Preface

This thesis is the result of the Master project of Rob Pessers. The focus of the project, discussed in this thesis was on the design of a new steerable tip for laparoscopy. I have chosen for this project since I like the creative/out of the box reasoning, combined with the technological background. Lately my interests have also extended to the biologically inspired design. This reasoning I have also used during the construction of the solution space. An example of such a biologically inspired design is a concept where the cables are coupled. This coupling was inspired by the tendons controlling a human finger.

The result of this Master project is that a concept is presented in which the bending stiffness of the tip and the lifespan of the cables is equal or superior to the EndoWrist and MiFlex. Since the design still is in a conceptual phase, more research is needed to optimise the remaining variables. Hopefully this design will eventually result in a new commercially available laparoscopic instrument.

During my Master thesis I had my ups and downs. I would like to thank Katinka for sharing the ups and supporting me during the downs. It would have been much more difficult without you. I would also like to thank my family for their support during my study and Master thesis. Furthermore I really appreciate that Jenny Dankelman has taken time to provide me with feedback during the MISIT meetings. Finally I want to thank Paul Breedveld and Filip Jelinek for the creative discussions and for all their time and effort they have spent being my supervisors. Thanks to you all!
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Abstract

This thesis discusses the design of a new steerable tip for a laparoscopic instrument. A new tip design is required since current steerable tip designs have problems with the bending stiffness and the lifespan of the cables. Underaction is a main cause of the low tip stiffness. Since one of the design requirements is that the tip needs to be able to rotate in two perpendicular planes, the tip has two rotational degrees of freedom (DOF). The simplest way to fully actuate the tip and to rotate each DOF over 90 degrees in a clockwise (CW) and counter clockwise (CCW) direction is by using two cables for each DOF, resulting in a total of four cables in the tip.

A limiting factor of the lifespan of the tip is the fatigue of the cables. The fatigue is the result of the cables being forced to make a sharp bend during a rotation of the tip. To reduce the fatigue of the cables, the cables therefore need to be guided and to make a bend as large as possible in a \( \varnothing 5 \) mm tip.

As a prove of concept, two prototypes have been produced. From these prototypes it can be concluded that each DOF in the tip is able to rotate up to an angle of 90 degrees in CW and CCW direction. It can also be concluded that the tip is fully actuated. The bending stiffness of the tip therefore only depends on the stiffness of the cables and the rigid bodies of the tip. Since the cables and rigid bodies will be produced from steel, the bending stiffness of the tip will be high.

Considering the cables to have a diameter of 0.5 mm, the cables will be guided over a guiding with a radius of 3.48 mm. Compared to the EndoWrist, where the radius of the pulley with similar cables would be 2 mm, the radius is almost 1.75 as large. The result is that the lifespan of the cables in the new design will be superior.

1 Introduction

1.1 Introduction to laparoscopy

Open surgery is the traditional way of operating by making a long incision in the patient’s skin. This type of surgery results in relatively long recovery time and leaves much scar tissue [1] [2]. To reduce these inconveniences, minimally invasive surgery (MIS) was introduced. One of the minimally invasive procedures is laparoscopy. Laparoscopy is a procedure performed in the abdomen and was first performed on a human in the year 1910 by Hans Christian Jacobaeus [3]. For the surgeon to access the abdomen, small incision(s) need to be made in the abdominal wall or pelvis. These incisions are required for the insertion of trocars. The trocars are used to inflate the abdominal or pelvic cavity, as a portal for instruments and to provide an airtight seal around the instrument to keep the abdominal cavity inflated. The laparoscopic instruments are long and slender and have the goal to provide visual feedback, grasp or cut.

1.2 Laparoscopic instruments

In laparoscopy two types of instruments can be found, non-steerable and steerable instruments. Non-steerable instruments are instruments comprising a rigid shaft and tip. An example can be seen in Figure 1.1. During surgery, a non-steerable laparoscopic instrument has four DOF, illustrated in Figure 1.2. A disadvantage of these non-steerable instruments that the range of motion is limited to these four DOF. The tip of the instrument therefore is not able to move around a corner, making it more difficult for the surgeon to approach tissue from the side.

![Figure 1.1: Example of a rigid instrument, applied in MIS [4].](image1)

![Figure 1.2: The four DOF of non-steerable instruments inserted through the abdominal wall resulting in a fulcrum effect [5].](image2)
The steerable tip of the MiFlex can be seen in Figure 1.3. The tip of the MiFlex has eight hinges. Each hinge has one rotational DOF resulting in a total of eight rotational DOF in the tip. The motion of the tip is controlled by twelve steel cables running from a joystick, which are present in the handle of the instrument, to the end of the tip. The actuation of the cables is performed by the surgeon operating the joystick (Figure 1.4). The surgeon controls the angle of the joystick with respect to the handle. A rotation of the joystick initiates forces on the cables resulting in a bend of the tip.

Figure 1.3: Example of a steerable instrument [7].

Figure 1.4: A surgeon operating a steerable instrument by controlling the joystick [8].

The Da Vinci master-slave system is a robotic surgical system designed by Intuitive Surgical Inc. [6]. The EndoWrist (Figure 1.5) is the steerable tip of the Da Vinci system. The Endowrist has two rotational DOF acting in two perpendicular planes. Each DOF is individually controlled by a single cable. This cable is looped around a pulley and returns back to the place where it is actuated.

Figure 1.5: Tip design of the EndoWrist [6].

1.3 Steerability versus stiffness and endurance

Since the cables of the EndoWrist are continuously under tension there is no play of the cables in the tip. The bending stiffness of the tip therefore is dependent on the stiffness of the cables and the rigid bodies. Since the cables and the rigid bodies are produced from steel, the stiffness of these parts are high and therefore the EndoWrist has a high bending stiffness. Although the bending stiffness of the EndoWrist is high, the lifespan is only about 20 procedures [9]. A main cause of the short lifespan is due to the lifespan of the cables. The lifespan of the cables is reduced, since the cables of the EndoWrist are forced over relatively small pulleys, resulting in fatigue of the cables.

The steerable tip of the MiFlex has a different design. In this design the bending stiffness is not as high as the EndoWrist, but has a larger lifespan of the steel cables. In the MiFlex, the cables are not guided over small pulleys, but are guided via the eight DOF and an inner work of elements. Due to the large number of DOF, the cables do not make a bend as sharp as in the EndoWrist. Since the cables are not guided over small pulleys, the fatigue of the cables will be less, resulting in a superior lifespan of the cables. A drawback of the tip design of the MiFlex is that the tip turns out to have a low bending stiffness. During a laparoscopic procedure, external forces are applied on the tip of the instrument by the interaction between the instrument and the patient’s tissue. Due to the low bending stiffness of the tip and the external forces, the tip will result in an uncontrolled bending motion. As a result, the surgeon is no longer able to accurately control the angle of the tip.

A main cause of the low bending stiffness of the tip of the MiFlex is underactuation. Underactuation is a phenomenon where the number of DOF in the mechanism exceed the number of actuators. In the MiFlex there are eight DOF and twelve controlling cables. All twelve cables are attached to the very
end of the tip. As a result, only two DOF in the tip are actuated. Since only two DOF are actuated, the remaining six DOF are not actuated, resulting in the low bending stiffness of the tip, defined by the bending stiffness of the cables and the other internal tip components.

1.4 Objective of the research

The main goal of the project, discussed in this thesis, is to design a new steerable tip for a laparoscopic instrument, with a high bending stiffness. Since underactuation is a main cause of the low bending stiffness of the tip of the steerable instrument, the tip needs to be fully actuated. The second goal is to design the tip such that the lifespan of the cables are as large as possible. Since the lifespan of the cables is related to the bending radius of the cables, the bending radius needs to be as large as possible.

