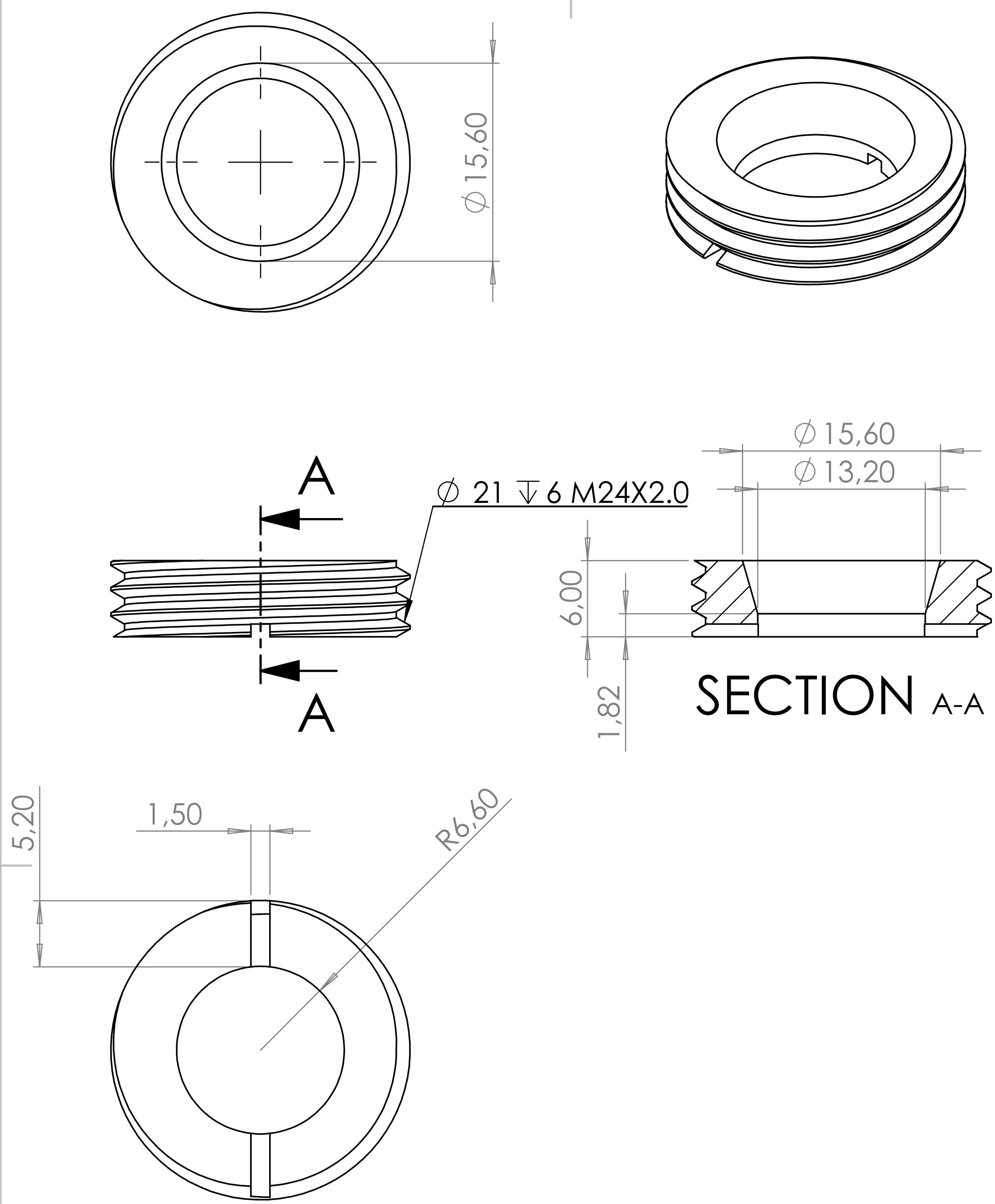


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