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Flexible Instruments for a snake-like robot for Minimally Invasive Surgery

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Submitted in part fulfilment of the requirements for the degree of
Doctor of Philosophy in Computing of Imperial College London, April 2020

SELE

(Qapla) Klingon: *May you be successful.*

– *Lt. Worf, son of Mogh* ¹

¹Fictional character from *Star Trek: The Next Generation*

Abstract

Minimally Invasive Surgery (MIS) is a widely adopted technique due to the many advantages it holds for patients, e.g., reductions in healing times. In MIS one procedure within many is using a snake-like robot for scarless endoscopic surgery, such as gastrointestinal endoscopic surgery. In this type of surgery, the snake-like robot is inserted through a natural orifice and is directed towards a chosen surgical site. Once the robot is in place, small robotic instrument arms are deployed from the head of the robot to perform surgical tasks, e.g., cutting or suturing. These instruments need to have a small diameter of approximately $\varnothing 3\text{-}4\text{mm}$ such that they can be inserted through working channels or biopsy ports within the snake-like robot. Multiple designs of surgical instruments have been proposed in research, such as concentric tube robots, soft robots or rigid-links tendon-actuated robots. On the instrument tips grippers to hold the tissue, small scissors, or knives can be mounted. Other more special types of instruments are available as well. Surgeons can control the instruments remotely and see them through a camera which is mounted on the tip of the robot.

This thesis is part of the the *i²Snake* project which developed a homonymous snake-like robot with a length of 36.6cm and a diameter of 16mm. The length can be adapted by adjusting the length of the passive part to adapt to different procedures. In the scope of this thesis robotic instrument arms for the *i²Snake* robot were developed. Prototypes of these arms were built with a diameter of $\varnothing 4\text{mm}$ and $\varnothing 3\text{mm}$. Similar instruments with a diameter of $\varnothing 5\text{mm}$ and above were published before. For the new prototypes a rolling gear joint was developed to improve the accuracy of the arm and a gripper with an embedded distal roll. A shape sensor prototype was developed which only needs 3 receiving fibers. The 3mm instrument was optimised with a newly developed optimisation algorithm. To combine the developed approaches, a control was implemented which incorporates a reinforcement learning inverse kinematics and a mathematical model to compensate for backlash and joint coupling. The 4mm instrument with 7 DOF can bend up to 72° in each joint and has a rolling motion of 165.65° . The final 3mm instrument has 5 DOF, including a prismatic joint, and can bend up to 82° in each joint and roll



for 90° . The learned inverse kinematics is more precise in position and orientation error than the common Damped least-squares Jacobian pseudo-inverse, mainly because it has no problems with joint limits or complex situations. Using the proposed compensation methods, the backlash was significantly reduced so that the overall average positioning error was improved to 1.49mm.

Acknowledgements

I have studied computer science and learned a lot of programming for robots, but I was never able to learn how to build them. So the dream grew to see behind the curtains and start something new.

Starting my PhD at one of the most renown universities and being successful in a new field was due to the great guidance of my supervisor Professor Guang-Zhong Yang. I am grateful for all the support and that he always believed in me.

I would also like to thank Professor Lord Ara Darzi. I am honoured to have worked alongside and learned from such an incredible surgeon.

I would like to express my gratitude to my colleagues at the Hamlyn Centre, who became good friends over the time. I want to thank Piyamate, who helped me, especially in the early stage with a lot of creative ideas. He always had good advice in all kinds of situations. Furthermore, thank you to Konrad, who was a good friend during the time and beyond. Moreover, I want to thank Carlo, who introduced me to mechanical engineering, a new field for me in which I needed to gain a lot of experience. This part was later taken over by Shen, who helped me with his unlimited mechanical engineering knowledge. I hope I was able to pay something back by helping with the programming. A special thanks goes to Alex who helped me with my first publication, taught me how to work scientifically and later became my secondary supervisor. Another sincere thanks is for Pierre, who, although he was doing his own PhD, basically became my unofficial supervisor. He had so many good ideas, helped me when I was desperate, and we made many publications together. Without him, my PhD would not have been successful.

Moving to London and starting my PhD would not have been possible without the unwearied commitment of my parents, who always supported me with all their great wisdom. My brother Thomas was my inspiration and my motivation to follow in his footsteps. He helped me to endure in stressful times, such as writing up. All my love goes to my fiancée Ann-Katrin who gave me the energy and support to work on my thesis and took on all the flights to make this long-distance relationship work.

Declaration of Originality

I confirm that this thesis is my own work and that I have not used inadmissible help of third parties. All material in this dissertation, which is not my original work, has been properly acknowledged and referenced accordingly.

This thesis has not been submitted for any degree or other purposes.

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Abbreviations

ABS	-	Acrylonitrile butadiene styrene
ABME	-	Annals of Biomedical Engineering
ADC	-	Analog-to-digital converter
CPU	-	Central Processing Unit
DCM	-	Dexterous continuum manipulator
DH	-	Denavit-Hartenberg
DLS	-	Damped least-squares
DOF	-	Degrees of Freedom
DQ	-	Dual quaternion
EC	-	Electronically Commutated (Motor)
EGaIn	-	Eutectic Gallium-Indium
EM	-	Electromagnetic
ENT	-	Ear, Nose and Throat
ESD	-	Endoscopic Submucosal Dissection
FBG	-	Fiber Bragg Grating
FDA	-	Food and Drug Administration
FK	-	Forward Kinematic
FLS	-	Fundamentals of Laparoscopic Surgery
FOS	-	Fiber Optical Sensing
GA	-	Genetic Algorithm
HARP	-	Highly Articulated Robotic Probe
HD	-	High Definition
HTM	-	Homogeneous Transformation Matrices
ICRA	-	International Conference on Robotics and Automation
IEEE	-	Institute of Electrical and Electronics Engineers

IK	-	Inverse Kinematics
IROS	-	International Conference on Intelligent Robots and Systems
LED	-	Light-Emitting Diode
LIM	-	Light Intensity Modulation
MIS	-	Minimally Invasive Surgery
MLP	-	Multi-layered Perceptron
MMF	-	Multi-mode Optical Fiber
MRI	-	Magnetic Resonance Imaging
NA	-	Numerical Aperture
ND	-	Neutral density
NN	-	Neural Network
NOTES	-	Natural Orifice Transluminal Endoscopic Surgery
PhD	-	Doctor of Philosophy
PMDS	-	Polydimethylsiloxane
POEM	-	Per-oral Endoscopic Myotomy
PPO	-	Proximal Policy Optimization
PTFE	-	Polytetrafluoroethylene
QC	-	Quad Counts
RL	-	Reinforcement Learning
RMS	-	Root Mean Square
ROS	-	Robotic operation system
SLM	-	Selective Laser Melting
SVD	-	Singular Value Decomposition
VR	-	Virtual Reality

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Chapter 1

Introduction

Although open surgery is still the most common kind of surgery, Minimally Invasive Surgery (MIS) is a widely adopted technique due to the many advantages it holds for patients, e.g., reductions in healing times. In MIS one or more small incisions are created to insert laparoscopic tools, which are long shafts with small instruments at the tip. These instruments include grippers to hold the tissue, small scissors or knives, and a camera to enable the surgeon to see the operation site on a monitor. Other more special types of instruments are available as well. Currently, tools of MIS are stiff and cannot reach all operation sites.

In recent years, snake-like robots [5, 33, 34, 35, 36, 37, 38] for Minimally Invasive Surgery usable in endoscopic surgery, e.g., ear, nose, and throat (ENT) surgery, have gained increasing interest in the research community. These are articulated robots which can access areas deep inside the human body through natural orifices, such as the mouth, urethra or anus. The snake-like robot (in the thesis abbreviated as snake or snake robot) is inserted through a natural orifice and is directed towards a chosen surgical site. Then small instruments are deployed from the head of the robot to perform minimally invasive surgical tasks, e.g., cutting or suturing. These instruments need to have a small diameter of approximately $\varnothing 3\text{-}4\text{mm}$ such that they can be inserted through working channels or biopsy ports within the snake-like robot. Multiple designs of surgical instrument have been proposed in research, such as concentric tube robots, soft robots or rigid-links

tendon-actuated robots. The surgeon can control these instruments remotely and see them through a camera which is mounted on the tip of the robot. The focus of this work is to develop rigid-link tendon-actuated instruments. This means that the motors are placed at the proximal end and the force is transmitted through cables to the rigid links. The design is based on a design for 5mm instruments by Shang *et al.* [14].

1.1 Medical Motivation, Background, and Application

To design the instruments in an appropriate way, the possible applications of the instruments and the snake-like robot need to be defined and evaluated.

MIS is a well adopted technique. It uses laparoscopic tools to operate in areas through only small incisions. MIS reduces the impact on the patient significantly. The patients experience

- reduced exposition of organs,
- faster recovery,
- reduction of lengths of time for which patients are hospitalised, and
- fewer and smaller scars, which is increasing the quality of life.

MIS has numerous applications. In [1] Burgner-Kahrs *et al.* describes different areas of surgery already targeted by robotic surgery platforms. The authors mentioned the following areas (see Figure 1.1):

- Neurosurgery
- Otolaryngology
- Ophthalmic Surgery
- Abdominal Surgery

- Cardiac Surgery
- Vascular Surgery
- Urologic Surgery

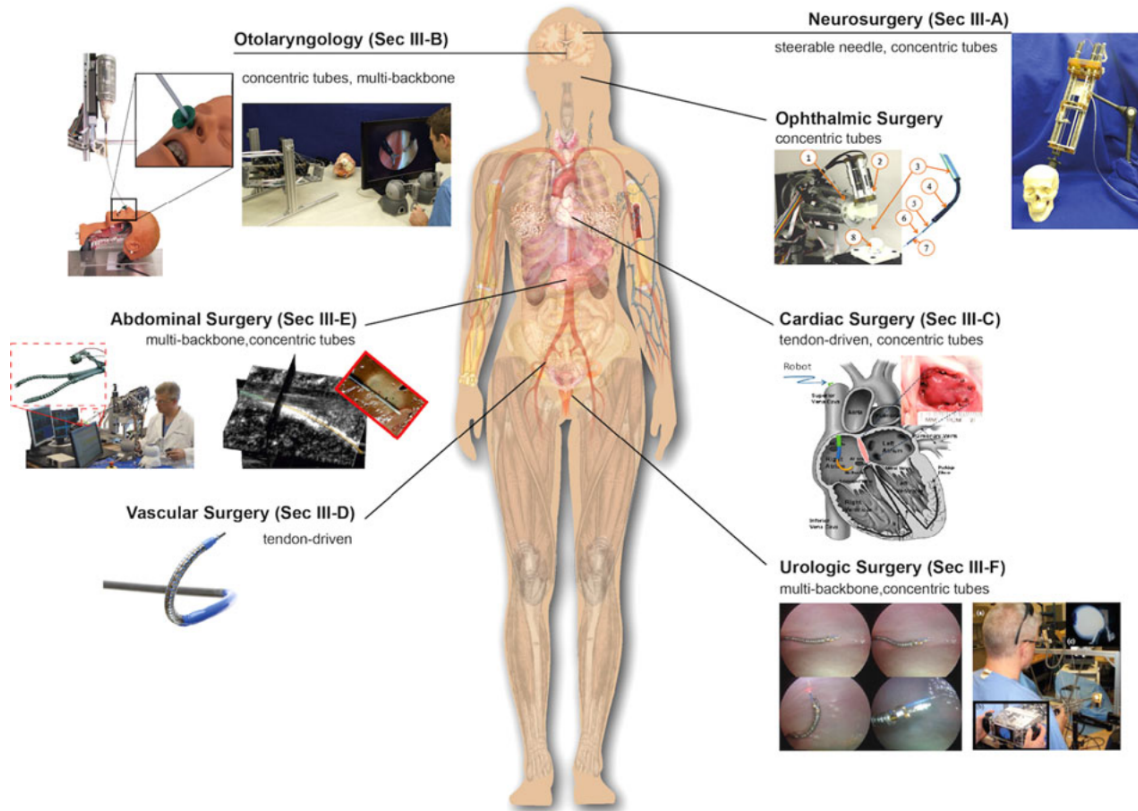


Figure 1.1: The surgical areas targeted by different research platforms. (Source: [1])
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Beside these areas, another very interesting area for robotic surgery is ear, nose, and throat (ENT) surgery and gastrointestinal surgery. Although it is not mentioned in the summary in [1] there are some research projects targeting this area. For the project of this thesis, the focus lays on ENT surgery. An extended version of the snake-like robot presented in this thesis could reach the stomach revealing potential additional applications in upper gastrointestinal surgery.