Besides these two goals there are also some additional design requirements. These requirements are that tip of the steerable instrument should:

- be mechanically actuated.
- be fully actuated.
- have at least two DOF working in two planes perpendicular to each other.
- have a range of motion of 90 degrees in both directions (±90°).
- be able to fit in a trocar of 5 mm.

1.5 Structure of the thesis

The structure of the thesis is as follows. Chapter 2 discusses two main methods of solving the problem of underactuation, ending with the choice of the best concept. In Chapter 3 the best concept is discussed in more detail. A planar design and prototype are presented in this chapter. Chapter 4 discusses the spatial design of the same concept. This design is able to rotate in two perpendicular planes. In Chapter 5 the options for different assumptions and future work are discussed. Chapter 6 ends with the conclusions of the project.

2 Solution space

2.1 Introduction to solution space

Underactuation the a result of having DOF in the tip which are not actuated. Underactuation can be solved by matching the number of DOF with the number of actuators. Since the tip needs to be able to rotate within two perpendicular planes and per plane needs to be able to make a rotation of ±90°, each DOF can be simplest controlled by two cables. One cable controls the clockwise (CW) rotation and the other for the counter clockwise (CCW) rotation of the joint. Since underactuation is the result of having unactuated DOF in the mechanism, there are two methods of solving underactuation:

1. Increase the number of actuators to the number of DOF in the tip.

2. Reduce the number of DOF in the tip to the number of actuators.

2.2 Increase number of actuators to tip DOF

The first method to solve underactuation is to increase the number of actuators to match the number of DOF in the tip. For example, when a tip comprises three DOF, six actuating cables are required in the tip in order to solve the underactuation. Figure 2.1 illustrates an example of such a mechanism. Due to the increase in DOF, multiple joints and joint actuators are required which increases the complexity.

![Figure 2.1: Increase the number of actuators to the number of DOF in the tip.](image)

Many different solutions have been found for this method. These solutions are not further elaborated in this thesis, since the method turned out to be not promising enough due to the disadvantages concerning high complexity. Solutions to solve underactuation by increasing the number of actuators to the number of DOF can be found in Appendix A.
2.3 Reduce tip DOF to number of actuators

The second method to solve underactuation is to reduce the number of DOF in the tip to match the number of actuators. For example, when only one actuation is present, the number of DOF also needs to be one. Figure 2.2 illustrates an example of such a mechanism. One of the design requirements is to have a steerable tip which can be operated in two perpendicular planes. Each plane needs to have at least one DOF; therefore the minimum number of DOF for the tip is two. The aim for this method is therefore to design a steerable tip comprising only one DOF per plane. Advantages, due to the low number of DOF are:

- small number of joints.
- small number of actuators.
- easily controllable.
- large bending stiffness of tip.

Figure 2.2: Reducing the number of DOF in the tip to the number of actuators.

Having only one DOF per plane has also a strong drawback. The steel cables, controlling the joint, will make a relatively sharp bend during rotation. The result is that the lifespan of the steel cables, and thus the lifespan of the instrument, will reduce due to fatigue. This problem can be reduced by a new tip design, which is discussed in this thesis.

3 Planar (2D) design

3.1 Tip design

3.1.1 Maximising bending radius

As discussed in Section 2.3, one of the problems of reducing the number of DOF in the tip is that the bending radii of the cables are reduced, decreasing the lifespan of the cables or require thinner more vulnerable and less stiff cables. Figure 3.1(a) illustrates this problem. The small bending radii of the cables are the result of the lack of a proper guiding in combination with the forces applied on the cables during the rotation of the joint. As can be seen in Figure 3.1(a), the guiding for the inner cable forces the cable to make a bend with a very small radius. The guiding of the outer cable is restricted to the guiding channels in the bodies. To increase the lifespan of the cables, the cables need to be guided over an arc with a larger radius. An example of the arc shape can be seen in Figure 3.1(b).

Since the lifespan of the cables is related to their bending radius, the bending radius needs to be as large as possible. To have a bending radius as large as possible the guiding element, supporting the cables, need to have a radius as large as possible as well. As can be seen in Figure 3.2, there are four guiding elements present in a single body of the joint: two inner (1 and 3) and two outer (2 and 4). If one of the radii is smaller than the rest, the guiding elements will guide that cable over a smaller bending radius, decreasing the lifespan. To give all the cables a maximal and equal lifespan, the radii of all the guiding elements therefore need to be equal and as large as possible. In order to find the maximum bending radius, the cables are assumed to be infinitely thin. The result of this design can be seen in Figure 3.2. The cable thickness will be included in Section 3.3. In Figure 3.2 the numbers 1 to 4 can be seen relating to the arcs of the guiding elements. The arcs are related as follows:

- Radii of arcs 1, 2, 3 and 4 are equal.
- Arc 1 is tangent to arc 2 and 3.
- Arc 2 is tangent to a vertical line running at the width of the instrument.
Arc 4 is tangent to arc 3 and a vertical line running at the width of the instrument.

Figure 3.2: Maximising bending radius when infinitely thin cables are applied.

Range of motion

One of the design requirements is that the tip needs to be able to make a rotation of 90° in both directions (±90°). To be able to guide the cable throughout these angles, the four guiding elements of Figure 3.2 are required. The new joint design at different angles (-90°, 0° and +90°) can be seen in Figure 3.3. When the tip is in its straight position (0°) both cables run partly over the outer guidings (2 and 4). The trajectory of these cables is indicated by the black lines. In the -90° angle, the right cable will partly run over the outer guiding element (4) and the left cable partly over the inner (1). These cables are indicated by the green lines. At an angle of +90°, the right cable will run over the inner guiding element (3) and the left cable over the outer guiding element (2). These cables are indicated by the red lines.

The design of the guiding elements depends on the relations of the guiding elements and the required range of motion. At the maximum angle, the cable still needs to have a smooth transfer going from one body of the joint to the other. In order to control the smooth transfer, the outer guiding elements, arcs 1 and 3 of Figure 3.3, need to have a combined angle of 90°. Due to the symmetrical design and a need for a smooth transfer of the cable in the maximum rotation, angle α needs to be at least 45°. When α is smaller than 45°, the cables could not be tangent to both of the inner guidings at the maximum joint rotation. The result would be that the cable is forced to rotate around a sharp point where the guiding stops, resulting in a locally small bending radius of the cable. When α is larger than 45°, this problem does not occur. However, the drawback of increasing angle α to an angle larger than 45° is that the radius of the arc would have to decrease in order for the guiding body to fit in the width of the instrument. Therefore α is chosen to be 45°. The angle α is used for calculating the radius of the guiding elements (Figure 3.4). The radius R can be calculated as follows:

\[ R = \frac{W}{2} + B \]  

(3.1)

Where W is the width of the instrument and B is the horizontal distance between the centre-point of the radius of the inner guiding element to the closest outside of the instrument.

\[ B = A - \frac{W}{2 \tan(\beta)} \]  

(3.2)

\[ \alpha = 45° \]  

(3.3)

\[ \beta = \alpha/2 \]  

(3.4)

Where A is the vertical length of the inner guiding elements. Since α is 45°, A and B are equal. The angle β is half of α. The radius (R) of the guiding elements therefore is:

\[ R = \frac{W}{2} + \frac{W}{2 \tan(\beta)} \]  

(3.5)
\[
R = \frac{\tan(\beta) + 1}{2 \times \tan(\beta)} \times W \\
= 1.71 \times W
\] (3.6)

**Figure 3.4:** Calculation of the radii. \(\alpha = 45^\circ\), \(\beta = \alpha/2\), \(B = A\), \(W = \text{Width of instrument (5 mm for laparoscopic instrument)}\), \(R = \text{Radius of guiding}\).

