Design of a 4 DOF slave robot instrument manipulator for MIS

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Design of a 4 DOF slave robot instrument manipulator for MIS

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Abstract

In this report a part of a slave robot is designed for a master slave system for minimally invasive surgery (MIS). The master slave system will be used for operations in the abdominal and thoracic region. During this traineeship the design of the manipulator, to actuate the instruments is investigated.

Using MIS, three or more small incisions of about 10 mm are made into the skin in stead of one large incision during normal surgery. In this way the recovery time of the patient is much shorter. When the instruments are actuated by hand, there are some challenges in manipulation. To solve these problems robotic surgery is necessary to actuate the instrument during the operation.

At this moment the only company who produces a master slave system for surgical purpose is Intuitive Surgical Inc. The present system is called the “Da Vinci” robot. The dimensions of this robot are very large because the base of the robot is standing at some distance from the operation table. On this base three manipulators are fixed. The length of these manipulators is about 2 meters, to be able to position the instruments above the patient.

When the surgeon executes the operation he has only stereo vision to actuate the instruments. So the surgeon is not able to feel the forces executed by the instruments.

For this reason a new STW / IOP project has been started, to design a master slave system with force feedback. To add force-feedback it is important to have a short force loop. For this reason a small island, called instrument base will be positioned above the patient. The three manipulators are fixed on this instrument base.
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1. Introduction

This project contains the design of an instrument manipulator for surgical purpose. The complete project contains the design of a master slave system, what will be used during minimally invasive surgery (MIS). These operations take place in the abdominal and thoracic cavity. The design of the instrument manipulator is part of the project of PhD student Linda J.M. van den Bedem. She designs the slave part of the robot.

1.1 Overall design

The da Vinci telesurgery system of ‘Intuitive Surgical’ is currently used in several hospitals in the Netherlands. It consists of a master, slave and control system. The slave contains a large base standing near the operation table, for this reason the arms of the robot have to be very long. This length is coupled to a large force loop. In Figure 1.1 the robot is placed behind the operation table. The surgeon controlling the robot is positioned at the left side of the picture.

An important part of the new design of the slave is the patent, requested by TU/e. This patent contains a variation on the present system; a small instrument base will be placed above the patient with three manipulators. The instrument base will not placed on the floor but will be fixed to the operation table, this results in a much smaller force loop compared to the “Da Vinci telesurgery system”. Another advantage of fixing the instrument base to the operation table is that the orientation of the table can be adjusted during surgery without readjusting the robot. Furthermore force-feedback will be added so the surgeon can feel the force he executes with the instrument.

1.2 Minimally invasive surgery (MIS)

During the last years more and more operations are executed using minimally invasive surgery (MIS). This implies that instead of one large incision only three small incisions are made in the skin of the patient. Through these incisions the instruments and endoscope (camera) enter the
The instruments are shaped like a tube with a diameter of about 8 -10 mm and a length of 350 mm. At the end of the tube a thermal knife, gripper or other instrument is connected. The abdominal cavity is inflated during surgery to create space so the instruments and endoscope can be manipulated without injuring organs. This is done with CO₂, what is pumped into the body. To prevent the gas flowing away, a valve is used. This is built in a small tube, called trocar and is placed into the incision. Both instruments and the endoscope enter the cavity through these trocars. In this way, the operation can be executed in the body, by actuating the tools at the outside. During this operation the instruments are driven by the surgeon’s hands. The endoscope is used to get view on the target organs. This endoscope has also to be actuated during the operation.

![Diagram](image)

**Figure 1.2: schematic overview of the instrument actuation during surgery**

The advantages of MIS are a shorter recovery time of the patient and less scar tissue in the body and on the skin. Using MIS has also some disadvantages; the first one is the existence of a rotation point in the skin. For this reason it is not possible to move the instruments like a normal (open) operation. When the handle of the tool is moved to the right the tip of the instrument moves to the left (see Figure 1.2). So the movements of the surgeon are mirrored at the tip of the instrument. Furthermore the ratio of the lever changes continuously during surgery depending on the insertion depth of the instrument. Also the friction in the trocars gives some problems, because the force feedback is influenced by this friction. So the surgeon does not feel the exerted force. Another difficulty has to do with the eye-hand-coordination of the surgeon. It is important to position the surgeon, vision, robot and target organ in one line (see also Figure 2.1).

The last disadvantage of using MIS is the pose of the surgeon. During operations in the abdomen and thoracic region the instrument sticks into body with different angles and positions. To move the instruments, the surgeon has to hang over the patient. This not ergonomic pose position contributes to lots of physical problems of the surgeon.