The typical area of application of ENT-Surgery is shown in Figure 1.2. Due to the targeted size the snake-like robot can be used in surgeries in areas of mouth, tongue, and esophagus. Several surgery procedures exist in this area which are performed on a

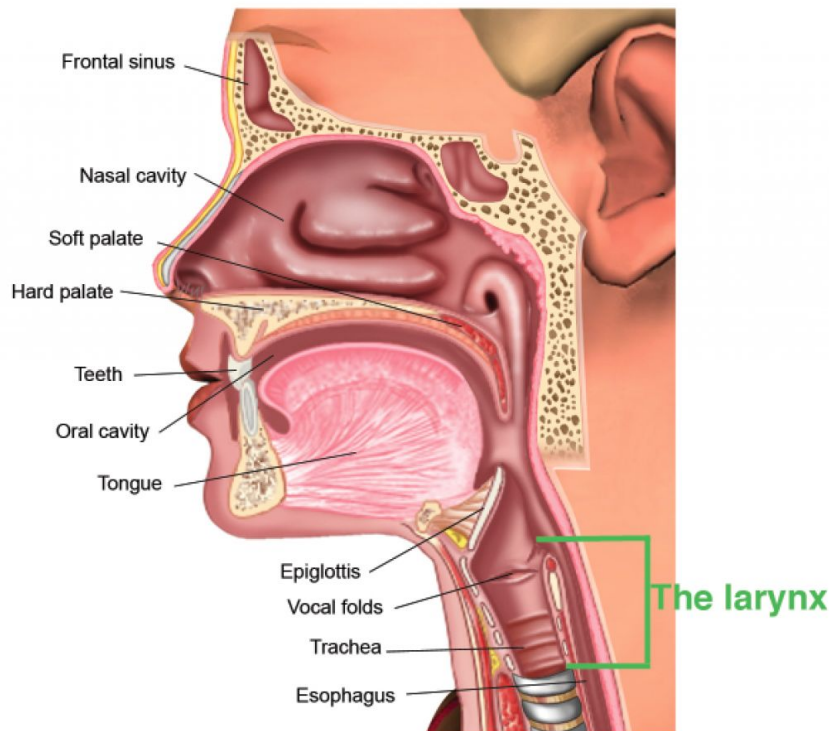


Figure 1.2: Structure of the upper respiratory tract. (Source: [2]) ©

daily basis. The following, surgical ENT procedures are well suited for a snake-like robot as they can be performed through the mouth and the traditional methods are usually invasive and difficult to access [39]:

- **Tonsillectomy and Adenoidectomy (T&A)** is one of the most common procedures performed today. Tonsils and adenoids are located in the back of the mouth. They are lymph nodes of which the removal has only a minimal impact on a patient's immune system. It is not unusual for children to have enormous tonsils or adenoids which can cause functional problems, e.g., trouble with swallowing, which is a sleeping disorder where the breathing of the affected person can suspend during the sleep. Because the surgery site is in the mouth area, there is a large working space for the robot.
- **Nasal and endoscopic sinus surgery** is now performed entirely through the nose without any incisions. The most common reason is chronic sinusitis which is a swelling of the nose and sinuses. Infections, nasal polyps, allergies, or irritants may

be a cause. Due to the limited space in this area it is not possible to use a snake-like robot for nasal and endoscopic sinus surgery.

- **Thyroidectomy** is a surgical procedure to remove parts or all of the thyroid gland. The thyroid gland is a hormone steering, butterfly shaped organ, which is located at the trachea at the height of the neck. It is often performed when a patient has thyroid cancer, hyperthyroidism or goiter. Despite there is small space in the trachea, it is possible to work here with a snake-like robot.
- **Radical neck surgery** is a surgery method for the excision of cancerous lesions in the area of the neck. Classic radical neck dissection is an open surgery procedure and still the criterion standard for surgical control of a neck metastasis. An Minimally Invasive Surgery method for parts of neck metastasis disease would be a huge improvement, if no external procedure is needed. Although there is only limited space in the trachea area, it is possible to work there with a snake-like robot.
- **Laryngotracheal reconstruction surgery** widens the trachea to provide a safe and stable airway. In this procedure small pieces of cartilage (stiff tissue) are inserted into the narrowed section of the trachea to make it wider. The problem of a narrow trachea may occur for many reasons, e.g., injury, infection, or a birth defect.
- **Surgery for throat cancer** is the preferred treatment for early-stage throat cancers. There are several different procedures available for different locations of cancer and different stages, e.g., vocal cord stripping, Cordectomy, (partial or total) Laryngectomy, Pharyngectomy, Myocutaneous flaps, Free flaps, Tracheoesophageal puncture, Lymph node removal, or Tracheotomy/Tracheostomy. All these procedures try to cut away the tumor at a specific location. For some of them, a Minimally Invasive Surgery using a snake-like robot may be possible.
- **Per-oral Endoscopic Myotomy (POEM)** is a Minimally Invasive Surgical procedure used for the treatment of achalasia using a flexible endoscope. The entire procedure can be done without external incisions. Achalasia is a disease because of which the lower esophageal sphincter is unable to open. It makes it impossible

for food or liquids to pass into the stomach. To solve this problem the inner circular muscle layer of the lower esophageal sphincter is divided through a submucosal tunnel. This procedure is perfect for a snake-like robot to perform, although a long robot is needed to reach this point.

- **Endoscopic Submucosal Dissection (ESD)** is a surgical procedure using an endoscope to remove gastrointestinal tumors. ESD can be done in the esophagus, stomach, or colon. It is possible to use a snake-like robot for this procedure in the esophagus.

In the Section 1.3 these procedures are evaluated to find the necessary requirements for the instruments of the snake-like robot.

1.2 The *i²Snake* Project

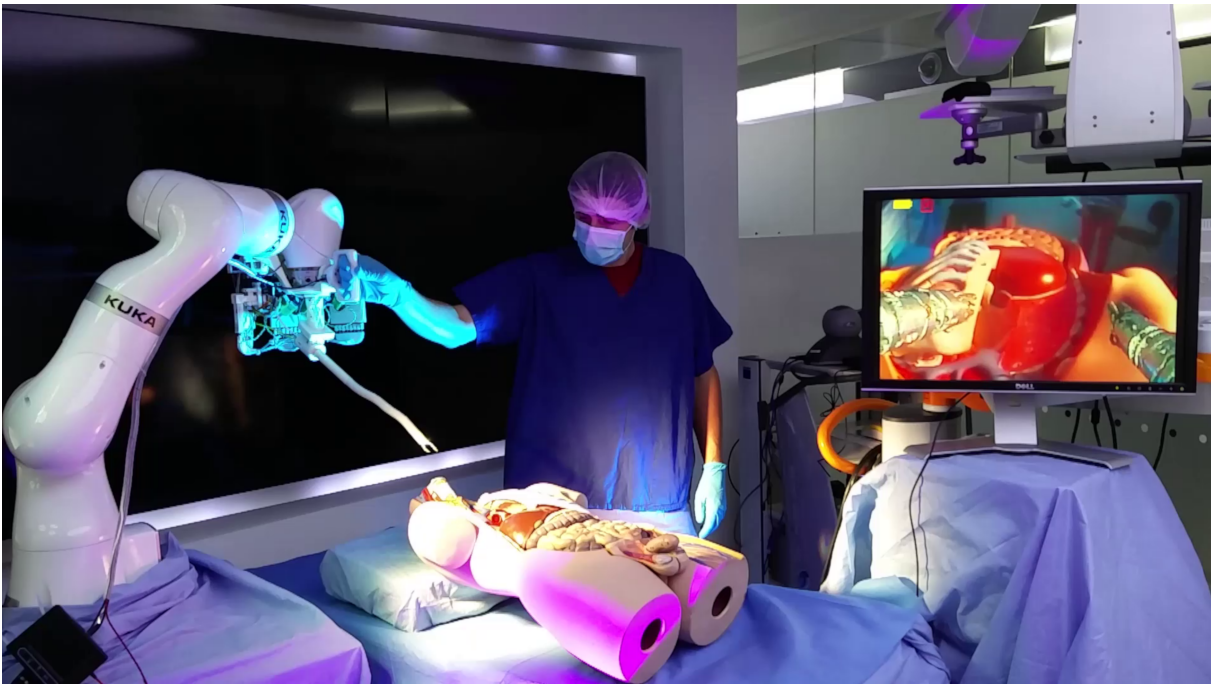


Figure 1.3: The snake robot using instruments developed in this thesis for a demonstration. ©

The developments of this thesis are in the scope of the *i²Snake* project. The goal of the project was to create a snake-like robot for the surgery applications discussed in Section

1.1, e.g., ENT surgery. Figure 1.3 shows a demonstration of such a surgery. Multiple PhD students worked on the project. The focus of this thesis lays on the development of the two instruments, including mechanical and control aspects.