As calculated, the radius of the guiding elements is 1.71 times the width of the instrument. Two common sizes for laparoscopic instruments are 5 mm and 10 mm. In this thesis the focus is on the instruments with a diameter of 5 mm since this is the most common size. The result is that the maximum radius of the guiding elements is 8.54 mm.

As discussed in Section 1.3, the EndoWrist has the disadvantage of fatigue of the cables. In case when the cables are assumed to be infinitely thin, the maximum diameter of the pulley in the EndoWrist is equal to the diameter of the instrument. For the 8.5 mm instrument, the pulleys can therefore have a maximum radius of 2.5 mm. With the new design, where the radius is 8.54 mm, the radius of the guiding elements is more than three times as large. The advantage of having a larger radius is that fatigue of the cables will reduce, increasing the lifespan of the cables.

**Moment arm**

Maximising the radius of the guiding elements comes with some drawbacks. When the joint is rotated to an angle of 90°, the outer cable will run through the point of rotation, as illustrated in Figures 3.2 and 3.3. As a result this cable has no moment arm with respect to the point of rotation anymore and therefore is not capable of generating a moment around the joint. The tip therefore is not able to rotate back to the straight position. Figure 3.5 illustrates the moment arms of the inner and outer cables during rotation. The moment arm is the distance between the cable and the point of rotation, where the cable runs tangent to the guiding element of both bodies of the tip.

**Figure 3.5:** Moment arm during rotation of 90°. Moment arm of outer cable turns zero at angle of 90°.

As illustrated in Figure 3.5, the moment arm for the outer cable reduces as the angle increases, introducing another drawback. Since the moment arm reduces, the instrument will become more sensitive to external forces. External forces on the tip of the instrument result in a moment around the joint. To keep the joint in place, an equal but opposite moment must be generated by the cables. Due to the small moment arm of the outer cable, the force on that cable will become increasingly larger, reaching a theoretical infinite at the joint angle of 90°. Due to the high forces on the outer cable, the cable will easily deform, causing a low bending stiffness of the tip.

**Figure 3.6** shows the lengths of the cables during rotation. The cable length is the length of the cable as illustrated in Figure 3.3. A drawback of this design is that only a small displacement of the cable is required to operate a large angle (Figure 3.6). For example, when the joint is in the straight (0°) position, the length of the outer cable in the joint is 30.78 mm. At a joint angle of +90°, the length of the same cable will be 32.12 mm. The 90° of rotation therefore is controlled by a length difference of the cable of only
1.34 mm. For a rotation from 50 to 90° this length difference is even 0.12 mm. This length difference is very small, meaning that the joint will be sensitive to play and deformation of the cables. The calculations of the moment arm and cable lengths can be found in Appendix B.

### 3.1.2 Equalising moment arms

To solve the problem of the zero moment arm and to minimise the influence of play and deformation of the cables a different type of joint is chosen. Instead of having a fixed point of rotation, a joint is preferred in which the point of rotation changes during rotation. By changing the point of rotation, a moment arm can be obtained throughout the joint rotation, even at an angle of 90°. A joint having this property is a rolling joint. A rolling joint is a joint which uses one or two arc-shaped surfaces rolling over each other (Figure 3.7). Since the two surfaces roll over each other, the point of contact and therefore the point of rotation will change during rotation of the joint.

As can be seen in Figure 3.7, the rolling surfaces are cylindrically shaped. The size of these cylinders is based on the width and the maximum angle of rotation of the tip. Due to the rolling motion of the two surfaces, the angle of the circular surface $\gamma$ is equal to the maximum joint angle (90°). The other variable is the width of the instrument. The larger the width of the instrument, the larger the radius of the rolling joint. The radius of the rolling joint can be calculated by:

$$ R = \frac{W}{2 \sin \left( \frac{\gamma}{2} \right)} $$

Since the width of the instrument is 5 mm and $\gamma$ is 90°, the radius of the rolling joint is 3.54 mm.

The problem of the zero moment arm occurred at the maximum angle. Therefore a new design requirement of the joint is introduced. The requirement states that ‘at the maximum angle of 90°, the moment arms for the inner and outer cable need to be equal’. Equalising the moment arms at an angle influences the radius of the guiding elements. Compared to the previous design of the guiding elements, two changes need to be made to the design in order to have the moment arms equal. The relation in Figure 3.2, in which arcs 1 and 3 are tangent, needs to be replaced by the relation of having equal moment arms.

The new relation of having equal moment arms states that the distance between the point of rotation and both cables are equal at 90°. Due to the tangent relation between the cable and the guiding elements of the different bodies in the tip, the only possible solution is when the moment arms of the inner and outer cables are 2.82 mm. This value is obtained from a Solidworks model of which an illustration can be seen in Figure 3.8. A drawback of this design is that, by equalising the moment arms, the radius of all the guiding elements will become smaller, reducing the lifespan of the cables or requiring thinner and therefore more flexible cables. As can be seen in Fig-
Figure 3.8, the radius of the guiding elements for a 5 mm tip will be 3.98 mm. The relation between the width of the instrument and the radius is:

\[ R = 0.8 \times W \]  

(3.8)

Compared to the radius of the guiding elements of Section 3.1.1, the radius is reduced by more than a factor 2 to 0.8 times the width of the instrument. Compared with the EndoWrist, in which the radius is 0.5 times the width of the instrument, the radius of the guiding elements are still larger by a factor 1.6, resulting in a superior lifespan of the cables.

Figure 3.8: New joint design at an angle of ±90°.

The length of the moment arms for the inner and outer cable, during the rotation of the joint, can be seen in Figure 3.9. These lengths are obtained from the Solidworks model at angles between 0° and +90° with increments of 10° (Appendix C). Due to the symmetry in design of the guiding elements, the moment arms for 0° to -90° will be equal. As can be seen in Figure 3.9, the maximum difference in moment arm between the inner and outer cable is only 0.16 mm. The difference between the mean value of the inner and outer moment arms (Figure 3.9) is only 0.084 mm. These small differences are considered to be negligibly small and therefore the moment arms can be considered to be equal. The forces acting on the cable, required to rotate the joint, are therefore also considered to be equal to the CW rotation. A CW rotation therefore requires virtually the same force as the CCW rotation.

Since the moment arms of the cables are nearly equal, the forces, acting on the cables, are also nearly equal. The result is that the bending stiffness of the tip in the CW and CCW directions is nearly equal at every joint angle.

During surgery, external forces are applied on the tip of the instrument by the tissue of the patient. The joint in the tip needs to be resistant to these external forces. Since the bending stiffness of a rolling joint depends on friction and since the contact surface between the bodies is small, the joint will not be able to withstand all forces. The low resistance against the external forces can lead to slip between the bodies resulting in uncontrolled behaviour of the joint. To solve the problem of the slip, gears are applied (Figure 3.10(a)).