To prevent these problems for the surgeon and make more accurate operations possible, a new manipulator has to be designed, what can actuate the instruments and endoscope and can measure the force executed by the instrument.

In this report the design of the manipulator will be explained. First some requirement of the robot will be given and the degrees of freedom desired. Then a virtual point of rotation is explained and some principal designs with a virtual point of rotation. One of these designs will be elaborated upon further.
2. Requirements

The most important design point of the manipulator is to create a small force loop between the table and the instruments. So attention has to be paid to the mass, stiffness and accuracy of the manipulator. But also the stroke of the different degrees of freedom is very important. The most important requirements will be summed up in this chapter.

Accuracy
The accuracy of the tip of instrument has to be 50 micrometers. This accuracy is an accumulation of all the deviations in the rotating points. The better the cuts and stitches can be made and positioned, the shorter the recovery time of the patient. When stitches are made at a constant distance, the risk of tearing will be smaller, just as the production of scar tissue.

Mass
The mass of the complete manipulator has to be as small as possible. A guideline for the mass of one manipulator is about 5-8 kg. In this way it is possible to lift the arm by hand, by one person. This makes it possible to change the manipulator very fast when a defect occurs.

Stiffness
The stiffness of the manipulator is very important. The stiffness is in combination with the mass responsible for the natural frequency of the complete construction. The overall stiffness of the manipulator depends on of all stacked components. For this reason it is important to make every part stiffer, than the prescribed value. The stiffness at the tip of the instrument has to be 2e5 N/m.

Strokes
Before the operation starts the manipulator has to be positioned above the trocar. This means the manipulator has to be able to translate to the trocar in X, Y, Z-direction. Also some rotations have to be able to make. The rotations of the $\phi$-axis have to be 140 degrees and the rotations of $\psi$ have to be able to make a total stroke of 180 degrees.

During surgery the instruments have to be able to move into a specified domain. This domain is prescribed by the procedure, which will be executed. An overview of the coordinate system used here is given in Figure 3.1. During an operation the rotation angles $\phi$ and $\psi$ have a total stroke of about 60 degrees. The stroke in z-direction of the instrument is about 350 mm. This is the depth variation of the instrument in the body of the patient. The rotation of the instrument in $\theta$-direction is about 360 degrees, but preferably it has to be a bit larger.

Position of the endoscope and manipulators
It is not only important that the instruments can reach the target organ, but it is also important to get the right orientation of the instruments with regard to the endoscope when the incisions for the trocars are made in the body. This has to do with the eye hand coordination of the surgeon. The best workable environment will be created when the instruments and the endoscope are placed at an angle variation of 30° [1]. This angle is important during the coarse movements of the manipulator. An overview of the placement of the trocars is given in Figure 2.1.
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Figure 2.1: ideally placed components during an operation. T = trocar for instrument, V = the vision trocar. $\alpha$ = angle of 30°, S = the position of the surgeon and R the position of the da Vinci robot [1]

**Dimensions**
The dimensions of the manipulator have to do with the distance between the trocars. The minimal distance between the trocars is about 80 mm. For this reason the manipulators have to be very flat, especially the manipulator for the endoscope because this one sticks between the instrument trocars.
The length of the manipulator has to be as short as possible, to get a small force loop, as long as the different angles and strokes can be made.

**Modular construction**
Another point of interest is using a modular construction. In this way the robot arms can be changed easily. This means the robot arm has to be able to uncouple from the instrument base.

**Force feedback**
In current master-slave systems force information is derived from visual information.
The current system provides the surgeon with stereo view, this is a kind of 3D-view. In this way the surgeon controls the manipulator. It is desirable to add force feedback to distinguish between the current systems. Therefore the force on the tip of the instrument and forces in the construction need to be measured by force sensors. This force information can be used by the control system to provide the surgeon with force feedback while handling the master.

**Manufacturing costs**
In the future these manipulators will be made in small series. For that reason it is important to pay attention to the manufacturability of the parts. Also the interchangeability and availability of the standard parts have to be evaluated. If it is possible to use one type of manipulator for the instruments and the endoscope, the development costs and production costs can be as low as possible.
3. Design

In this chapter three different ideas to create a rotation point about the skin will be discussed. But first an overview of the degrees of freedom of the instrument will be given and an explanation of the “virtual point of rotation”.

3.1 Degrees of freedom

During a MIS operation in the conventional manner (no master-slave system) four degrees of freedom are used by the instrument. An overview is given in figure 3.1, where the instrument can rotate about the $\phi$ and $\psi$ axis. The depth variation of the instrument is given by $z$. Furthermore it is possible to rotate the instrument around $\theta$.