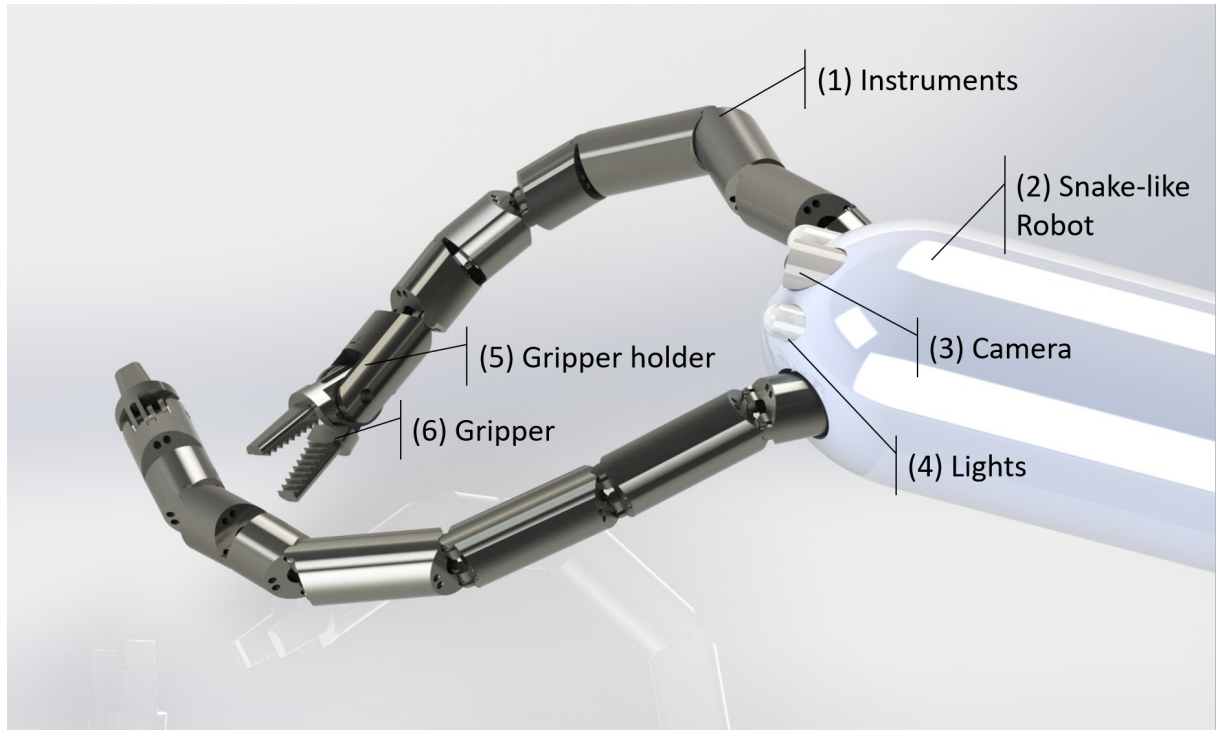


Figure 1.4: The i^2Snake head with lights, camera, and two robotic instruments. ©

The robotic actuated i^2Snake surgical robot has a diameter of $\varnothing 16\text{mm}$, a length of 36.6cm , and 7 degrees of freedom (DOF). All DOF are tendon driven, using Bowden cables. All Bowden cables are guided along the centre of the snake body. This limits the problem for joint coupling. A Bowden cable is a tendon with a housing constructed of a helical winded coil cable. It is used to transmit a force by changing the difference in the tension between the tendon and the housing cable. The total length of the i^2Snake can be adapted by adjusting the length of the passive part to adapt to different procedures.

At the tip the i^2Snake robot has a head with a camera and two LED-lights, shown in Figure 1.4. Two channels which go through the entire snake body end at the head. These channels can guide two flexible fully-articulated robotic instrument arms (in this thesis abbreviated as instruments) and deploy them from the snake head. Through the camera the instruments can be seen by the operator. The snake robot is used as a master positioning system for the instruments.

The instruments for the *i²Snake* consist of rigid links which are combined to joints. The instruments are also tendon actuated and most of the joints are loosely connected by tensioning the tendons. Most of the joints are controlled by two antagonistic wires which are driven by one motor. At the tip the instruments have a surgical instrument like a cutter, a knife, or a gripper.

The *i²Snake* and the instruments are controlled by two handles, also called controllers. By pressing a button at the hand controllers the operator can switch between snake and instruments. The instrument tips follow the movement of the handles using inverse kinematics.

The design is based on a design for instruments for single-port transanal microsurgery with a diameter of $\varnothing 5\text{mm}$ published by Shang *et al.* [14] and developed in Hamlyn Center. These instruments cannot fit into the *i²Snake*. One main focus of the thesis is to reduce the diameter to $\varnothing 4\text{mm}$ and further to $\varnothing 3\text{mm}$. The smaller diameter of the instruments and thus the smaller diameter of the master positioning system (in this case the *i²Snake*) allows to use the *i²Snake* for transoral surgery while the 5mm-instruments are used for transanal surgery.

1.3 Requirement Analysis

Minimally Invasive Surgery is usually done with manually operated endoscopes. So the question arises, why is there a need for robotic endoscopic surgery? The reason is that the currently used endoscopes have some typical drawbacks:

- Although there are flexible endoscopes available, endoscopes are usually rigid which leads to a reduced triangulation.
- Endoscopes have a reduced tactile perception. The surgeon can only indirectly feel the force he is exerting to the tissue. The perception of the tissue is entirely gone.

- Since the endoscopes use an entry point to reach the operation site this entry point is a pivot point which leads to an inverse movement of the endoscope's tip. An up movement of the surgeon's hand results in a down movement of the tip. This is called fulcrum effect.

Nowadays there are some robot aided systems for endoscopic surgery shown in current research literature and even available on the market. These systems still have some drawbacks:

- Since most robot systems use small incisions to enter the body, they are limited to areas easily accessible from the outside.
- Many current systems suffer from backlash and joint coupling. Although this is improved in commercial systems by perfecting the manufacturing procedure, these problems are still unsolved. Software compensation has to be established.
- During most surgery, surgeons often use in-place rolling. In-place rolling is a motion in which the instrument shall remain in place and only the rolling motion should be applied. However, currently the used instruments are lacking a rolling motion of the end-effector. If a axial roll at the instrument shaft is used, all joints need to move which leads to an unstable end-effector.
- The currently presented robotic systems often have diameters beyond $\varnothing 20\text{mm}$ and are used for Anoscopy or Rectoscopy. For Gastrosocopy the size of a robotic endoscope in diameter has to be reduced. Often the diameter of the instruments is a limiting factor.
- During an operation the joints may slip, which then acts as a sudden unpredictable movement of the instrument arms. This can lead to dangerous situations.

In the previous section possible clinical applications for a snake-like robot were presented. Based on these, the requirements for the length of the instruments used in the *i²Snake* have been derived. The results are shown in Table 1.1.

Surgery Procedure	Operation Area	Space	Instrument length
Tonsillectomy and Adenoidectomy (T&A)	Operation in mouth area	much space	few cm long
Nasal and Endoscopic Sinus Surgery	Nasal area, snake needs to be very small, is it possible to just use the instruments?	If fitting inside, much space	few cm long
Thyroidectomy	In trachea	little space	As small as possible. The maximal length depends on the possibility to stretch or inflate the environment. Further investigation needed.
Radical Neck Surgery	In trachea	little space	
Throat, Laryngotracheal Reconstruction Surgery	In trachea	little space	
Surgery for throat cancer	In trachea	little space	
Per-oral Endoscopic Myotomy (POEM)	Deep in trachea, long snake-like robot needed, working along the channel	medium space	few cm long
Endoscopic Submucosal Dissection (ESD)	- In esophagus - In stomach, long robot needed	- little space in esophagus - much space in stomach	

Table 1.1: Requirements of the maximal length of the instrument.

In summary, the instrument has to be just a few centimeters long to be able to work in large spaces. In the narrow environments the space depends on the possibility to inflate or stretch the environment. Therefore, the acceptable instrument length depends on the inflation. Further, these instruments need to have a small diameter of approximately $\varnothing 3\text{--}4\text{mm}$ such that they can be inserted through working channels or biopsy ports within the snake-like robot. Smaller diameters, such as 3mm, enable smaller diameters for the snake robot. This increases the patients comfort and reduces skin irritations in the Trachea. Due to the deployment of the instruments through the snake robot, these instruments need to have a flexible shaft. In addition, ideal instruments should be inexpensive and disposable to allow for sterile operation. To be disposable, the instruments themselves need to be kept as simple as possible, with complex components such as motors being transferred to the proximal end.

The robot needs to have enough joints to be able to reach a sufficient workspace. For that, it needs a distal-roll to be able to rotate the gripper. Further, it is helpful to use a wrist to minimize the length of the instrument. Simulation tests and workspace analysis can be used to analyze the design of the instruments.

1.4 Research Objectives

Following the requirements, the goals of this thesis were to create instruments for the *i²Snake* robot. In more detail:

- Investigate how the diameter of robotic instruments arms can be minimised (e.g., to $\varnothing 4\text{mm}$ or $\varnothing 3\text{mm}$) and still have full motion capabilities, like a wrist including a rolling motion with a flexible body to guide the tendons through the channels of the *i²Snake*.
- Investigate how shape sensing could be integrated into these instruments.
- Investigate how to improve the control of these instruments, especially to reduce the backlash and joint coupling.

Overall, the work done in this thesis contributes in a number of significant steps towards a fully integrated robotic instrument system for the *i²Snake* project.

1.5 Contributions

The contributions to the research field by this thesis are listed here for each chapter. Most of the contributions are published in journals or high ranking conferences, such as ICRA or IROS. The publications are shown in Section 1.6.

Chapter 3 – Mechanical Design of the Instruments for a Snake-like Robot

- Flexible instruments with diameters below $\varnothing 4\text{mm}$ were designed and fabricated for use with the *i²Snake*.
- A flexible shaft was introduced to the instruments instead of a rigid shaft, which is used in previously reported instruments. This was needed because the tendons need to pass through the articulated body of the *i²Snake* robot. This shaft needs to transmit force to articulate the arms.
- One of the major contributions is the introduction of a distal-roll gripper. It was necessary because the flexible shaft makes a proximal roll by axial roll of the shaft impossible. Additionally, it enabled stable in-place rolling, because all other joints are unaffected by the roll motion in contrary to a proximal roll solution.
- A rolling gear joint was developed to reduce non-linearities while steering one joint with one motor. This helps with the problem that the tension inside the tendons change dramatically with hinge joints during movement. Instead of using common rolling joints with flat surfaces, a gear is used to resolve slip which is common when using rolling joints.
- The instrument diameter was decreased to a diameter of $\varnothing 4\text{mm}$ and later further to a diameter of $\varnothing 3\text{mm}$. In research similar instruments using rigid links with a

diameter of 5mm are common. An instrument for each diameter was built, an arm-like 4mm-instrument with 7 DOF and a more simple one with 5 DOF. For the 4mm instrument, a 4mm ball joint and a gimbal joint were developed. A 3mm-instrument was build. The design for the instrument was optimised using a genetic algorithm. A rolling gear joint was developed for this arm and the distal-roll gripper was reduced in size.

Chapter 4 – Design Optimisation

- An automated design optimisation and generation method was developed using a genetic algorithm, which exploratively tests tens of thousands of designs to solve a recorded task considering mechanical constraints. The task was a recorded suturing trajectory, carried out by a human.
- For this method a down-sampling algorithm was developed to speed up the search. The down-sampling also includes key points, like extrema, and keeps the data synchronous. It also scales the data to the targeted operation area, because the recorded data was in a human hand scale.
- Multiple optimal designs with different focuses were studied and the importance of some key features of the instruments were investigated. The outcome showed the importance of the prismatic joint and the distal-roll.

Chapter 5 – Shape Sensing Using Optical Fibers

- To search for a shape sensing possibility other than fiber Bragg grating, a light intensity modulation based angle measurement was developed. Three optical fibres in the proximal link of one joint were used to receive light reflected from the distal surface.
- Multiple link designs were tested to find the optimal design and fibre placement.
- A shape sensing algorithm based on machine learning was developed and tested.