The gears prevent the bodies from slip with respect to each other. Gears are designed to withstand and transfer tangent forces. If the gears would replace the rolling joint, radial forces, as a result of the cables keeping the joint together, would also be applied on the gears. These forces, acting on the teeth of the joint, could jam the joint, deform or even break the teeth. To prevent the radial forces to act on the gears, both a gear and a rolling joint are applied in the joint. Combining the gear and rolling joint splits the forces; the tangent forces are applied on the gear and the radial forces on the rolling joint (Figure 3.10(b)). Since there should not act any radial force on the gear, the gears need to be designed such that the contact diameter between the gears is equal or smaller than the diameter of the rolling joint. For the design of the gears, gears with an involute profile are applied. An
advantage of using involute gears is that they can be designed based on the contact diameter, also known as the pitch diameter [10]. The pitch diameter needs to be smaller than or equal to the diameter of the rolling joint (7.07 mm). The design parameters of the involute gear profile can be found in Appendix D.

The new joint design is assumed to be planar and therefore forces are applied in only one plane. Without cables, there are two DOF present in the tip, one rotational and one translational. The translational DOF is eliminated by the cables and the rotational DOF is required to make the bend of the tip. The assumption of having DOF and forces acting in only one plane is not realistic for the joint since it is being applied in a laparoscopic instrument. In this instrument external forces are applied on the joint from all directions. The joint therefore needs to be considered as a 3-dimensional joint. Considering the joint as 3-dimensional, the joint results in two additional DOF, one rotational (around x-axis) and one translational (z-axis), as can be seen in Figure 3.10(c). When external forces are applied on the tip, these additional DOF will result in an uncontrolled behaviour of the tip. To eliminate the additional DOF, a protrusion was made in one of the bodies and a cut out in the other body, matching the protrusion (Figure 3.11). The effect of the combination of the cut out and protrusion is that the number of DOF of the joint are reduced to one, which is required.

3.2 Handle design

The joint design of the 5 mm tip has been discussed in Section 3.1.2. The joint is a combination of a rolling joint and a gear. The cables are guided by the guiding elements, having a maximum radius (3.98 mm). The tip of the planar design is actuated by only two cables. For the surgeon to control these cables, the cables are attached to the handle of the instrument.

One way of controlling the tip joint is by duplicating the bodies of the tip into the handle. Duplicating these bodies leads to a kind of parallelogram motion of the cables. Since the bodies are identical, the length of the outer cable in the handle is identical to the outer cable in the tip. The same is valid for the inner cables. The total cable length of the left side of the instrument is the sum of the inner cable in the handle, the cable in the shaft and the outer cable in the tip. Due to symmetry, the length of the right cable is identical to the left cable (Figure 3.12). Since the cable length of the shaft is always equal, the cable length of the shaft is excluded from further
calculations. The length of the cables for both the left and right side can be seen in Figure 3.13.

As can be seen in Figure 3.14 a CW rotation of the handle results in a CW rotation of the tip. This motion is caused by pulling forces of the cables and increasing/decreasing length of the cable trajectory in the tip and handle (Figure 3.15). For example, when the handle is rotated CW from a straight position, the trajectory of the outer cable in the handle increases. Due to this increase, the cable starts pulling on the inner cable in the tip, causing the joint to rotate CW as well. This rotation of the tip leads to a reduction of the cable trajectory of the inner cable in the tip. The reduction of the inner cable trajectory in the tip is possible since the cable is able to slide over the guiding elements. The rotation of the tip stops when the increased length of the outer cable trajectory in the handle is equal to the reduced trajectory length of the inner cable in the tip. Since the outer cable of the tip is attached to the same body in the handle as the inner cable, a CW rotation of the tip leads to an increase in cable trajectory for the outer cable in the tip. Since the handle was rotated CW, the cable trajectory of the left cable in the handle will decrease. The increase in cable trajectory in the tip is possible due to the decrease of cable trajectory of the inner cable of the handle.

Since the design of the tip and handle are based on the maximum positions of $\pm 90^\circ$, the handle should not be able to rotate over an angle larger than $90^\circ$. A physical stop has therefore been designed in the handle (Figure 3.16). Since the tip is controlled by the handle, the angle of the tip therefore is also limited to $\pm 90^\circ$.

**Slack on cables**

Duplicating the bodies of the tip to the handle comes with the drawback that the cables are slackened during the rotation of the handle and tip. The slack in cable leads to play in the tip. During a CW rotation, the cable length of the outer cable in the handle increases and the inner cable in the tip decreases. The decrease of the cable length in the tip is larger than the increase of the cable length in the handle. The result is that the sum of the outer cable of the
handle and the inner cable of the tip is smaller than in the straight position and therefore is longer than required, resulting in slack of the cables.

Due to the symmetry in the design the length of the left and right cables, running from the handle to the tip, will always be equal to each other. The slack of the cables therefore is also equal. As can be seen in Figure 3.17, the maximum slack on the cables, for a 5 mm wide tip, is 0.18 mm. The slack of the cables results in play in the tip. Figure 3.18 illustrates the angular play of the tip at certain handle positions. Since the maximum play is ±3.6° the play on the joint is assumed to be negligibly small. The bending stiffness of the tip therefore is only dependent of the stiffness of the cables and rigid bodies in the tip.

3.3 Prototype

The design of the 5 mm tip and handle has been discussed in Sections 3.1 and 3.2. In these sections the cables have been assumed to be infinitely thin in order to find the optimal design for the handle and tip. Since infinitely thin cables do not exist in reality, the cables need to have a certain thickness in the prototype. The design was made such that cables of Ø0.5 mm should fit in the instrument. The thickness of the cables have a negative influence on the radius of the guiding elements. The radius of the guiding elements reduce with the cable diameter. For 5 mm instrument and a cable with a diameter of 0.5 mm, the radius of the guiding elements would reduce from 3.98 mm to 3.48 mm. Compared to the
EndoWrist, where an 0.5 mm cable would reduce the radius of the pulley to a radius of 2 mm, the radius is still almost 1.75 times as large, meaning that the lifespan of the cables is still superior.

Due to the complex geometry and the size of the joints, it was decided to produce the prototype via rapid prototyping. Rapid prototyping (also known as 3D printing) is a technique where layers of plastic are printed on top of each other, creating 3-dimensional bodies. Since the stiffness of the tip also depends on the stiffness of the cables, steel cables are preferred to actuate the tip. However, since the prototype is made out of plastic, steel cables would cause wear of the guiding elements since the cables slide over the guiding elements. To reduce the wear of the guiding elements, the choice was made not to use steel cables for the prototype. Instead Dyneema cables were applied, since Dyneema is known for its cable strength [11]. Since the Dyneema cable is synthetic, the prototype will not wear down as fast as with steel cables. The Dyneema cable used for the prototype has a diameter of 0.5 mm and a breaking load in tension of 70 kg.

In order to control the tip and to have symmetrical forces on the joint, two looped cables are used. Looping the cables also increases the stiffness of the tip to an equivalent of two cables. The cables are looped over a guiding as can be seen in Figures 3.20 and 3.21. The tensioning and fixation of the cables is done in the handle by a clamping plate.

The prototype was made to prove that the concept works and to find any remaining challenges in the design. A 5 mm prototype, produced by rapid prototyping, would be very fragile. The size of the prototype therefore is increased to a width of 30 mm. Since the width of the instrument is related to the radius of the rolling joint (Equation 3.7) and the guiding elements (Equation 3.8), these bodies were equally scaled. The shape of the joints will therefore stay the same. The 30 mm prototype can be seen in Figures 3.20 and 3.21.

3.4 Results

As expected, the prototype (Figures 3.20 and 3.21) is able to rotate over an angle of ±90° which is one of the requirements.

The point of rotation of the joint changes during its rotation, resulting in a continuously non-zero moment arm for both inner and outer cable in tip and handle. The result is that only small forces are required to rotate the tip.