Also at the tip of instrument, some degrees of freedom are available, for example to open and close a cutter and wrist movements. These degrees of freedom will not be discussed in this report.

![Virtual point of rotation](image)

**Figure 3.1:** The four remaining degrees of freedom of the instrument tip and the virtual point of rotation in the muscular layer

**Virtual point of rotation**

During surgery the instruments and endoscope have to rotate about the skin. The skin is built up of different layers, which can be seen in Figure 3.1. In the skin, the muscular tissue has the largest stiffness, for this reason the instrument has to rotate about this layer. Because the incision needs to be as small as possible, it is not allowed to apply a hinge in this layer. Moreover it is not possible to grip this point directly because the fatty tissue lays on it. To make a rotation about the muscular layer possible, it is necessary to create a virtual point of rotation. The instrument rotates about a point without placing a hinge at the required position. During the design of the manipulator it is important to pay attention to this property.

There are three methods to create this virtual point of rotation; passive, active and kinematical. Passive stability is used during the normal minimally invasive operations. The instrument is
supported by the muscular layer of the patient. In this way forces in the trocar will be executed on the body of the patient. During an operation the muscular tissue is not completely stiff, so the surgeon has to correct his movements. 

Using active control the virtual point of rotation will be orientated by control of the actuators. This is only possible when the controller knows the exact position of the virtual rotation point. Using this method increases the possibilities for the mechanical part of the construction, but controlling the system will be more difficult. 

The last option is creating a kinematical point of rotation, the construction of the manipulator prescribes this point exactly. Using parallel mechanisms or placing some additional rotation points the construction can prescribe a virtual point of rotation.

### 3.3 Mechanisms with a virtual point of rotation

In this chapter an overview is given of three solutions to create a virtual point of rotation. The parallelogram mechanism and “φ, ψ non-orthogonal cardan joint mechanism” use a kinematical point of rotation. However the six rods mechanism uses an active point of rotation. The three mechanisms are able to rotate the instrument around the φ and ψ-axis. The z-translation and θ-rotation can not be actuated by the three different mechanisms and have to be added later.

#### 3.3.1 Parallelogram mechanism (kinematical)

The first option to actuate the instrument is a kinematical solution; a parallelogram. Using this mechanism it is possible to create an element, which rotates around a point, without fixing this point directly. The virtual point of rotation of the parallelogram lies on the continuation of the line of both fixed rotation points (point A and B), in Figure 3.2 this line is dotted. The point where the instrument crosses this dotted line is the virtual point of rotation. During surgery, this point lies in the muscular layer of the patient. In this way forces executed on the skin of the patient can be low if properly adjusted.

![Figure 3.2: kinematical virtual point of rotation](image)

The rotation about the φ-axis can be made by rotating either lever around point A and B respectively (see Figure 3.2). For the rotation about the ψ-axis, the complete parallelogram has to rotate. In this way the two rotations about the virtual point of rotation can be made. The z-translation has to be added on the line where the instrument is positioned in Figure 3.2.
3.3.2 \( \varphi, \psi \) non-orthogonal cardan joint mechanism (kinematical)

The claw mechanism consists of two bodies, rotating about a virtual point of rotation. In Figure 3.3 an overview is given of the mechanism. Body 1 rotates around axis 1 and the body 2 rotates around axis 2. These two rotation axis intersect each other in the virtual point of rotation. The instrument is connected on body 2 and has to pass through the virtual point of rotation as well. By rotating the mechanism around axis 1 and 2 simultaneously or not, the instrument is able to rotate around \( \varphi \) and \( \psi \).

In Figure 3.3 axis 1 is placed in vertical position. This is not necessary, the axis can be rotated in \( \varphi \) and \( \psi \)-direction. In this way the instrument can also be placed in a more horizontal position, which enlarged the usability during some operations.

In this mechanism, both bodies are curved. The angle (\( \alpha \)) of bending is not specified and can be chosen. The angle of the body dependents on the desirable rotation angles of the instrument.

When the angle is 45 degrees, the instrument can be placed in a horizontal and vertical position. This horizontal position is used to enter the body on the side.