Chapter 6 – Control of Instruments

- An instrument control architecture was developed.
- Beside using a Jacobian pseudo-inverse solver for inverse kinematics, a learned inverse kinematics using Proximal Policy Optimisation reinforcement learning was developed. It has the advantage to find solutions even in hard configurations and to be fast and reliable. A safety layer was developed to filter out possibly dangerous cases.
- A mathematical model for controlling an instrument using the rolling gear joint solves the joint coupling problem and analyses the tendon slack.

1.6 Publications and Awards

1.6.1 Journal Publications

- Berthet-Rayne, P., Gras, G, Leibrandt, K., Wisanuvej, P., **Schmitz, A.**, Seneci, C. A., and Yang, G-Z., "The *i²Snake* robotic platform for endoscopic surgery". Annals of Biomedical Engineering (ABME), 2018

1.6.2 Conference Publications

- **Schmitz, A.**, Berthet-Rayne, P., and Yang G-Z., "Endoscopic Bi-Manual Robotic Instrument Design Using a Genetic Algorithm", IEEE International Conference on Intelligent Robots and Systems (IROS), 2019
- **Schmitz, A.**, Treratanakulchai, S., Berthet-Rayne, P. and Yang, G-Z., "A Rolling-Tip Flexible Instrument for Minimally Invasive Surgery", International Conference on Robotics and Automation (ICRA), 2019.
- **Schmitz, A.**, Thompson, A. J., Berthet-Rayne, P., Seneci, C. A., Wisanuvej, P., and Yang, G-Z., "Shape sensing of miniature snake-like robots using optical fibers",

In IEEE/ RSJ International Conference on Intelligent Robots and Systems (IROS), 2017.

- **Schmitz, A.**, Berthet-Rayne, P., and Yang, G-Z., "Optimization of Simple Endoscopic Instruments using a Genetic Algorithm", in Hamlyn Symposium, 2019.
- **Schmitz, A.**, Thompson, A.J., Berthet-Rayne, P. and Yang, G-Z., "Discussion of Link Designs for Fibre optic Shape Sensing in a Snake-like Robot", Hamlyn Symposium on Medical Robotics, 2017.

1.6.3 Awards

- Best Demonstration: **Schmitz A.**, and Berthet-Rayne P., "The i2Snake VR simulator", Hamlyn Christmas Showcase, 2017, see Appendix B.
- Best Design Prize, Hamlyn Symposium on Medical Robotics, Robotics Challenge, 2017, shown in Appendix A. The best design prize is awarded by an independent judging panel composed of 8 persons from academia, industry and the medical field.

1.6.4 3D Printer Lab Leader

- Head of the Printer Lab: For the two last years of the PhD, I was in charge of the 3D printer lab.

1.7 Chapters overview

This thesis presents the design and implementation of fully actuated robotic surgical instruments for the *i²Snake* project.

Chapter 2 reviews the existing research in the different fields which needed to be targeted by this thesis. It first gives a brief overview over the existing commercial systems.

Then, the mechanical designs of snake-like systems and robotic instrument arms are discussed. Especially, a focus is given on a wrist joint and distal rolling motion. Further, Shape sensing is reviewed in detail. Although the fiber Bragg grating (FBG) is currently dominant in the research, there are other intriguing ideas. Last, the focus lays on the control of the instruments.

Chapter 3 describes the mechanical design of the developed instruments. It starts with an overview of the whole system, explains the two instrument iterations designed in this thesis with a diameter of $\varnothing 4\text{mm}$ and $\varnothing 3\text{mm}$, and explains all joints used. A special focus is given to the rolling gear joint and the distal-roll gripper, which were developed and published in this thesis.

Chapter 4 describes an automatic design optimisation method using a genetic algorithm developed to design instruments for surgery tasks. A suturing task was manually executed and the trajectories recorded. The data was used by the algorithm to automatically test thousands of different designs and to find different solutions. It was developed during this thesis and applied for the 3mm instrument. Further, the chapter discusses different solutions and stresses out important endoscopic design features.

Chapter 5 introduces an optical shape sensing approach. It uses optical fibres for Light Intensity Modulation (LIM) to transmit light to the joint and to measure the reflected light. It was possible to measure the angle of that joint with neglectable errors.

Chapter 6 explains the control of the robotic endoscopic instruments in detail. The control uses an inverse kinematic, which is trained using reinforcement learning, instead of an inverse kinematics solver, as well as backlash compensation and cross-talk compensation. This chapter explains the integration of all components into one system.

Chapter 7 finally summarises the achievements, discusses the limitations and outlines the future work.

Chapter 2

Literature Review

Actuated, snake-like, endoscopic robots and their surgical instrument arms are an important research area. Many new designs appear on the market and in research. For this thesis the following relevant main topics are further discussed. First, an overview over commercial systems is given in Section 2.1. A main focus of this thesis is the mechanical design of the robotic instrument arms. Different designs are discussed in Section 2.2. Shape sensing is reviewed in depth in Section 2.3 and control algorithms in Section 2.4.

2.1 Commercial Systems

Some surgery robot systems reached a high quality and have made it to a commercial product. An overview about some of the important commercial systems is given in Table 2.1. The first robotic surgery system approved by the Food and Drug Administration (FDA) in USA was the AESOP system in 1990, which was built by Computer Motion, Inc. and later became the ZEUS Robotic Surgical System [40]. In 2003 the company was acquired by Intuitive Surgical, Inc. [41]. TCAT from Think Surgical Inc. [42], which is based on Robodoc, is an MIS system which got FDA clearance. In [43, 44] Schulz and Pransky published experiences and results from the operative use. The Flex Robotic System is a commercial continuum robot made by Medrobotics Corporation [45]. It was

former known as CardioARM and HARP, Highly Articulated Robotic Probe [46]. The Flex Robotic System received FDA clearance in 2015.



Figure 2.1: Sample scene with daVinci Xi System from Intuitive Surgical Inc. together with the operation table TruSystem™ 7000dV OR Table from Trumpf Medical, a subsidiary of Hill-Rom, Inc. (Batesville, IN, USA) since 2014. (Source: [3])

The daVinci Surgical System is the most famous surgical robot system made by Intuitive Surgical, Inc. [47]. It consists of a large robot base with several robot arms (currently 4). A surgical instrument is mounted at each arm. With a surgeon console the surgeon can see the surgical area from the point of view of a camera mounted on one arm. Thus the surgeon can see the tools in front of him. The new daVinci Xi System, which is the successor of the daVinci Si System, is shown in Figure 2.1. One of the biggest improvements is that the arms are mounted on a holder, which positions the center of the arms above the patient. This allows the practitioner to operate from both sides. Currently, Intuitive Surgical is developing daVinci Single-Site Surgery, a system based on their previous systems, but which only needs one access port to access the operation site. There are some known introductions of this system. In May, 2016 a 60-year-old woman from Chicago underwent a gallbladder removal using a daVinci Xi at Ingalls Memorial Hospital (Chicago, USA) [48] and in June, 2016 a 15-year-old child had her gallbladder removed at Nicklaus Children's Hospital (Miami, USA) [49].

Institution	Robot Name	FDA Approved	Type	Comment
Computer Motion	AESOP Robotic Surgical	FDA 1990	Single robotic laparo-	First robotic surgical sys-
	System		scopic surgery	tem with FDA-approval, became ZEUS Robotic Surgical System
Computer Motion	ZEUS Robotic Surgical	FDA 2001	Multi robotic laparo-	In 2003 the company
	System		scopic surgery	was acquired by Intuitive Surgical, Inc. [41]
Think Surgical Inc.	TSolution One Surgical	FDA 2014	Robotic milling laparo-	
	System / TCAT		scope	
Intuitive Surgical	daVinci Xi System	FDA 2014	Multi robotic laparo-	The daVinci Surgical
			scopic surgery	System is the most fa- mous surgical robot sys- tem made by Intuitive Surgical, Inc. [12]
Intuitive Surgical	daVinci Si System	FDA 2020	Multi robotic laparo-	
			scopic surgery	

Medrobotics	Flex Robotic System	FDA 2015	Robotic endoscopic surgery	It is a snake-like robot
Sofar	Alf-x	No FDA	Multi port surgery	TransEnterix acquired the ALF-X Surgical Robotic System
Aktormed Robotic Surgery	Soloassist	No FDA	Robotic laparoscopic control	
TransEnterix	Senhance Surgical System	FDA 2017	Multi robotic laparoscopic surgery	Senhance is based on Alf-x
TransEnterix	SurgiBot	Failed FDA [50]	Single port laparoscopic surgery	
Tuebingen Scientific	r2-drive, r2-curve	No FDA, but CE	Robotic augmented laparoscopic surgery	
Endocontrol	Jaimy	No FDA, but 2011 CE	Laparoscopic Instrument	
Endocontrol	Viky EP	FDA 2008	Endoscope Camera Positioner	
Virtual Incision	-	No FDA	Single port laparoscopic surgery	Arm thick body, two finger thick instruments

Titan Medical Inc.	SPORT Surgical System	No FDA	Single port laparoscopic surgery, two instruments
Endotics	Endotics System probe	No FDA	Single Port Surgery Snake-like single port robot, rare movement method
Invendo Medical	Invendoscopy E200 System	FDA 2016	Robot augmented Endo-scope Uses a cable to cut or grab tissue, has water jet and sucking system
Dexterite Surgical	DEX agile robot	N/A	Robot augmented laparoscopic surgery It is hold in hand by the surgeon
Hansen Medical	Sensei / Magellan Robotic System	FDA 2007	Single port endoscopic heart surgery Sized down to 2mm, bought by Auris Surgical Robotics, Inc. [51]
Catheter Robotics	Amigo Remote Catheter System	FDA Aug 2012	Catheter remote control
Accuray	CyberKnife	FDA 1999	Massive Robot arm for radio surgery

Stryker Corporation	Mako Robotic-Arm As- sisted Surgery	FDA March 2015	Robotic milling laparo- scope
Stereotaxis	Niobe	FDA 2010	Catheter
Restoration Robotics	ARTAS Robotic System	FDA 2011	Robot Arm for hair transplantation
Medtech	Rosa	N/A	Robot Arm Stiff endoscopy for brain surgery
Corindus Inc.	CorPath GRX	FDA 2012	Vascular Catheter Philips has a co- operation and sells Corindus CorPath® 200 Robotic-assisted PCI system
Renishaw	Neuromate Gen II	N/A	Robot arm for neuro- surgery

Table 2.1: Robotic Surgical Systems

2.2 Mechanical Design of the Instruments

Snake-like instruments' arms in general share similar problems as snake-like robots, except that they are much smaller and therefore have a special focus on miniaturization and problems attached to this. This increases the complexity even more. In research a lot of different designs have been proposed.

Burgner-Kahrs *et al.* tried to specify and categorize the different designs in [1]. They showed the different clinical applications of the robot designs and categorised them by their structure and actuation into eight groups, see Figure 2.2. The focus of this thesis is on tendon/cable actuation with discrete rigid structures. Table 2.2 shows different systems from different institutions. It uses the categorisation of [1] for specifying the type.