Another result which can be seen in the prototype is that the cable lengths of the left and right cable remain equal. The fact that the cable lengths are equal can be seen during the rotation of the handle. Both cables will have approximately the same slack on the cables, which is an indication of the cable lengths.

As expected, the slack of the cable is a minor issue between the interaction of the joint in the tip and handle. As can be seen in Figures 3.19(a) and 3.19(b) the play in the joint, positioned in the maximum angle of 90°, is approximately ±4°. As discussed in Section 3.2, the expected play in the joint was ±3.6°. This difference is assumed to be negligibly small.

When the handle is placed in a certain angle, the tip will have some play. When an external force is applied on the tip (as illustrated in Figures 3.19(a) and 3.19(b)) the joint will rotate till the cable is under tension. Increasing the force on the tip, results in a negligibly small additional rotation in the tip. This additional rotation is the result of the stretch of the cables.

![Figure 3.19: Results of play of the joint. (a) A proximal 4° in CW direction. (b) A proximal 4° in CCW direction.](image-url)
Figure 3.20: Prototype of planar model. The angle of the tip/handle is 0°.

Figure 3.21: Prototype of planar model. The angle of the tip/handle is 90°.
4 Spatial (3D) design

4.1 From planar to spatial

Chapter 3 has discussed the planar design of the new steerable instrument. In this design the tip only works in a single plane. The handle of the planar design is a duplication of the bodies in the tip. The rotation of the tip is coupled to the rotation of the handle via cables. Only two cables are present in the tip. These cables run from the beginning of the handle to the end of the tip and are looped through the tip, back to the handle.

One of the design requirements is that the tip needs to be able to have a spatial motion, acting in two perpendicular planes. Since the planar design is only working in a single plane, bodies need to be added to the design to meet this requirement. The design needs to be such that the rotation of the joint is perpendicular to the one of the planar design.

An increase in DOF in the tip also leads to a similar increase of DOF in the handle. The additional bodies, required for the additional DOF, are identical to the bodies of the planar design. Sketches of the new, spatial, design can be seen in Figure 4.1.

The increase of bodies will result in an increase of the number of cables, required to control the two joints in the tip. In the planar design two looped cables are applied to control the rotation of the tip. One cable controls the CW and the other the CCW rotation. The spatial design has two DOF in the tip. To prevent underactuation of the tip, the number of actuators/cables need to be increased. Two additional cables are used to control the additional DOF of the tip. The total number of cables in the tip therefore is four. All four cables are looped at the end of the tip. The blue cables in Figure 4.1 control the rotation of the green bodies (HJ2 and TJ2) and the grey cables the rotation of the red bodies (HJ1 and TJ1).

Since all cables run through all the bodies of the instrument, some adjustments need to be made in the design of the trajectory of the cables. Instead of having a single cable running through the bodies, the spatial design has two cables next to each other as can be seen in Figure 4.1. The size of the channel, guiding the cables through the bodies, therefore is increased to 1x4 mm. As shown in Figure 4.1, the cables need to make a twist in order to go from the red body to the green body. A close-up of the twist is shown in Figure 4.2.

Since all cables are attached to the handle and looped at the end of the tip, one would expect that a rotation of the red bodies would influence the rotation of the green bodies and vice versa. Due to the symmetry in design this is not the case.

Figure 4.1: Sketches of the spatial design. The red parts are positioned as in the planar design. The green parts are the additional parts introducing the spatial motion of the tip. The blue cables control the rotation of the green parts and the grey cable rotation of the red parts.
A rotation of the green body of the handle requires additional cable length for the outer cable in the handle, resulting in a pulling force on the cable. The cables at the red bodies (both handle and tip) are not able to provide this additional cable length since the cables run on both sides of the point of rotation of the joint. The result is that the forces, acting on the cable, only cause the green body of the tip to rotate. The rotation stops when the required additional cable length of the outer cable in the handle is equal to the shortening of the inner cable in the tip. The rotation of green body of the tip results in a required increase of cable length of the outer cable of the green body of the tip. This increase in cable length is possible due to the decrease of the required cable length of the inner cable of the green body of the handle.

A rotation of the red body in the handle has a different result. The rotation requires the outer cables of the red body in the handle to increase in length. The only cables capable of providing this increase in cable length are in the red body of the tip. The rotation of the red body in the tip results in a decrease of required cable length for the inner cable. The decrease is possible since the required length of the inner cables of the red body in the handle will decrease. Since the motion of the two DOF in the tip are individually controlled, the tip is therefore fully actuated.

As discussed in the Section 3.2 there is minor slack on the cables during the rotation of the handle. As a result, there will be some rotational play present in the joint. For the spatial design, the slack on the cables and play on the joint are similar. The difference between the two designs is that the play of the planar design acts in a single plane whereas the play of the spatial design acts in two planes. The result is that the joints of the red bodies will have an angular play of $\pm 3.6^\circ$ in a single plane. The green bodies of the tip are placed on top of the red bodies. As a result, the play of the red bodies will also act on the green bodies. Additional to this play, the green bodies themselves will have also play of $\pm 3.6^\circ$. The green body at the end of the tip will be affected by play in two perpendicular planes. As in the planar design, this play on the joint is assumed to be negligibly small and therefore the bending stiffness is dependent on the stiffness of the cables and rigid bodies in the tip.

4.2 Prototype

To verify whether the spatial design works, a prototype has been produced (Figure 4.3). Just as in the prototype of the planar design, the width of the tip is 30 mm, it is produced by rapid prototyping and Dyneema cables are applied for the actuation.

The cables start at the base of the handle, run through all the bodies, are looped at the end of the tip and return to the base of the handle, where they are fixed. The cables are fixed by clamping them between the handle and a clamping plate, fastened by a nut and bolt.

4.3 Results

As expected, the DOF in the tip are individually controlled by the DOF in the handle. The rotation of a single joint in the handle only actuates the matching joint in the tip. Besides individual actuation, the joints of the tip can also be actuated simultaneously. The spatial motion of both the DOF is $90^\circ$ in both directions.

The forces, required to actuate the joint in the tip (TJ1 and TJ2) (Figure 4.1) are not equal. To rotate TJ1, the cables will only slide over the guiding element of HJ1 and TJ1. However, in order to rotate TJ2, the cables need to slide over the guiding elements of HJ2, HJ1, HJ1 and TJ2. Since the cables slide over a longer trajectory, there will be more friction between the cables and the guiding elements. As a result, the required forces to rotate TJ2 are larger than TJ1.
Figure 4.3: Prototype of the spatial design.
As already discussed in Section 4.1, minor play exists in the joints. The play of TJ1 is similar as in the prototype of the planar design. The play of the other joint also is approximately \( \pm 3.6^\circ \). The play of the TJ1 however also affects the other joint, TJ2. Due to the relatively large length of the bodies, a small rotation leads to a relatively large displacement of the end of the tip (TJ2).

5 Discussion

5.1 Evaluation of current design

5.1.1 Modifying range of motion

One of the design requirements is that the tip should have a range of motion of \( 90^\circ \) in both directions. As already discussed in Section 3.1.1, the range of motion influences the size of the radius of the guiding elements. When the range of motion is decreased, the cables will need to be guided over a smaller angle, resulting in an increase of radius of the guiding elements. A drawback of this increase is that the overall length of the bodies in the tip will also increase, making it more difficult to manoeuvre the tip in small spaces.