To get a small construction, the mechanism has to be placed as close as possible to the virtual rotation point. Because it is desirable to make the complete stroke in \( \varphi \) and \( \psi \)-direction, the instrument is not allowed to stick out at the back side of body 2. In Figure 3.3 this means, the instrument runs through body 2. When the instrument orientation is aligned with axis 1 it will hit body 1. The stroke in \( z \)-direction is very large, for this reason body 1 and 2 have to be placed at a large distance of the trocar point. Body 1 and 2 two have to be large then to realize the required strokes. This is a disadvantage of this construction.
3.3.3 Six (active) rods mechanism

Another possibility to actuate the instruments or endoscope is using six rods. The six rods are not coupled directly to the instrument but are fixed on a tube. The tube is only actuated in \( \varphi \) and \( \psi \)-direction. The \( z \) and \( \theta \) direction of the tube are fixed. The instrument is positioned in this tube. In the tube a \( z \) and \( \theta \)-actuator will be positioned to move the instrument in these degrees of freedom. An overview of this mechanism is given in Figure 3.4. In this Figure rod \( a_1, a_2, b_1 \) and \( b_2 \) are used to actuate the instrument in \( \varphi \) and \( \psi \)-direction. When both rods are controlled in the right way, the virtual point of rotation will be positioned in the muscular layer of the skin. The \( z \)-direction of the tube is fixed by rod \( c \).

![Figure 3.4: overview of the six rods mechanism. Rod \( a_1, a_2, b_1 \) and \( b_2 \) are used for \( \varphi \) and \( \psi \)-rotations and rod \( c \) is used to fix the \( z \)-direction of the tube](image)

In figure 3.5 a top view is given for the upper three rods. Rod \( A \) and \( A' \), take care of actuating the instrument in \( \psi \)-direction. This means the instrument will rotate around the \( \psi \)-axis. To fix the \( \theta \)-rotation of the tube, an intermediate body is used. This intermediate body is fixed by rod \( D \).

![Figure 3.5: upper view six rods mechanism](image)
To create a virtual point of rotation, the six rods have to be actuated in the right way. Rod a1 and a2 make a large stroke to rotate the instrument in Φ and Ψ direction. During this motion the lower three rods correct the movements so the instrument rotates around the virtual point of rotation. In Figure 3.6 an overview is given. In this situation rod a1 has to make twice the stroke of rod b1.

Figure 3.6: overview of 2 rods, which rod b1 has to make half the stroke of rod a1 to create a virtual point of rotation

### 3.3.4 Conclusion / comparison

The three mechanisms discussed use different ways to create a virtual point of rotation. Every mechanism has some advantages and disadvantages. To make a well-founded choice of one of these constructions, they have to be compared on some points and requirements. Because of lack of time, the three mechanisms have not been elaborated upon same level. The parallelogram construction was chosen to develop in more detail because every degree of freedom is actuated by only one actuator. Because the different degrees of freedom are uncoupled it is a Single Input Single Output system (SISO). This has advantages controlling the manipulator and adding force feedback, but this will be explained in the next chapter. The “φ, Ψ non-orthogonal cardan joint mechanism” and six rods mechanism have to actuate more actuators in the same time to move one degree of freedom. For this reason it is called a Multiple Input, Multiple Output system (MIMO)

The “φ, Ψ non-orthogonal cardan joint mechanism” and the six blades mechanism will be elaborated in a subsequent assignment. When they are elaborated upon till the same level as the parallelogram mechanism, a choice will be made and the appropriate mechanism will be engineered further.

In the next chapter the parallelogram mechanism will be elaborated upon further. Also the coarse movements of the manipulator, the actuation of the φ and Ψ-axis, the z-actuation and the connection between the manipulator and the instrument base will be discussed.
4. Parallelogram mechanism (design)

In this chapter, the parallelogram mechanism will be explained furthermore. Also the coarse movements of the manipulator will be explained. These coarse movements are used to position the virtual point of rotation in the muscular tissue of the incision. At the end some properties of the mechanism are discussed.

4.1 Coarse movements before the operation

Before the operation starts, the virtual point of rotation of the manipulator has to coincide with the corresponding incision. The position of these incisions is different for every operation and patient. For this reason each virtual point of rotation has to be placed above the trocars after connecting the manipulators to the instrument base. This is possible by using coarse translations and rotations of the manipulator. The movements are executed by hand, before the operation starts. During surgery, the coarse movements are not allowed to move anymore. For this reason a brake will be used.

The coarse movement in y-direction is made with a parallelogram, placed in vertical direction (see Figure 4.1). By rotating the two vertical plates around their rotation points, the additional body (and complete manipulator) translates in y-direction.

In this way the manipulator can be translated closer or further from the instrument base. The parallelogram is placed upwards because above the instrument base there is more space to make a large stroke. The cross-section of the plates of the parallelogram have to be large enough to prevent bending and buckling.

To make a coarse movement in z-direction a second parallelogram is stacked on the additional body (see Figure 4.2). In the right part of this figure the two parallelograms are given in a random position. During the movements the plates are considered rigid, so the plates are only able to turn around the rotation points.