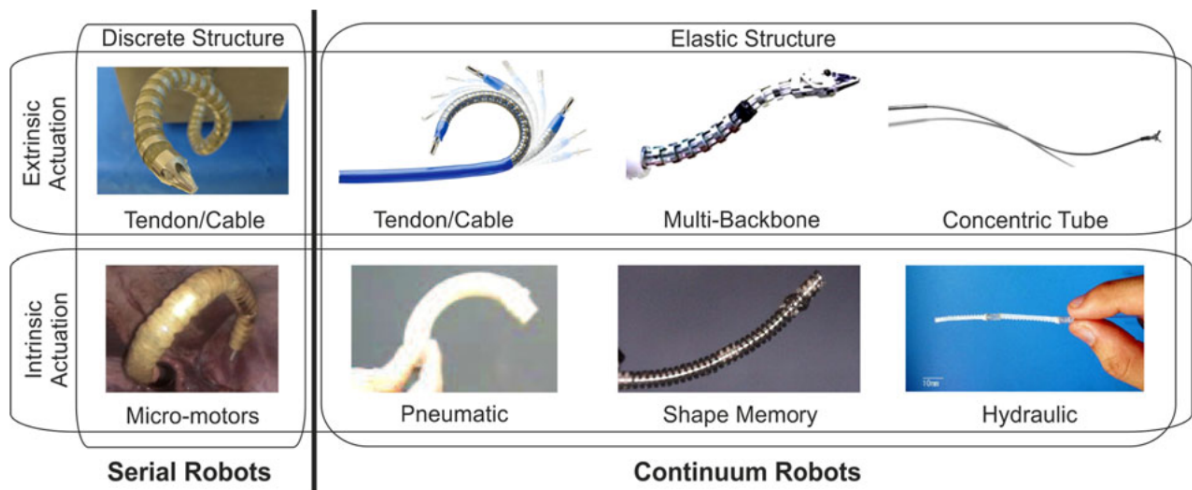


Figure 2.2: Categorization in different dimensions of surgical robots found in research. (Source: [1]) © 2015 IEEE

A comprehensive study of mechanical designs from different research groups is displayed in Table 2.2. Some highlights are discussed in this Section.

Group / Institution / First Year	Research	Type	$\varnothing \times l$ [mm]	Max DOF
Nakamura, <i>University of Tokyo, Japan</i> (2000)	90° moving range in one direction. In total the instrument can bend in two directions. [52, 53]	Extrinsic Actuation / Discrete Structure / Tendon/Cable	6mm x 14mm	4 DOF+G
Nishizawa <i>et al.</i> <i>Hitachi Ltd.</i> (2004)	Complex joint with gears and pulleys. The gripper tendon-lengths are mechanically independent from the wrist joint. Due to the complexity only 2 DOF + Gripper is shown. [54]	Extrinsic Actuation / Tendon/- Cable	5mm x N/A	2 DOF+G
Ikuta <i>et al.</i> <i>Nagoya University, Japan</i> (2003)	Tendon driven joint with spring to tension the tendons. [55]	Extrinsic Actuation / Tendon/- Cable	3mm x N/A	5 DOF +2G
Degania, Choset <i>et al.</i> <i>Carnegie Mellon University,</i> <i>USA</i> (2006)	HARP. Can only control the first part. Movement of 15° [56, 7, 46]	Extrinsic Actuation / Discrete Structure / Tendon/Cable	12mm x 300mm	17 DOF (extendable)

Ishii <i>et al.</i> <i>Shibaura Institute of Technology, Japan</i> (2010)	Skrew driven joints, very strong (4N) but limited number of joints possible. 30° bending motion [8]	Extrinsic Actuation / Discrete	50mm x 635mm	3 DOF+G
Meer <i>et al.</i> <i>University of Toulouse, France</i> (2005)	Arm consisting of Ball joints with wires for driving and wires for rotation avoidance. [57, 10]	Extrinsic Actuation / Discrete Structure / Tendon/Cable	6mm x N/A	5 DOF+G
Guckert <i>et al.</i> <i>The University of Western Ontario, Canada</i> (2011)	Ball joint with four tendons [11]	Extrinsic Actuation / Discrete Structure / Tendon/Cable	3mm x N/A	3 DOF joint
Simaan, Taylor <i>Johns Hopkins University, USA</i> (2004)	Instrument with stiff backbone, tendon driven [9]	Extrinsic Actuation / Elastic Structure / Multi-Backbone	4mm x 30mm	2 DOF joint
Tappe <i>et al.</i> <i>Leibniz Universität Hannover, Germany</i> (2015)	Electromagnetic joints, discreet motion [58, 6]	Intrinsic Actuation / Discrete Structure / electromagnetic	16mm x N/A	
Minor, Mukherjee <i>Michigan State University</i> (2001)	Gear driven device, approx. [59]	Extrinsic Actuation / Discrete Structure / Gear driven	10mm x 30mm	2DOF+G

Yamashita, Dohi <i>The University of Tokyo, Japan</i> (2004)	Uses slider embedded into rigid links to pull and push a joint [60]	Extrinsic Actuation / Discrete Structure / Slider Linkage	10mm x 40mm	2 DOF+G
Madhanir, Kenneth Jr. Salis-bury <i>Massachusetts Institute of Technology</i> (1998)	Tendon driven instrument [61]	Extrinsic Actuation / Discrete Structure / Tendon/Cable	8mm x 10mm	2 DOF+2G
Seibold, Hirzinger <i>German Aerospace Center, Germany</i> (2004)	Cable driven instrument with Stewart platform based force sensor. 40° moving range [62]	Extrinsic Actuation / Discrete Structure / Tendon/Cable	10mm x 10mm	2 DOF+G joint
Peirs, De Gerssem <i>Katholieke Universiteit Leuven, Belgium</i> (2002)	Cable driven, elastic instrument. [63]	Extrinsic Actuation / Elastic Structure /Tendon/Cable	5mm x 37mm	2 DOF

Cooper, Manzo <i>Intuitive Surgical, Inc., USA</i> (2010)	Minimal oval links which are tendon driven. Because of the minimal oval design of each link, a high mobility is reached by short length. The disadvantage is that it has doubled the tendons. [64]	Extrinsic Actuation / Discrete Structure / Tendon/Cable	5mm x 15mm	9 DOF
Dupont <i>Harvard Medical School</i> <i>Boston, USA</i> (2010)	Concentric tube robot consists of bent tubes which are sticking into each other. The robot moves by shifting these tubes. [65, 66, 67, 68]	Extrinsic Actuation / Elastic Structure / Concentric Tube	in [65] 3mm x 200mm	6 DOF
Roh <i>Samsung Electronics CO. LTD</i> (2015)	A snake-like robot using links described in [64] with 4 tendons and instruments using special rolling joints [5]	Extrinsic Actuation / Discrete Structure / Tendon/Cable	30mm x 250mm	2x7 DOF inst., 3 DOF cam., 5 DOF snake
Zorn <i>ICube Laboratory, Strasbourg</i> <i>University, France</i> (2017)	STRAS system [69] uses Olympus instruments, based the manual Anubiscope platform	Extrinsic Actuation / Discrete Structure / Tendon/Cable	16mm x 535mm	3 DOF+G

Li	The LESS System [70]	Extrinsic Actuation / Elastic	22mm x	4 DOF+G
<i>Tianjin University, China</i> (2016)		Structure / Tendon/Cable	130mm	inst., 2 DOF snake
Xu	The IREP System [71] uses a stiff	Extrinsic Actuation / Elastic	15mm x	5 DOF+G
<i>Columbia University, USA</i> (2009)	stem and two instruments	Structure / Tendon/Cable	66mm	
Low	The MASTER system [72]	Extrinsic Actuation / Discrete	25mm x	5 DOF+G
<i>Nanyang Technological University Singapore</i> (2006)		Structure / Tendon/Cable	N/A	

Table 2.2: Shape sensing used in surgical robotics

A comprehensive review of mechanical joints usable in instrument arms for deeper study is provided in [4]. A summarising overview of them is shown in Figure 2.3. Of special interest are the *Rolling Toothed Joint* and *Sliding Curved/Hinged Joint*.

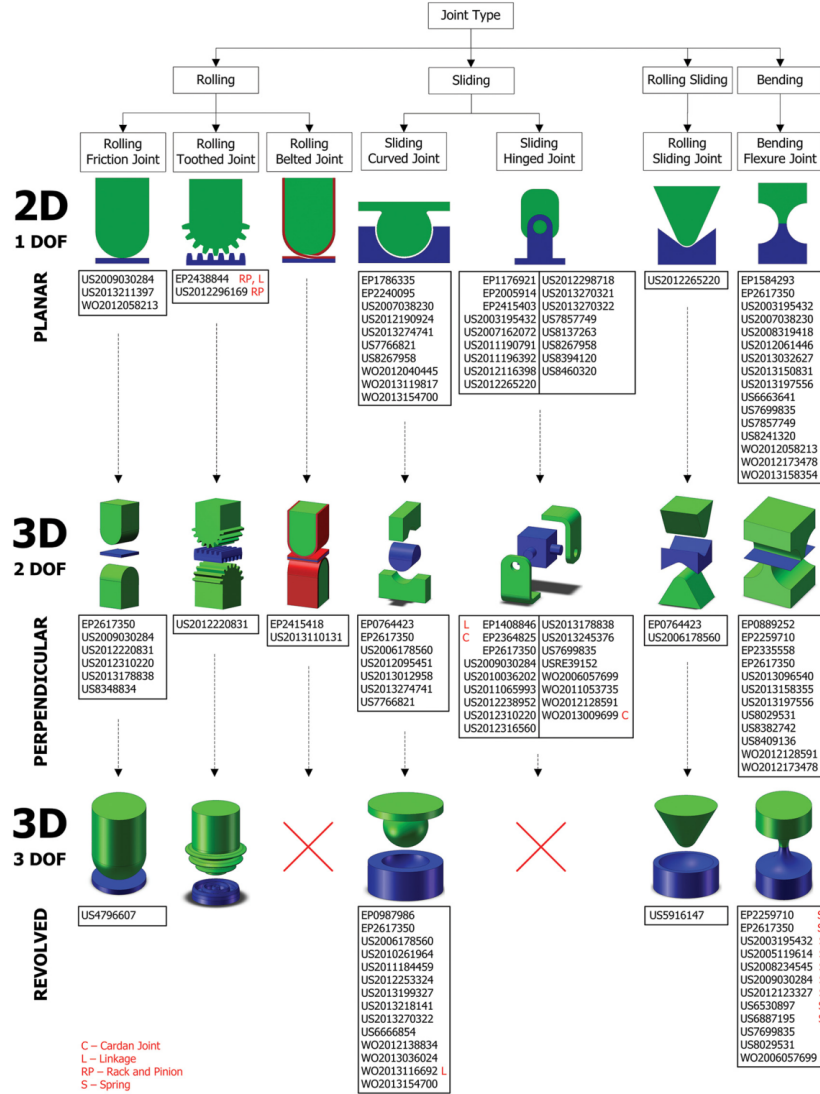


Figure 2.3: Overview over mechanical joints. Especially the categories *Rolling Toothed Joint* and *Sliding Hinged Joints* are relevant. (Source: [4]) © 2015 ASME

In [5] Kyung Shik Roh *et al.* presented a snake-like robot shown in Figure 2.4 including two instruments and using links described in [64]. The snake-like robot uses two segments of 2 DOF, each of them are controlled with four tendons. It has a diameter of 30mm and a length of 250mm. The instruments use rolling joints and have 7 DOF. Additionally, the device has a camera which can be controlled in 3 DOF.