Table 5.1 gives a few examples of different ranges of motion for a 5 mm tip. The required range of motion of the new tip design is \( \pm 90^\circ \). For this range of motion, the radius of the guiding elements is 3.98 mm and the length of a single body of the joint is 7.84 mm. As shown in Table 5.1, a decrease of the range of motion to \( \pm 60^\circ \) results in an increase in the radius of the guiding elements (6.57 mm) and body length (9.89 mm). Increasing the range of motion to \( \pm 120^\circ \), results in a decrease of radius of the guiding elements (3.14 mm) and body length (7.23 mm).

Table 5.1: Radii of guiding elements and length of elements during different ranges of motion for a 5 mm instrument

<table>
<thead>
<tr>
<th>Range of motion</th>
<th>Radii [mm]</th>
<th>Element length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pm 60^\circ )</td>
<td>6.57</td>
<td>9.89</td>
</tr>
<tr>
<td>( \pm 90^\circ )</td>
<td>3.98</td>
<td>7.84</td>
</tr>
<tr>
<td>( \pm 120^\circ )</td>
<td>3.14</td>
<td>7.23</td>
</tr>
</tbody>
</table>

The maximum range of motion is \( \pm 180^\circ \), in which the radius of the guiding elements is equal to half of the width of the instrument. The length of the body would be 6.83 mm. An overview of the joints for different ranges of motion is illustrated in Figure 5.1.

The range of motion has a large influence on the radii of the guiding elements and the length of the bodies and therefore needs to be optimised for a future design.

5.1.2 Equalising moment arms

To prevent the moment arms of the cables approaching zero, the moment arms for the inner and outer cables were designed to be equal at a 90° angle. Equalising the moment arms is possible since the inner guiding elements are not tangent to each other (as discussed in Section 3.1.2). Removing the constraint of equal moment arms results in a body in which the design is not fully constraint. The design is limited by two extremes in design: 'the inner guiding elements are tangent to each other' and the 'outer guiding elements are tangent to each other' (Figure 5.2).

When the inner guiding elements are tangent to each other, the guiding elements of a 5 mm tip will have a radius of 8.54 mm. At the maximum joint rotation of 90°, the cables will have a moment arm of 2.50 mm (outer cable) and 5.56 mm (inner cable).
For the other extreme, where the outer guiding elements are tangent to each other, the two outer guiding elements would form a single pulley. The radius of this pulley would be 2.5 mm. At the maximum joint rotation of 90°, the cables will have a moment arm of 3.23 mm (outer cable) and 1.63 mm (inner cable).

For both extremes both the inner and outer cable would have a moment arm during rotation. The size of the radius of the guiding elements is in a range between 2.5 mm and 8.54 mm for a 5 mm instrument. The size of the moment arms is in a range between 1.63 mm and 5.56 mm. Figure 5.2 illustrates the different extremes. A compromise needs to be found between the length of the bodies, the moment arm and the range of motion of the joint.

5.1.3 Modifying handle design

As discussed in Section 3.2 the slack on the cables has been assumed to be negligibly small. The increase of cable length of the outer cable in the tip is also nearly equal to the decrease in cable length of the inner cable in the tip, during a rotation of the tip. A maximum length difference of only 0.18 mm is present between the inner and outer cables when the tip is at the maximum angle. If the 0.18 mm length difference between the inner and outer cable is assumed to be negligibly small, the handle design for the new instrument can be simplified. Instead of using a complex design (combination rolling joint, small gears, protrusions/cut-outs and guiding elements) in the handle, the design can be simplified and controlled by a regular pulley.

Besides a simplification of the handle, more research is required to optimise the ergonomics of the handle. Examples of possible design are the joystick of the MiFlex and the handle of the Realhand from the company Novare Surgical Systems inc. [12].

5.1.4 Reducing slack on cables

As discussed in Section 3.2, the cables will have some slack during a rotation of the handle. This slack (0.18 mm) results in a maximum play on the joint of 3.6° in both directions. This play is assumed to be negligibly small. If the play cannot be considered to be negligibly small, the play can be reduced by tensioning the cables during rotation of the handle. A few options how to continuously tension the cables are:

- adjusting the design of guiding elements.
- adjusting the design of the rolling joint.
- placing a cam and a follower in the handle.
- placing a spring in the handle.

The current applied circular design of the guiding elements can be adjusted such that slack will be prevented. Instead of using a arc with a single radius, the guiding elements should have multiple variable radii, increasing in size at increasing joint angles. At an angle of 90°, the design of the adjusted guiding elements should be such that the cables have followed an additional trajectory of 0.18 mm. The exact design is not known and so more research required when this option is applied.

Adjusting the design of the rolling joint has a similar result. By changing the geometry of the rolling joint, to contain multiple variable radii, a linear displacement can be obtained, preventing slack on the cables. The design of the rolling joint can be like the contours of a cam.

Attaching the cables to a cam and follower in the handle is another option of preventing slack on the cables. Adding a cam in the handle can result in a linear displacement of the handle with respect to the shaft and tip. The result is that slack on the cables will be prevented.

A final option of reducing the slack on the cables is by placing a linear spring in the handle. When the instrument is placed in a straight position, the cables will already be under tension and the spring needs to be fully compressed. During the rotation of the tip the cables want to slacken, but this is prevented by the stiffness of the spring. Although the spring prevents slack of the cables, the bending stiffness of the tip during this phase is dependent on the stiffness of the spring. To attain high bending stiffness of the tip, the stiffness of the spring would have to be very
high. An spring with a high stiffness has a negative impact on the controllability of the instrument, since high forces would be required to change the angle of the handle.

### 5.1.5 Increasing lifespan of cables

A factor of the lifespan of the cables is its bending radius. In the new design, the bending radius of the cables depends on the radius of the guiding elements. The radius of the guiding elements has been optimised to be as large as possible. Compared to the bending radius of the cables in the EndoWrist, the bending radius of the current design is larger, resulting in a superior lifespan of the cables.

Literature has been found discussing the relation between the diameter of a pulley (D) compared to the diameter of the cable (d) \[13\] \[14\]. The D/d ratio is a ratio used in the industry as a rule of thumb for the minimum bending radius without reducing the lifespan due to fatigue. A D/d ratio for thin and flexible steel cables is 18.

The D/d ratio is in principle only applicable to the cables making at least one full encirclement around the pulley. In the new tip design the cables will only encircle one quarter of a pulley at the maximum tip angle of 90°. Since the cables will only encircle one quarter of a pulley, it might be possible that the stress on the cables will be less and therefore the cables can be guided over a smaller pulley than required for the D/d ratio. Further research is required on the fatigue of the cables.

If the result of that research is that the radii of the guiding elements is too large enough for the required cable thickness, the cables can be redesigned. Instead of using a single relatively thick cable, multiple thinner cables can be used next to each other, forming a sort of a belt. Since thinner cables are applied, the required diameter of the pulley also decreases. Another possibility of redesigning the cables is to use other, more flexible, materials. The drawback of using more flexible materials is that the bending stiffness of the tip will reduce.

### 5.1.6 Reducing number of cables

In both the planar and spatial design, the cables are looped at the end of the tip. By looping the cables, they do not have to be physically fixed at the tip. By looping the cables, the same cable will also return to the handle. Hence, there actually are two cables controlling the CW rotation and two cables controlling the CCW rotation. For the prototype, in which the size of the tip is increased to a width of 30 mm, this number of cables is not an issue. However, the number of cables can become an issue at a tip size of 5 mm, where the thickness of the cables will be relatively much larger. As a result the structure of the rigid bodies possibly will be altered such that the inner structure of the bodies will be weakened, resulting in fragile bodies. Instead of looping a total of four cables, the number of looped cables can be reduced to two. Since the cables will start to slide over the guiding of the loop, the cables need to be fixed at the tip.