On body C some extra rotation points for the coarse adjustments will be placed. To make it possible to rotate the instrument in a downwards vertical position, it is necessary to create some space (P). This is done by adapting the horizontal parallelogram. As can be seen in Figure 4.2, plate d is moved to the right in comparison with plate c.
Looking at the Figure 4.2, the two parallelograms cross each other. To prevent this, plates c and d will be placed within the additional bodies B and vertical plates a and b (see Figure 4.3). In this Figure plate b is U-shaped to make it possible to move plate c and d in between.

To get good dynamic properties of the mechanism the horizontal parallelogram is placed at the inside of the intermediate body. The same goes for the vertical parallelogram, (for horizontal translations) which is placed at the outside of the intermediate body. The instrument base is built around the vertical parallelogram for the same reason.

To prevent that the parallelogram will come down in z-direction, a spring is added. This spring compensates for the weight of the manipulator. A schematic overview of the spring is given in Figure 4.4.
It also has to be possible to adjust the $\phi$, $\psi$ and $\theta$-rotation by hand before the operation. The $\theta$-rotation is introduced to make it possible to bend the manipulator. In this way the tips of the 3 manipulators can be placed at a smaller distance without colliding into each other. This is necessary, because the trocar distance between the trocars can be 80 mm (see Figure 4.5). The $\phi$ and $\theta$-rotation of the course movements of the manipulator can be seen in Figure 4.6.

During some operations the instruments are used in a horizontal position. This happens when the trocar is positioned in the abdominal cavity and the operation takes place into the thoracic region. To make it possible to rotate the instrument in horizontal direction, a rotation point is introduced that makes it possible to rotate the robot arm around the $\phi$-axis (see Figure 4.6). The rotation axis for $\phi$, $\psi$ and $\theta$-direction cross in the same point, a kind of cardanic joint.
Sometimes the instruments are put into the human body from the side. To make this possible the $\psi$-rotation has to be adaptable. This rotation is also used during the operation, but then it is driven electrically. Because this rotation is a combination of coarse and motorized movement, it has to be able to fulfill both wishes; this will be explained in Section 4.2.2.

### 4.2 Actuation of the instrument during surgery

During surgery the instruments and endoscope are driven by electric drives. In this chapter possibilities to actuate these degrees of freedom are discussed. An overview of these degrees of freedom is given in Section 3.1. First the $\phi$ and $\psi$-rotation and at last the $z$-translation will be discussed.

#### 4.2.1 $\phi$-rotation

When the instrument rotates around the $\phi$-axis, the vertical beams a and b rotate around point A and B (see Figure 4.7).

![Figure 4.7: Schematic overview of the parallelogram mechanism with rotations around the $\phi$ and $\psi$-axes](image)

The actuation of the parallelogram is executed by actuating the beam a, rotating around point A. An advantage of this position is that the actuator will be placed close to the instrument. The force loop within the construction will then be as small as possible. In this way the actuation force has to pass through parts a, c and d.
The motor, used for actuation is of the company Maxon Motors. This company has motors with a relative small diameter (about 25 mm) and a large length (130 mm). The large length is caused by the reduction interface, in front of the motor and the encoder unit at the back side.

The small diameter makes it possible to suspend the motor below the $\psi$-axis to realize a compact construction (see Figure 4.8). The motor is fixed in longitudinal direction. In this situation the rotating axis of the motor is not parallel to the rotation axis of the parallelogram, so it has to be rotated 90 degrees by a worm-wheel transmission. The worm wheel rotates around point A and the worm will be fixed on the motor axis (Figure 4.8).

The worm wheel will rotate with a smaller angular velocity than the driven worm. When the ratio is larger than 1:30, the transmission has a one way brake property. For a ratio smaller than 1:30 the parallelogram can be moved by hand, without actuating the motor. In this way the parallelogram can be placed in the right position, before the operation starts.

An advantage of using a worm wheel transmission is the corresponding speed reduction. The result of this is an enlarged accuracy of the movement. At this it is important to prevent clearances in the transmission by pre tensioning the worm-wheel.

![Figure 4.8: overview of the worm worm-wheel transmission of the $\phi$-axis](image)

Another option to make a coarse $\varphi$-rotation possible is decoupling the motor. An overview of a coupling in the worm wheel is given in Figure 4.9. The middle part of the wheel is connected with the axis. The outer part of the wheel can freely rotate when the coupling is opened. In this way the couplings surface is positioned on a large radius, which cause a larger contact surface and a smaller force on the coupling.

A disadvantage of decoupling the motor is that the encoder does not know in which position the parallelogram is positioned. This is because of the encoder is placed at the backend of the motor. To solve this problem an extra encoder has to be placed on the outer part of the worm wheel.