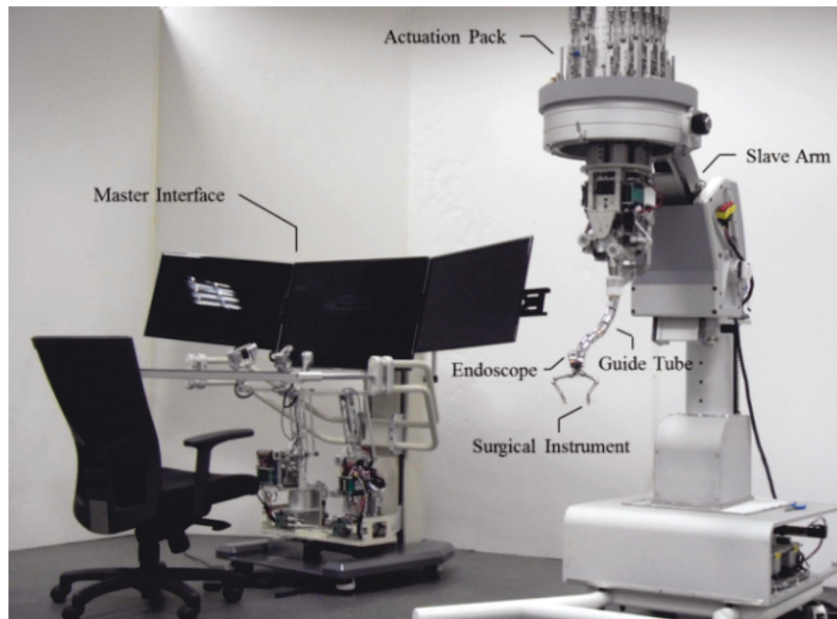


Figure 2.4: A snake-like robot with a camera, two instruments, and a diameter of 30mm. (Source: [5]) © 2015 Clearance Center

Nakamura *et al.* [52, 53] described an instrument for laparoscopic surgery. The mechanics of the joints used in their tool can bend in one direction (0-90 degrees). Thus, this instrument needs two joints for one DOF. The joints are driven by two tendons each. The instrument has two joints, one going up and one going left with a forceps at the tip. The authors compare their instruments with the range of motion the surgeon has in the first finger, which is the same. Thus, they were able to build a control for the instrument which captures the movement of the first finger and controls the instrument in the same way.

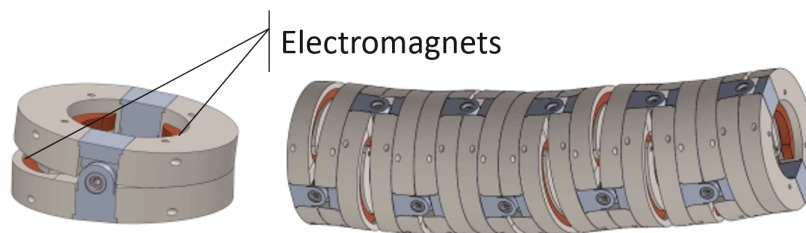


Figure 2.5: Tappe *et al.* presented a snake-like robot using magnets as joints. It can only move in discrete positions, but the shape is always known exactly. (Source: [6]) © 2015 IEEE

Tappe *et al.* introduced an innovative type of joint [6, 58], shown in Figure 2.5. They used round electromagnets to actuate a joint. The magnets are beveled so that the joint can bend. It has only two different states, bending left and bending right, without

any intermediate positions. Because of this, the robot has a discrete set of positions it can reach. If the robot should be straight, the joints have to be bent left and right in alternating order. Because of the binary joints a robot needs a lot of joints to get a useful working space. There is a trade-off in the angle of the beveling. If it is beveled much, it gets a small radius of curvature, but the reachable positions in the working space are placed rarely. On the other hand, if it is beveled less, it needs many joints to bend in a great angle. The advantage of these joints is that due to their binary states, the pose of the robot can be precisely calculated and predicted, they have neither backlash nor friction nor jittering.

In [54] a wire driven joint is described for a 2 DOF instrument with a gripper. In contrast to other wire based tools in publications, the wires in this instrument are not used as tendons. The joint consists of two gear wheels. One of it is connected to the motor with a circular cable. Joints of this type are mechanically complex. Unfortunately, the mechanical complexity increases if more joints of this type are embedded in a system. Although Nishizawa and Kishi were able to reduce the diameter to 5mm, it is still beyond the targeted scope of the instruments.

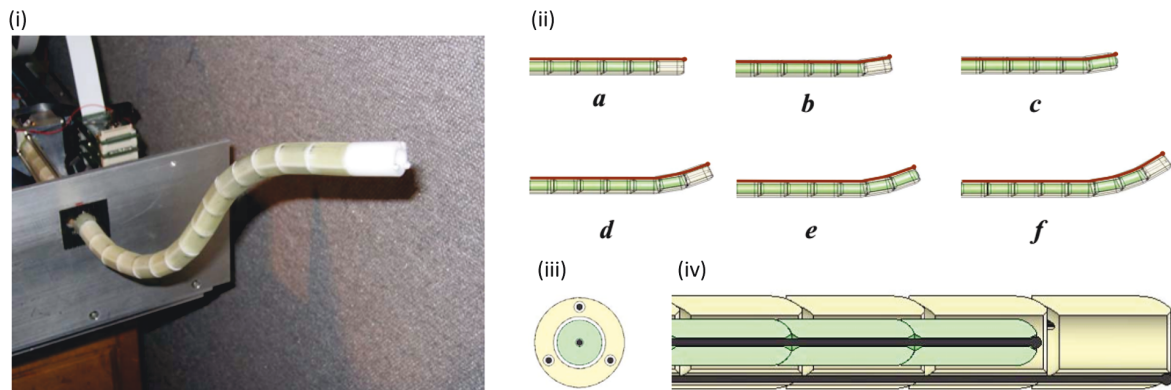


Figure 2.6: HARP (i) is a continuum robot with two segmented tubes, an inner and an outer tube (iv). The movement of this robot (ii) is shown in six different phases. (Source: [7]) © 2015 IEEE

Ikuta *et al.* present their progress in the development of a surgery robot in [55]. Unfortunately, the original sources are published in Japanese. In this article they show a joint which is chained to a motor with a circular cable. This cable lengthens itself over time.

Ikuta *et al.* used a spring to compensate for the elongation of the cables. Further, they depicted an outer-casing for cables with channels for each wire. This outer-casing ensures that the cables are not interfering with each other. In this thesis such outer-casings, which are called multi-catheters here, are used for the same reasons.

The Highly Articulated Robotic Probe (HARP), shown in Figure 2.6 (i), was developed by Degani *et al.* and published in [7, 46, 56]. HARP is an interesting idea of a continuum robot. Its idea is to have two tubes, an inner and an outer tube (iv), which can be controlled with three tendons (iii) and additionally made stiff or relaxed. To move (ii) one tube is made relaxed and the other one is made stiff. The relaxed tube is then moved forward one step and bent into the targeted direction. Then the stiff and relaxed tubes switch their status, the relaxed tube now becomes stiff and the stiff tube becomes relaxed. The new relaxed tube is moved forward two steps. The first step is following the stiff tube, the next step can be steered again. This is repeated until the target area is reached.

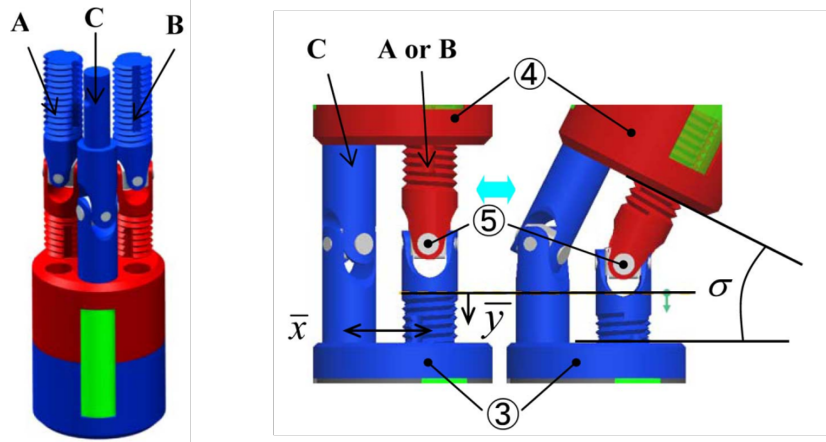


Figure 2.7: Ishii *et al.* presented a joint using two coupled double screws. A and B are the actuation for the joint. C is the actuation of a gripper. To bend the joint, one screw is shortened. (Source: [8]) © 2010 IEEE

In [8] Ishii *et al.* presented an actuation which uses joints consisting of two double screws and a small joint in between, see Figure 2.7. To bend a joint, screws are screwed inside the joint and thus the joint is shortened at one side. The shortening of one side and keeping the length of the other sides results in a bending motion. The advantage of this is that it is very stiff and has much torque. Once in a desired position, the device does not consume any energy to hold the position. Unfortunately, because of the screws the device

has a quite big diameter of 25mm and it is mechanically complex to connect arbitrary many joints together. Additionally, it is important that the instrument is made of metal instead of plastic, because the screws would damage the plastic after a while.

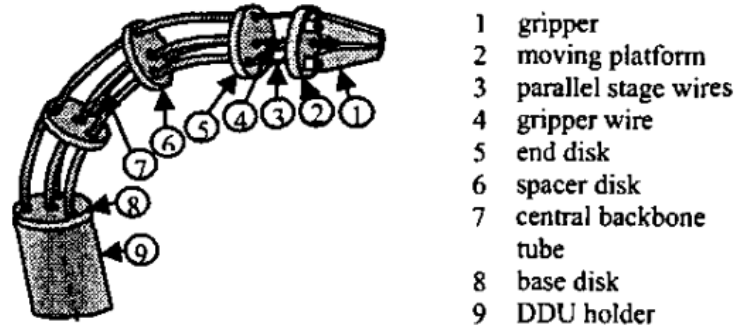


Figure 2.8: Simaan *et al.* published a tendon driven instrument with a stiff spine in the center of the robot. (Source: [9]) © 2004 IEEE

Simaan *et al.* [9] published a tendon driven device that consists of a stiff middle spine, connected plates, and tendons passing through the plates, as shown in Figure 2.8. The tendons are attached to the tip. Pulling one tendon results in the shortening of one side and thus in a bending motion of the device. Such an approach is widely used in research. The strength of the robot highly depends on the stiffness of the spine. Unfortunately, the flexibility of the robot counteracts the stability, because the stiffness should be low to get a high flexibility. This leads to a trade-off.

Nai *et al.* showed a 2 DOF spring based joint which is used in a so-called parallelogram configuration. By controlling the proximal end, the distal tip will mechanically move accordingly [73].

2.2.1 Design of Rolling Joints

Rolling joints are from special interest in this thesis and for the *i²Snake* project, in which scope Berthet-Rayne *et al.* presented a rolling gear joint in [74]. They use two touching round surfaces to achieve a smooth motion and a gear behind it to prevent the joint from slipping, see Figure 2.9. For the instruments this joint type needs too much space and cannot be incorporated in links with a diameter of $\varnothing 4\text{mm}$ or $\varnothing 3\text{mm}$.