### 5.2 Envisioned laparoscopic instrument

Up till now the tip has been designed to be square. However, the tip of the instrument needs to fit through a trocar with an opening of \(\text{Ø} 5\) mm. Figure 5.3 gives an illustration how the tip could look like when designed to fit through the trocar. The diameter of the tip is 5 mm and the cables have a diameter of 0.5 mm.

![Figure 5.3: Tip of the envisioned Ø5 mm instrument.](image)
5.3 Opportunities for a future design

5.3.1 Alternative solutions

As discussed in Chapter 2, there are two main methods to solve underactuation, 'reducing the number of DOF in the tip to the number of actuators' and 'increasing the number of actuators to the number of DOF in the tip'. In this thesis only the reduction of DOF in the tip to the number of actuators is discussed.

Although not discussed in this thesis, the method of increasing the number of actuators to the number of DOF in the tip has been further elaborated in during the construction of the solution space. The overview of the complete overview of the solution space can be seen in Appendix A. For a future research on new designs for steerable instruments for laparoscopy, these concepts can be evaluated.

5.3.2 From two 1-DOF joints to one 2-DOF joint

In Chapter 4 the design is discussed in which two DOF are present in both the tip and handle. These two DOF exist in the form of two rolling joints, working in two perpendicular planes. The result of having two separate DOF is that the tip of the instrument will be relatively long due to the length of the bodies. A drawback of having two long bodies in the tip, is that the control over the tip may be less intuitive. To improve the control over the tip, the two 1-DOF joints could be replaced by a single 2-DOF joint. Having only one joint in the tip of the instrument also reduces the size of the instrument.

During a literature study on steerable instruments of MIS, a classification of steerable instruments, was made [15]. In that report, different types of joints are discussed, including joints comprising two DOF. Solutions for the changing the design from two 1-DOF joints, to one 2-DOF joint may be found in that report.

6 Conclusions

The main goal for this project was to design a new steerable tip with a high bending stiffness. Since underactuation is a cause of a low tip stiffness, the tip had to be designed fully actuated. The number of DOF has been reduced to the minimum of one per plane, resulting in a total of two DOF in the tip. Since a spatial motion is required in two perpendicular planes, the number of DOF in the tip is two. The required range of motion for each DOF is 90° in a CW and CCW direction. To actuate this rotation two cables are used per DOF, resulting in a total of four cables. The tip therefore is fully actuated. The design of the handle is equal to the design of the tip. As a result the cables will have a minor slack on the cables of maximal 0.18 mm at a joint angle of 90°. The play on the cables causes rotational play on the tip of 3.6° in both CW and CCW directions, which is considered to be negligibly small. The cables therefore are continuously under tension. As a result, the bending stiffness of the tip depends on the stiffness of the bodies and the cables in the tip. Since steel cables and steel bodies will be applied in the tip, the tip is stiff. The exact stiffness is not known, but is superior to the stiffness of the MiFlex, due to underaction of in the tip of the MiFlex.

The second goal of this project was to design the tip such that the cables have a lifespan as large as possible. Fatigue is a cause of the low lifespan and therefore fatigue of the cables needs to be reduced. The fatigue of the cables is caused when the cables are forced to make a sharp bend. The bodies in the joint therefore are designed to guide the cables into a bending radius as large as possible where the radius depends on the diameter of the instrument. Applying cables of $\varnothing 0.5$ mm in a $\varnothing 5$ mm tip, the maximum bending radius of the guiding elements and cables is 3.48 mm. The bending radius of the cables is superior to the design in the EndoWrist and therefore the lifespan of the cables is superior. If and how much fatigue still remains on the cables is not known. Further research is required to investigate the effects of the fatigue on the cables.

Concerning the tip stiffness and lifespan of the cables, it can be concluded that the new tip design is superior to the tip design of the MiFlex and EndoWrist.
List of abbreviations and symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Angle inner guiding element [deg]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$\alpha/2$ [deg]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Angle rolling joint [deg]</td>
</tr>
<tr>
<td>$\varnothing$</td>
<td>Diameter</td>
</tr>
<tr>
<td>A</td>
<td>Vertical length of inner guiding elements [mm]</td>
</tr>
<tr>
<td>B</td>
<td>Distance between outer width instrument and centre point inner guiding element [mm]</td>
</tr>
<tr>
<td>D</td>
<td>Diameter pulley [mm]</td>
</tr>
<tr>
<td>d</td>
<td>Diameter cable [mm]</td>
</tr>
<tr>
<td>CW</td>
<td>Clockwise</td>
</tr>
<tr>
<td>CCW</td>
<td>Counter clockwise</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree(s) of freedom</td>
</tr>
<tr>
<td>HJ1</td>
<td>First joint, from the shaft, of the handle</td>
</tr>
<tr>
<td>HJ2</td>
<td>Second joint, from the shaft, of the handle</td>
</tr>
<tr>
<td>MIS</td>
<td>Minimally invasive surgery</td>
</tr>
<tr>
<td>R</td>
<td>Radius [mm]</td>
</tr>
<tr>
<td>TJ1</td>
<td>First joint, from the shaft of the tip</td>
</tr>
<tr>
<td>TJ2</td>
<td>Second joint, from the shaft of the tip</td>
</tr>
<tr>
<td>W</td>
<td>Width instrument [mm]</td>
</tr>
</tbody>
</table>

References


Appendices

A Complete solution space

Figure A.1: Overview of possible solutions, solving underactuation
B Calculations of moment arm and cable length for maximum bending radius

Figure B.1: Variables used for calculating outer moment arm.

Figure B.2: Variables used for calculating inner moment arm between angle of 0-63 degrees.
Figure B.3: Variables used for calculating inner moment arm between angle of 63-90 degrees.

%% Calculation RADIUS

% The letters used in these equations can be seen in a figure in the report
% where radii are calculated
C = 5; % [mm]
A = 45; % [deg]
D = (C/2)/tand(A/2); % [mm]
R = C/2+D; % [mm]

%% calculations OUTER moment arm
n = 1;
rotation_out = 0:n:90; % [deg]
initial_angle_out = 45; % [deg]

Alpha_out = rotation_out/2; % [deg]
Beta_out = 45-rotation_out; % [deg]
Gamma_out = (180-(Beta_out+Alpha_out))/2; % [deg]
Delta_out = 90-Gamma_out; % [deg]
L_out = 2*(R*sind((Alpha_out+Beta_out)/2)); % [deg]
M_out = L_out.*sind(Delta_out); % [mm]
L_straight_out = 2*(M_out./tand(Delta_out)); % [mm]
L_arc_out = ((31.40+31.40*(rotation_out/2))/360)*(2*pi*R); % [mm]
L_outer_total = (2*L_arc_out)+L_straight_out; % [mm]