![Figure 4.9: cross section of the coupling on the worm wheel. The outer ring can be decoupled from the inner part](image)
A course movement without uncoupling the motor can also be realized with an electrical solution. For this purpose some extra sensors have to be placed in the rotation point of the worm wheel. When a special button is pressed and the manipulator will be moved by hand, the sensors will notice these movements and send the information to the motor. Next the motor takes care of the movements of the parallelogram. The control loop is so fast that the manipulator seems to be driven by the person but in reality the motor takes care of the actuation.

**Parallelogram:**
A parallelogram is used for the transfer of rotations of beam a to the instruments. The angle of rotation of the instrument and parallelogram varies between -70° and +70°. An schematic 3D overview of the parallelogram mechanism is given in Figure 4.10. This figure gives only an impression of the construction and has to be elaborated upon further. Point A and B of the parallelogram are fixed on the motor frame, the motor frame will be discussed in the next Section. To make the large rotation angle possible beam a is executed in an upside down U-shape. The shape makes it possible to rotate the parallelogram clockwise till the upper part of beam A hits the horizontal positioned plate c. For the same reason the lower part of plate e is also U-shaped. Because the instrument has to intersect the rotation points between plate d and e, the base of plate e is placed backwards (to the right; see Figure 4.10). When the parallelogram is rotated clockwise, this guidance will collide with body c. For this reason body c is U-shaped.

![Figure 4.10: parallelogram mechanism to transfer the rotation of beam a to the instrument](image-url)
The z-actuator of the instrument has to be placed on plate e; different actuating principles will be discussed in Section 4.2.3. The instrument has to intersect the two rotation points in the horizontal beams c and d. The position of the instrument is given by the dotted line in Figure 4.11. In this way the rotation of beam a is exactly copied to the instrument.

![Figure 4.11: side view of the parallelogram with a dotted line for the instrument. The movements of beam a will be coupled directly to the instrument.](image)

4.2.2 ψ-rotation

The rotation of the instrument around the ψ-axis, is a combination of a coarse and motorized movement. Before the operation the manipulator has to be placed in the correct position by hand and during the operation a motor is used to actuate the instrument.

In Figure 4.12 an overview is given of a possible solution. The inner tube is fixed on the body for coarse movements (on the right side of the picture). The outer tube will be connected to the parallelogram mechanism.

On the left side two angular contact bearings are placed in an x-arrangement. The contact lines of the balls and the rings point to the centre line of the bearings. In this way axial forces are absorbed in both directions. A moment introduced will not be absorbed by this bearing arrangement; therefore a further needle bearing is placed at the right side of the axle.

![Figure 4.12: cross section of the ψ-axis. For this rotation point a needle roller bearing and two angular contact bearings are used in an X-position](image)
The actuation of the $\psi$-axis is executed by an electro motor and the corresponding transmission consists of two cogwheels. The cylindrical shaped electro motor is placed in the y-direction. The motor will be placed below the $\psi$-axis just as the motor for the $\phi$-rotation, see Section 4.2.1. In this way a compact construction is possible. In Figure 4.13 an overview is given of the position of the motor. The large cogwheel is fixed on the inner axis, the stationary part, the motor is fixed on the outer tube. When the motor rotates, the motor itself and the outer tube will rotate around the inner axis. Also the motor for the $\phi$-rotation of the parallelogram is fixed on the outer tube, so this motor will rotate as well.

The inner tube is hollow, to make it possible to guide some electric wires to the instrument base.

![Figure 4.13: placement of the motor in y-direction. It is placed under the $\psi$-axis to get a compact construction and because the motor for $\phi$-rotation is also placed there](image)

The rotation points for the $\phi$-axis depicted in Figure 4.12 are placed on the $\psi$ rotation axis to create the virtual point of rotation. One of the points is placed within angular contact bearings and needle roller bearing and the other is positioned at the left side of the angular contact bearings. In this way the rotation point sticks out. This has some advantages because the axis actuating the $\phi$-rotation can be made of one part to load the parallelogram homogenously.

A disadvantage of sticking out one rotation point is the decrease in stiffness of the construction. When a force is applied between two springs, like the left part of Figure 4.14, the stiffness felt by the force is equal to $2C$ with $C$ the stiffness of each spring in N/m. When a force is applied at the end of the beam, the spring is placed in the middle of the beam and the left spring is considered infinitely stiff, the stiffness felt by the force is equal to 0.25C. This gives a total stiffness of 0.2C. For this reason it is better to apply the load in between the bearings, this will be discussed in the next design.