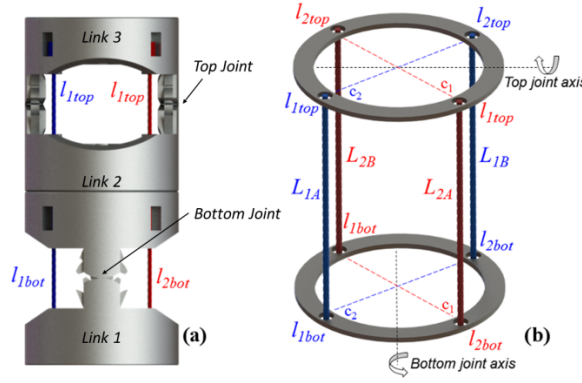


Figure 2.9: The rolling gear used in the i^2Snake robot. It uses small gears to prevent slip and two round surfaces.

A rolling joint using three gears combined in one link is used in [75] to create a chain of mechanically linked joints. If the first joint is moved, all other joints follow in the same direction and angle.

Blase [76] and Kleyman and Taylor [77] presented the toothed modification as a rack and pinion mechanism. However, this design cannot enable compact joint articulation. The perpendicular rolling joint consists of two planar rolling joints aligned perpendicular to each other. In the case of the rolling friction joint, tendons passing through all joints help to prevent transverse splitting and joint slippage to some extent. Furthermore, tendons also increase the torque resistance of the joint.

In the patent [78], the perpendicular rolling toothed joint is shown and the rolling motion is secured by the tendons. A kind of pulleyless rolling joint using gear teeth was applied to the 5mm daVinci EndoWrist [64] and Williams developed a similar rolling joint mechanism using multiple pairs of contact cycloidal surfaces [79].

Suh *et al.* [80] proposed guidelines to assist the development of various steerable instruments and some design parameters were analysed for the rolling teeth. However, there are many undesirable nonlinear problems with rolling tooth joints in tendon transmission.

2.2.2 Design of a Wrist and Distal-Roll Mechanism

For small instruments it is important to get high dexterity within a short length. Therefore, embedding a good wrist is especially important for these instruments. A wrist consists of a 2D joint which can move left/right and up/down and a roll motion at the tip. Usually, end-effectors of instruments in surgical snake-like robots perform in-place rolling by rotating the shaft at the proximal end and transmitting the force either through a stiff shaft or through a cable with rolling capabilities. To roll the instrument's end-effector, this shaft is rotated as presented in [14, 81].

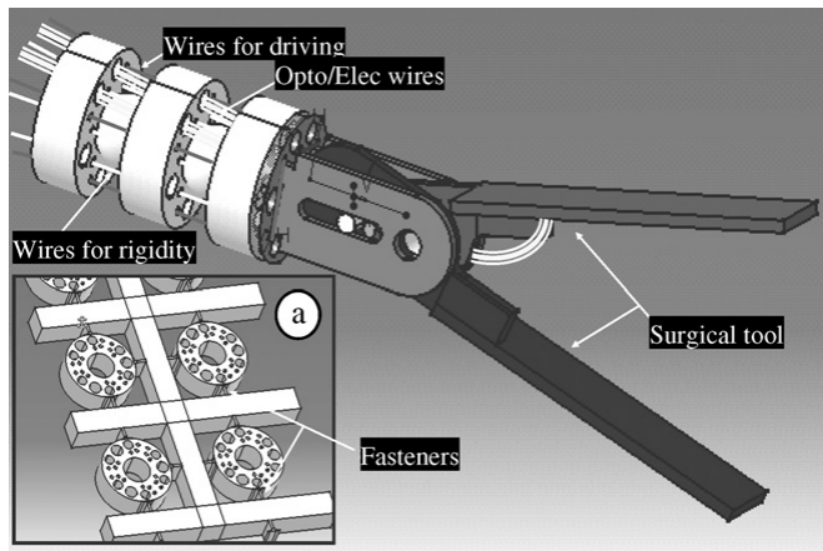


Figure 2.10: A 3D-printed ball joint was published by Meer *et al.* It consists of round plates with tendons and balls in between these plates. (Source: [10]) © 2011 ASME

In [57] and [10] Van Meer presented ball joints for small robots in MIS, shown in Figure 2.10. They consist of two round plates with a hole in the middle. Between these plates a ball is placed. Tendons are located along the joint. Pulling a tendon makes the joint bend. The advantage of this joint is that it is very small in size and can bend in two degrees of freedom. The size enables it to be used in the *i²Snake* instruments. Unfortunately, the joints have an uncontrolled rotational movement, which is reduced by using stable cables. However, the stable cables are increasing the force needed to bend the joint.

Guckert *et al.* describe a ball joint including rolling rotation in [11] which is shown in Figure 2.11. It has 3 DOF and is capable of a 20° rotation using only four tendons. Its

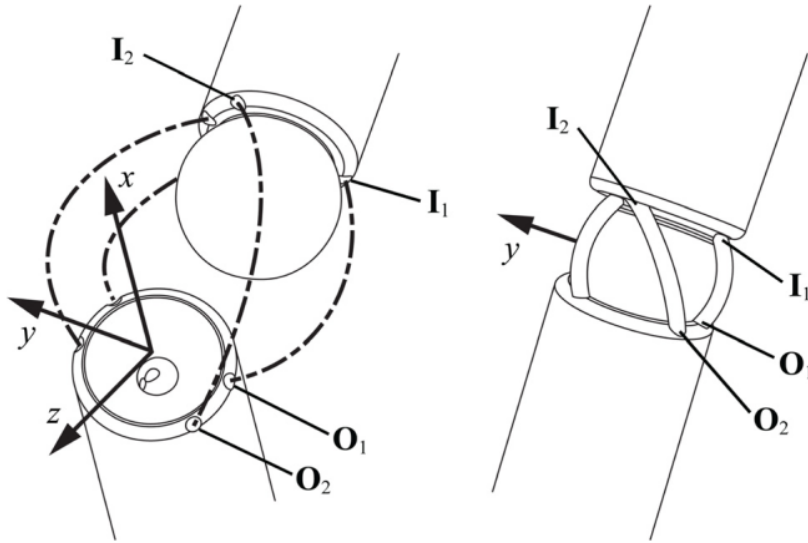


Figure 2.11: An improved ball joint which is controlled by only 4 tendons and also capable of rotation. (Source: [11]) © 2007 Elsevier

clear advantages are a design which is easy to build and the use of only 4 tendons for a 3 DOF motion. However, the small rolling angle limits its use, because 90° rolling motion is at least necessary to be used in surgical applications.

The US-patent published in [12] and shown in Figure 2.12 describes a wrist joint derived from the human hand for implants to replace the human hand wrist. It enables the patient to throw darts, as an example of a highly wrist depending motion. It can be used as a starting point to design a similar joint. In the patent [13] different designs of ball joints were published. They were used to design a controllable catheter. A selection of these joints is shown in Figure 2.13. A similar design is used by Hong *et al.* in [82], where the whole arm is built out of discs with a ball. It is used for a planar movement.

In the patent of Stahler *et al.* [13] different rolling mechanisms are presented. Most described mechanisms use a rotation from the proximal end with flexible tubes. These tubes have the drawback that they use a lot of space in the joints which is needed for tendons to allow for enough degrees of freedom. Also the force they can exert is limited and a counter force can hinder the end-effector from rolling. Seow *et al.* published a distal roll for a snake-like robot with a diameter of $\varnothing 14\text{mm}$ using miniaturized motors embedded in the tip [83]. It reached a maximum rolling motion of 180° .

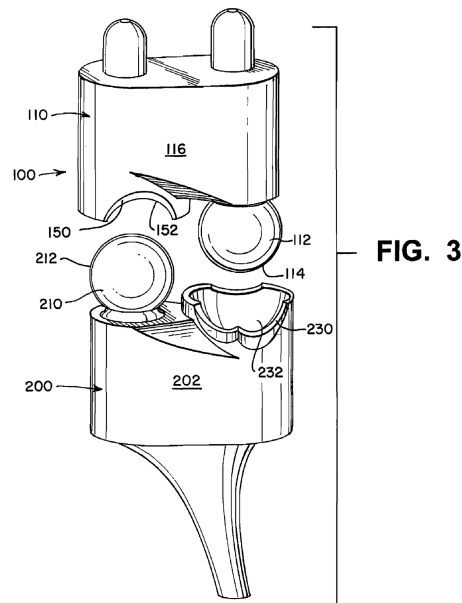


Figure 2.12: A wrist implant for the human hand can be used as a starting point for the design of a robot wrist joint. (Source: [12]) ©

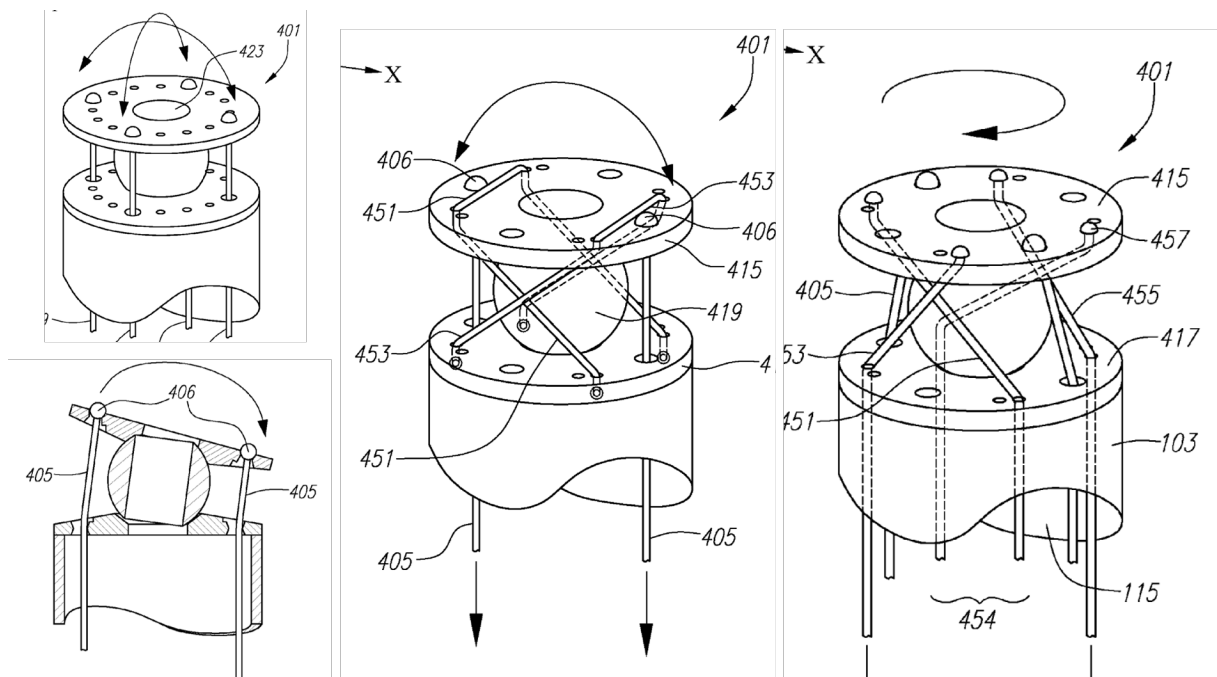


Figure 2.13: The patent by Stahler *et al.* shows different designs of wrist joints. All joints consist of two circular plates with a ball in between. The differences are the shape of the ball and the way the tendons are guided and attached. (Source: [13]) ©

Further, the patent of Stahler *et al.* [13] describes ball joints with rolling capabilities. Rolling ball joints have two major disadvantages: First, the rolling angle is often relatively limited, e.g., to 20°, and, second, the rolling leads to an unstable joint which needs to

be overcome with stiff backbones. In [84] Lee *et al.* present a snake-like system with instruments including a wrist with rolling capabilities with a diameter of $\varnothing 8\text{mm}$.