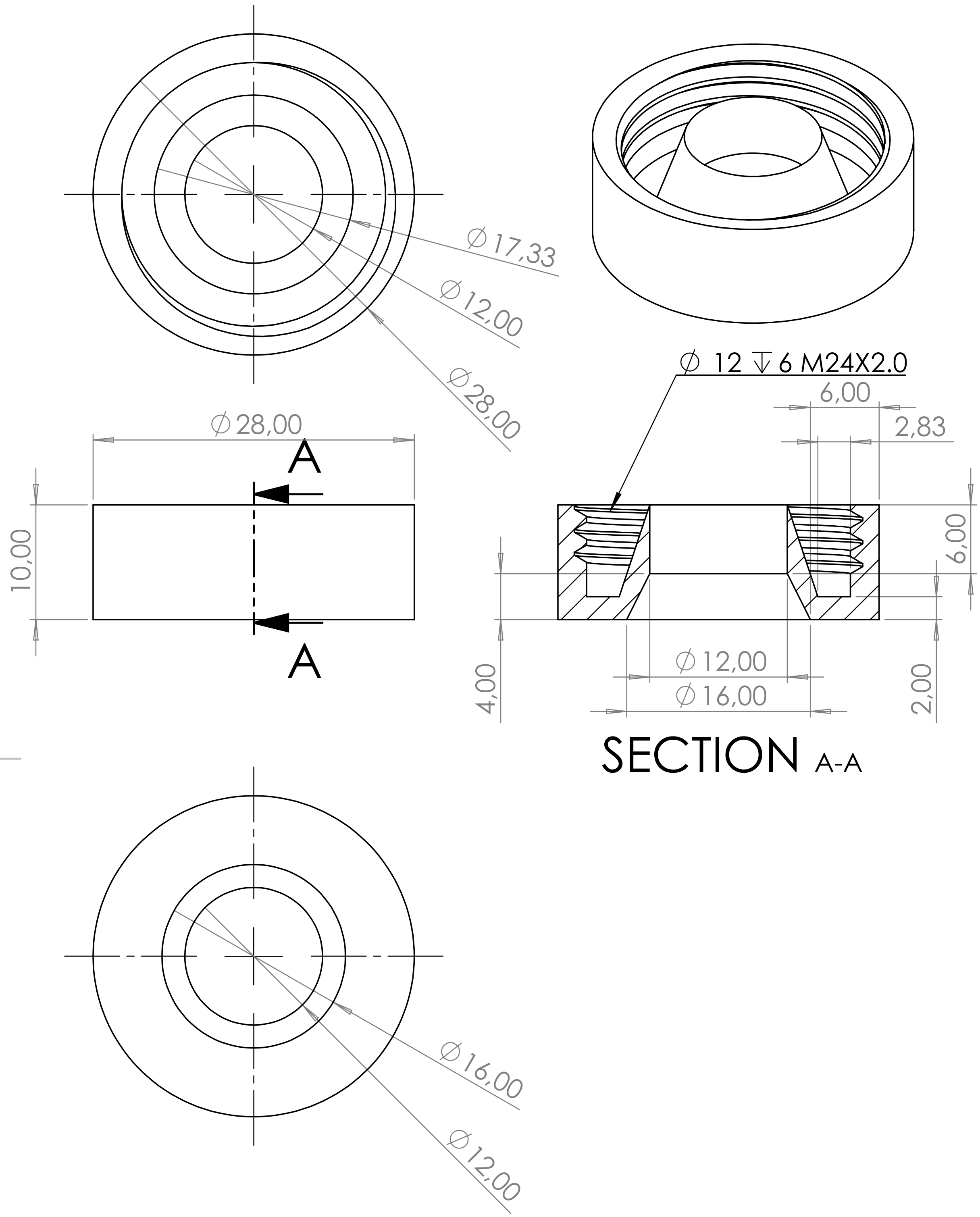


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