![Figure 4.14: bearing stiffness in two situations. In the left the force is applied in between the two bearings and in the right picture it is placed beside the bearings](image)
Another possibility for creating a rotation point is using two angular contact bearings. In Figure 4.15 an overview is given. Herein an angular contact bearing is placed on the left and right side of the axis. On the left side of the axis, thread is applied to make it possible to pre-tension the two angular contact bearings by screwing up the nut. When the bearings are pre-stressed clearances will be prevented.

![Figure 4.15: rotation point with 2 angular contact bearings. An advantage of this construction is that both φ-axes lie in between the angular contact bearings.](image)

The outer tube of this construction has a large wall thickness, so the end of the tube can be adapted to get the right diameter of the bearing to fix them. On the tube the connection points for the φ-rotation will be attached. The rotation points for the φ-axis are both placed within the two angular contact bearings. In this way the stiffness felt by the parallelogram is equal to the sum of the stiffness of both bearings (see Figure 4.14).

The exact position of the φ-axis and the beams of the parallelogram is determined by a bearing property. An angular contact bearing has a specified angle under which the ball contacts the housing. These contact lines are dotted in Figure 4.15. The intersection point of this line and the φ-axis will be the centre of a beam of the parallelogram.

In this way the forces of parallelogram are directly passed through the inner axis. This prevents the outer axis from bending when a force is applied.

The actuation of the ψ-axis can be in the same way as the previous construction. A large gearwheel will be placed on the inner axis and the motor and a small cogwheel are placed on the housing.
4.2.3 Z-translation

The instruments which are used during surgery have a length of about 350 mm. This length is necessary to reach the organs in the back of the abdominal region and to reach the organs in the thoracic region, when the instrument enters the abdominal region. A mechanism will be used that is fast enough to enter the abdomen cavity with the instrument and follow the movements of the surgeon. In this chapter different mechanisms will be discussed for this degree of freedom.

*Cable drive*
To make a large z-stroke a slide can be used, which can be actuated by a cable drive. The cable is guided by two wheels (1 and 2), under and above the z-guide (see Figure 4.16). The actuation of the cable takes place by an electric drive placed on wheel 2. Wheel 3 and 4 are the wheels of the slide and roll over the guidance during the z-actuation of the instrument. For the actuation of the slide only wheel 3 is used. This wheel has to be pre-stressed by an extra wheel on the backside of the guidance, to prevent slipping between the wheel and the guidance. On wheel 3 a large wheel is placed to guide the cable. The cable is turned one time around the wheel to create friction between the wheel and the cable. By taking a large diameter the forces in the cable can be less high and the friction between the cable and the wheel is placed on a large diameter.

![Figure 4.16: overview of the z-actuation using a cable. Wheel 3 of the slide is actuated by the cable.](image)

*Spindle drive*
Another option to actuate a slide is using a spindle drive. A spindle transposes a rotational movement into a translation by a screw. Rotating the spindle, the wagon with screw thread translates. The speed of the slide depends on the pitch and the rotational speed of the spindle.
**Z,θ-drive**  
In this design three wheels are placed in radial direction of the instrument (top view: Figure 4.17). The wheels execute a specific normal force the instrument to create friction between the wheel and the instrument. By rotating one wheel, the instrument starts to translate in z-direction. Some centimeters beneath these three wheels, 3 further a wheels will be added. These wheels prevent the instrument from rotating around the φ and ψ-axis.

![Top view of Z,θ-drive](image)

**Figure 4.17: actuation of the instrument in z-direction by three radial positioned wheels**

The wheels actuating the instrument do not have a flat radial surface, but in fact they are slices of a sphere. Using a part of a sphere makes it possible to rotate every wheel around the axis perpendicular to their rotation axis. When all wheels are rotated over an angle of 90 degrees, the instrument rotates around the θ-axis (see left part of Figure 4.18). Rotating the wheels over a smaller angle the instrument rotates and translates in the same time. In this way a z, θ-actuator is created to actuate the instrument. An overview of this combination is given in the right part of Figure 4.18.

![Top view of Z,θ-drive combination](image)

**Figure 4.18: The wheels are rotated over 90 degrees which gives a θ rotation of the instrument. When the wheels are rotated over an angle α the instrument will be actuated in z and θ direction**

An advantage of this construction is that there is no slide necessary to guide the instrument which moves during φ and ψ-rotations. A disadvantage of this drive is the possibility of slip. During surgery the instrument gets wet, which cause a decrease of the friction coefficient between the wheels and the instrument.
4.3 Coupling between manipulator and instrument base

To get a modular construction and make the manipulators interchangeable, a connection will be made between the manipulator and the instrument base. This connection has to be strong enough to withstand the mass of the manipulator and the forces on the tip of the instrument. In this chapter two solutions will be given to create a connection.