%% Calculations INNER moment arm

rotation_in = 0:n:90;
for i = 1:length(rotation_in);
if rotation_in(i) < 63 % Switchpoint between inner and outer guiding
    Alpha_in(i) = rotation_in(i)/2; % [deg]
    Beta_in(i) = 45; % [deg]
    Gamma_in(i) = (180-(Beta_in(i)+Alpha_in(i)))/2; % [deg]
    Delta_in(i) = 90-Gamma_in(i); % [deg]
    Epsilon_in(i) = 90-Delta_in(i); % [deg]
    L_in(i) = 2*(R*sind((Alpha_in(i)+Beta_in(i))/2)); % [mm]
    M_in(i) = L_in(i).*sind(Delta_in(i)); % [mm]
    L_straight_in(i) = 2*M_in(i)*tand(Epsilon_in(i)); % [mm]
    L_arc_in(i) = (2*pi*R)*((2*31.40)-(rotation_in(i)/2))/360); % [mm]
else
    Zeta_in(i) = rotation_in(i)/2; % [deg]
    Eta_in(i) = Zeta_in(i)/2; % [deg]
    % [mm]
end

end
L_A_in(i) = 14.92965; % measured length 5 mm instrument [mm]
L_B_in(i) = R*sind(Zeta_in(i)); % [mm]
L_C_in(i) = L_A_in(i)-L_B_in(i); % [mm]
L_D_in(i) = R*cosd(Zeta_in(i)); % [mm]
L_E_in(i) = R-L_D_in(i); % [mm]
Theta_in(i) = Atand(L_E_in(i)/L_C_in(i)); % [deg]
Iota_in(i) = 90-rotation_in(i)/2; % [deg]
Kappa_in(i) = Iota_in(i)-Theta_in(i); % [deg]
M_in(i) = L_F_in(i).*cosd(Kappa_in(i)); % [mm]
L_straight_in(i) = 2*M_in(i).*tand(Kappa_in(i)); % [mm]
L_arc_in(i) = ((31.40+((rotation_in(i)-63)/2))/360)*(2*pi*R); % [mm]
end
H_line(i) = M_in(1,1);
H_line2(i) = L_outer_total(1,1);
end

%% Cable length Tip

% Inner cable
L_innern_total = L_straight_in + 2*L_arc_in; % [mm]

%% Figures
figure()
plot(rotation_out, M_out,'r')
hold on
plot(rotation_in, M_in)
plot(rotation_out, H_line,'k--')
grid on
title('Moment arm of outer and inner cable (5 mm instrument)')
axis([0 90 0 0.20])
xlabel('Angle joint [Deg]')
ylabel('Moment arm [mm]')
legend('Moment arm outer cable','Moment arm inner cable','location','Best')
figure()
plot(rotation_in,L_innern_total)
hold on
plot(rotation_in,L_outer_total,'r')
plot(rotation_in,H_line2,'k--')
grid on
title('Total length of cables in tip')
xlabel('Angle of rotation [deg]')
ylabel('Length of cable [mm]')
legend('Inner cable','Outer cable','Location','Best')
C Cable calculations for maximum bending radius

% This design is for the absolute maximal radius the guiding can describe.
% The maximum radius for this design is 3.98 mm (based on instrument width
% of 5 mm).
% width of instrument [mm]
w = 5;
d_alpha = 0:10:90; % [deg]
r_top = (w/2)/sind(45); % [mm]

%% Left cable
L_arc_outer = [2.18;2.53;2.87;3.22;3.57;3.92;4.26;4.61;4.96;5.30]; % [mm]
L_straight_outer = [7.39;7.13;6.87;6.61;6.36;6.11;5.87;5.63;5.41;5.20]; % [mm]
L_moment_arm_outer = [2.50;2.49;2.50;2.51;2.54;2.57;2.62;2.68;2.74;2.82]; % [mm]
L_mean_moment_arm_outer = mean(L_moment_arm_outer); % [mm]
L_tip_outer = 2*L_arc_outer+L_straight_outer; % [mm]

%% Right cable
L_arc_inner = [2.18;1.83;1.49;1.14;0.79;0.44;0.10;0.25;0.60;0.94]; % [mm]
L_straight_initial = [7.39;7.64;7.90;8.14;8.38;8.61;8.82;9.03;6.83;5.64]; % [mm]
L_moment_arm_inner = [2.50;2.52;2.55;2.59;2.64;2.71;2.78;2.84;2.86;2.82]; % [mm]
L_mean_moment_arm_inner = mean(L_moment_arm_inner); % [mm]
L_tip_inner = 2*L_arc_inner+L_straight_initial; % [mm]

for i = 1:(length(d_alpha))
    L_mean_moment_arm_in(i,1) = L_mean_moment_arm_inner(i,1);
    L_mean_moment_arm_out(i,1) = L_mean_moment_arm_outer(i,1);
end

%% Cable length handle + tip
L_handle_inner = L_tip_inside; % [mm]
L_handle_outer = L_tip_outside; % [mm]
Total_L_left_cable = L_tip_outside + L_handle_inside; % [mm]
Total_L_right_cable = L_tip_inside + L_handle_outside; % [mm]

Total_L_initial = Total_L_left_cable(1,1); % [mm]
Total_L_displacement = Total_L_initial-Total_L_left_cable; % [mm]

% Slack is the result of the play on the cables matched with a rotation of
% the tip
Slack_angle = [0; 0.2; 0.25; 0.7; 0.9; 1.4; 1.9; 2.5; 3; 3.6]; % [deg]
Slack_angle_max = [0 -0.2 -0.24 -0.6 -0.8 -1.3 -1.9 -2.4 -2.8 -3.6]; % [deg]

%% Figures
figure()
plot(d_alpha,L_arc Outer,'*-')
hold on
grid on
plot(d_alpha,L_arc inner,'*-r')
title('Length of cables around arc')
xlabel('Clockwise rotation [deg]')
ylabel('Length cables tip [mm]')
figure()
plot(d_alpha,L_straight outer,'*-')
hold on
grid on
plot(d_alpha,L_straight inner,'*-r')
title('Length of cables straight')
xlabel('Clockwise rotation [deg]')
ylabel('Length cables tip [mm]')
figure()
plot(d_alpha,L_tip outer,'*-')
hold on
plot(d_alpha, Slack_angle_c,'.-r')
plot(d_alpha, Slack_angle_cc,'.-b')
grid on
axis([0 95 -5 5])
title('Play on joint tip')
legend('Clockwise play','Counter clockwise play')
xlabel('Angle of rotation [deg]')
ylabel('Play [deg]')
D Involute gear profile

Variables for the design of the involute gear profile. The gears are designed for the prototype, where the width of the instrument is 30 mm. All variable are presented in inches.

% All diameters are given in INCH

\[
\begin{align*}
I &= 25.4; \quad \% \text{1 inch} = 25.4 \text{ mm} \\
W &= 30/I; \quad \% \text{Width of instrument [inch]} \\
N &= 20; \quad \% \text{Number Teeth [-]} \\
PA &= 20; \quad \% \text{Pressure angle [deg]} \\
D &= (W/\sin(45)); \quad \% \text{Pitch diameter [inch]} \\
R &= D/2; \quad \% \text{Pitch Radius [inch]} \\
P &= B/D; \quad \% \text{Diametral Pitch [inch]} \\
DB &= D\cos(PA); \quad \% \text{Base Circle Diameter [inch]} \\
RB &= DB/2; \quad \% \text{Base Circle Radius [inch]} \\
a &= 1/P; \quad \% \text{Addendum [inch]} \\
d &= 1.157/P; \quad \% \text{Dedendum [inch]} \\
DO &= D+2a; \quad \% \text{Outside Diameter [inch]} \\
RO &= R+a; \quad \% \text{Outside Radius [inch]} \\
DR &= D-2d; \quad \% \text{Root Diameter [inch]} \\
RR &= R-d; \quad \% \text{Root Radius [inch]} \\
CB &= \pi DB; \quad \% \text{Circumference Base Circle [inch]} \\
FCB &= RB/20; \quad \% \text{very close approximation [inch]} \\
NCB &= CB/FCB; \quad \% \text{[inch]} \\
ACB &= 360/NCB; \quad \% \text{[inch]} \\
GT &= 360/N; \quad \% \text{Gear Tooth spacing [inch]}
\end{align*}
\]