4.3.1 Connection with three pins

The first solution to couple the manipulator and instrument base is using a mechanism of a turning lathe. In Figure 4.19 an overview of the manipulator side is given. This part has 3 pins, which fall in three holes in the instrument base. The notches in the three pins are used to fix the pins in the holes.

![Figure 4.19: connection between instrument base and manipulator with three pins, fitting in three holes of the instrument base](image)

Advantages / disadvantages:

An advantage of this construction is that the connection is very rigid because of the three pins fitting in the instrument base.

A disadvantage of this coupling is that the three pins have to fit exactly in the holes. The pins have to be aligned with the holes of the instrument base. This is difficult when the instrument base is positioned above the operation table, because the surgeon has to lift the weight of the manipulator in an awkward position and has to position the manipulator in the same time.
4.3.2 Semi cylindrical clamp

Another way of fixing the manipulator and instrument base is using friction. The manipulator side of the connector has a half cylindrical shape with a small edge on it (see Figure 4.20). This edge will catch a ridge of the instrument base (see Figure 4.21). During the first step of coupling the manipulator on the instrument base, the manipulator is laid on the cylinder of the instrument base. In this way, the person who carries the mass does not have to support the manipulator and is able to position the manipulator and close the connection.

The manipulator will be fixed by pushing the cylinder into the instrument base (see Figure 4.22). The manipulator side is pressed against the instrument base by force F. In this way the manipulator is fixed by friction created between the two parts. An extra pin is added in the instrument base, which fits exactly in the hole of the connector, to prevent the connection from rotating around the cylinder axis.

Figure 4.20: manipulator side of the connection between instrument base and manipulator

Figure 4.21: instrument base side of the connection

Figure 4.22: side-view / cross-section of the manipulator is placed on the instrument base. The next step is pushing the cylinder into its base.
Advantages / disadvantages:
An advantage of this construction is that the person who carries the manipulator is able to close the connector. One person is able to fix the manipulator.
A disadvantage of this mechanism is that the anti rotation pin has to fit exactly in the hole of the manipulator. When a small clearance is present, the friction has to withstand the torsion force (see Figure 4.22). If this friction force is large enough the pin is not necessary anymore and can be left out.
5 Parallelogram mechanism (properties)

The parallelogram mechanism, discussed in the previous Chapter has some advantages to control and to add force feedback. These will be discussed in this Chapter.

5.1 Uncoupling of movements

An advantage of the parallelogram mechanism is that the different movements during surgery are uncoupled. This means that every translation or rotation is driven by one single motor. In this way every single movement is controlled separately, which means the parallelogram mechanism is a multiple SISO system (single input single output). For this reason, the control of this system is not complex like the 6 rods mechanism, where for one single movement several motors have to be actuated.

5.2 Force feedback

To provide the surgeon with force feedback during surgery, the forces executed by instrument on the organs or tissue of the patient have to be measured. A force sensor can be used for every particular degree of freedom. These sensors participate in the force loop therefore their stiffness is of great influence. The best position for the sensors is the point of application of the force. In this way the construction has no influence on the measurement. When it is not possible to position a sensor on the desirable place, it is important to get a stiff construction between the force spot and the force sensor. Then the influence of the construction can be neglected. Because of lack of time, the exact placement of these sensors is not elaborated upon in this report. During a masters thesis this will be investigated further.
Conclusion / recommendations

In this traineeship three different designs are discussed: the six rods mechanism, “φ, ψ non-orthogonal cardan joint mechanism” and parallelogram mechanism. All of them have a virtual point of rotation. Because of lack of time the different mechanisms have not been elaborated upon the same level. Only the parallelogram has been investigated out further. This mechanism fulfills the requirements, by using a coupling between the instrument base and manipulator; it is possible to change manipulators before and during the operation. Another important part of the construction are some the coarse movements. These are movements which are executed before the operation starts. The movements are used to position the instrument above the incision and to position the instruments in the right direction. The different coarse movements are executed by two parallelograms and a cardanic joint. During the operation the parallelogram is actuated in φ and ψ-direction. Also the z-direction can be actuated by a slide mechanism or a z, θ-drive. So for every degree of freedom, an actuator is available. Because of the mechanisms have not been elaborated upon the same level, a definite choice is not made during this traineeship. When all variants have been elaborated upon a well founded choice can be made. Also combinations of the three variants or even new designs have to be investigated first. When a choice is made, some sensors have to be placed to measure the force executed by the instrument. By adding some actuators in the master, the forces can be felt by the surgeon. Then the chosen mechanism has to be designed in detail.
References