2.2.3 Predecessor System

A number of surgical robots have been developed within the Hamlyn Centre, Imperial College London. These predecessor devices helped to guide the design and fabrication of the tools reported in this thesis.

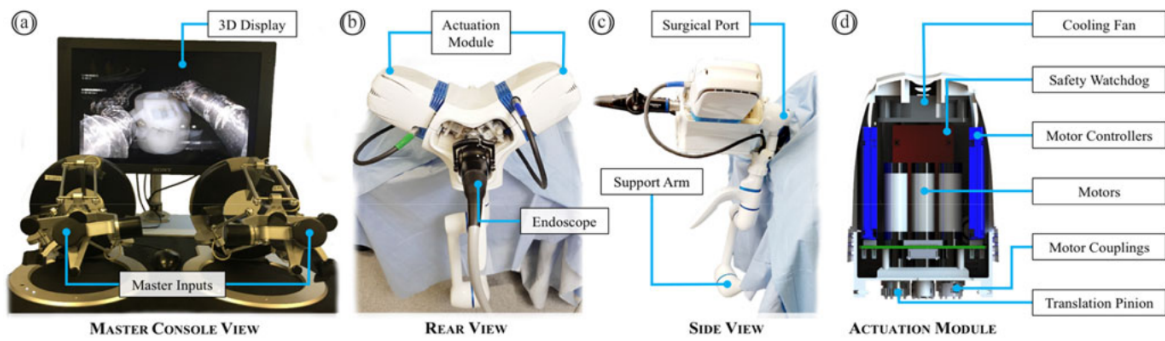


Figure 2.14: The system developed at the Hamlyn Centre and published by Shang *et al.* (a) shows the user interface, (b) the rear view with actuation modules, (c) a side view, and (d) shows an insight to the actuation module. (Source: [14]) © 2017 IEEE

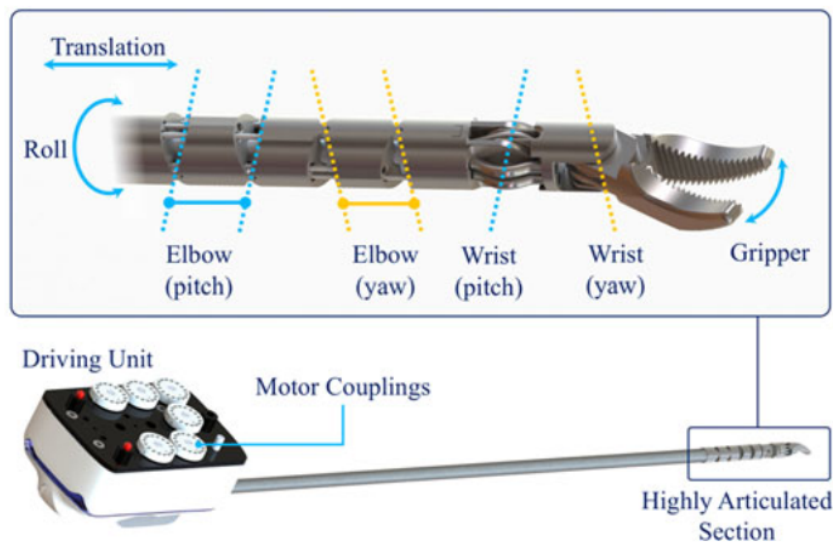


Figure 2.15: Image of the instrument used in the system with the depicted degrees of freedom. (Source: [14]) © 2017 IEEE

Shang *et al.* [14] describe one system developed at Hamlyn Centre, shown in Figure 2.14.

Figure 2.14 (a) shows the user interface, which has a 3D Monitor to display the site of

operation in 3D and a pair of input devices, which are omega.7 haptic devices (Force Dimension, Nyon, Switzerland). In addition to what is shown in the figure, there is a foot pedal to switch the instruments on and off and a clutch to increase the work space. Figure 2.14 (b) shows the instruments of the system from the rear view. It has two actuation modules to move the tendon-driven instruments. Additionally it has an endoscope to create the view displayed in (a). Figure 2.14 (c) shows the side view and the arm, which is holding the robot. Figure 2.14 (d) provides a view into the actuation module. Figure 2.15 displays the instrument used in that publication. The instrument has 7 DOF which are shown in the upper part. This system was a single port access robot. It provided the foundation for the *i²Snake* project, which was the next step.

2.3 Shape Sensing

Shape sensing is an important feature for robots that are capable to move continuously. It is less important for discrete robots, as the state of the robot is known as long as no external forces appear. Shape sensing enables the control of the robot in close-loop. This way the precision and accuracy of the control can be increased. It can also recognize external forces. It is important that the sensing is decoupled from the actuation as far as possible. For example, sensing the movement of the tendons in a tendon driven robot is highly coupled since it cannot recognize if the instrument is actually moving as intended.

For the instruments the shape sensing can be realised as multiple angle measurements, which makes the problem a lot easier. But the biggest challenge for shape sensing in the instruments is the size of the sensor. Since the diameter of the instruments has to be limited to a maximum of $\varnothing 4\text{mm}$ and the distance between two links to a few millimeters, there is not much space for most traditional sensors.

In this section current shape sensing methods and interesting sensors for a possible use in shape sensing are discussed. In [38, 85] a further overview over some techniques existing in research for shape sensing is given.

There are different types of shape sensing. A selection of publications of all types is given in Table 2.3. In the sections of the different types some examples are shown in more detail.

- **Fiber Bragg Grating (FBG) based shape sensing.** The most used shape sensing methods are FBG-based approaches, which is a subclass of fiber optical sensing. Special fibers with imprinted Bragg Gratings are used to measure the bending. Much work is done in this area and it leads to more and more complex designs. Section 2.3.1 briefly explains fiber optical sensors and FBG. Its advantage is that it can have multiple sensors in one fiber and still it is small and accurate. The disadvantage is that the fibers are complex to make and devices used to analyze the measurements are expensive.
- **Electromagnetic (EM) Tracking.** A second common shape sensing method is EM-based shape sensing. An EM tracking device is used to locate a series of magnets. Section 2.3.2 shows some examples of shape sensing publications using EM trackers. The advantage of EM tracking is that the system is relatively easy to set up, but the disadvantage is that the EM tracker drifts over time and it works poorly near any electrically conductive material.
- **Computer Vision.** The third common method is using computer vision in some sense, e.g., using cameras, x-ray, or ultrasound. This area is not further described here, since it does not belong to the scope of this thesis.
- **Further approaches.** There are plenty different approaches which have not led to final applications yet including inertial sensors, cable displacement, hall sensors, and shape memory alloy.

Further, interesting sensor approaches which are not directly used in shape sensing are presented in Table 2.4. The biggest disadvantage for the use as shape sensors for the instruments is their size. Probably some of them can be decreased in size, but there is more research needed.

- **Bending Sensors.** There are different techniques of sensors measuring bending deflections published in current research literature. Most of them are using a stretchable and bendable polymer, such as Polydimethylsiloxane (PMDS), and integrate channels for a conductive liquid. The liquid changes their electrical resistivity while bending. Others integrate a bendable strain gauge, such as a kind of textile or yarn, which changes its electrical resistivity while elongated.
- **Flex Sensors.** Flex sensors are a kind of bending sensor. Inside the flex sensor there are carbon resistive elements with thin flexible substrate. When the substrate is bent the sensor resistivity changes relative to the bent radius.
- **Strain Sensors.** Strain sensors can measure strain applied to the sensor which can be bending strain or stretching strain. So, in principle they could be used as a bending sensor. Unfortunately, their bending ability is often very limited and they break if they are bent too much. Targeted angles of nearly 90° are not reachable with most of the strain gauges on the market.

Research Group	Research
(1) Electromagnetic (EM) Tracking - Problems with drift over time	
Hongliang Ren, <i>National University of Singapore,</i> <i>Singapore</i> (2015)	Placed three EM sensors along a continuum robot for realtime shape estimation [19, 86, 87].
Howie Choset, <i>Carnegie Mellon University,</i> <i>USA</i> (2011)	EM Sensor at the tip of the HARP robot. Since the robot uses the follow-the-leader strategy, only the tip needs to be sensed [88, 89].
Mark R. Cutkosky, <i>Stanford University, USA</i> (2014)	Uses two EM Sensors for a 3D shape sensing needle [90] (This group also used FBG fibers for that).

Max Q Meng, <i>Harbin Institute of Technology, China</i> (2017)	Magnet sensor array used to track a magnet on the tip of a wire-driven flexible robot [91].
Michael R. Zinn, <i>University of Wisconsin, USA</i> (2012)	An evaluation of closed-loop control options for continuum manipulators [92].
Pietro Valdastri, <i>Vanderbilt University, USA</i> (2013)	Control capsule with external magnets, which uses hall effect sensors and accelerometers to track the pose [93]. Used this pose tracking for closed loop control [94].
Farrokh Janabi-Sharifi, <i>University of Toronto, Canada</i> (2009)	EM tracking used in robot-assisted catheter [95].
Kensaku Mori, Xiongbiao Luo, <i>University of Technology, Australia</i> (2012)	Merging of sensor information from 3D computed tomography, 2D endoscopic video and EM tracker positional sensor [96, 97, 98].
Nassir Navab, <i>University of Munich, Germany</i> (2009)	Combines EM tracking and optical tracking of the shaft for reducing errors [99, 100].
Toshio Fukuda, <i>Nagoya University, Japan</i> (2011)	Sensor fusion of ultrasound and magnetic tracker [101] used for real-time reconstruction and navigation of intra-vascular robot [102].
Yoshinobu Sato, <i>Osaka University Graduate School of Medicine, Japan</i> (2008)	Magnetic and optical tracker used for intra-operative magnetic tracker calibration in laparoscopic surgery [103].
Zheng Li, <i>The Chinese University of Hong Kong, China</i> (2017)	Uses EM tracker shape-reconstruction to measure the force [104].

Gabor Fichtinger, <i>Queen's University, Canada</i> (2011)	Uses SLAM [105] and sensor fusion [105] to calibrate EM tracker and optical tracker. With SLAM they map the distortion of the environment to reduce the influence of the environment to the error [106].
(2) Fiber Bragg gratings (FBG) - Most used solution	
Heinz Woern, <i>Karlsruhe Institute of Technology, Germany</i> (2013)	Describes a simulation tool for FBG-based shape sensors including optimization of measurement points [107].
John J. van den Dobbelsteen, Jenny Dankelman, Sarthak Misra, <i>University of Twente, Netherlands</i> (2012)	Accuracy measurements of FBG sensors [108]. FBG shape sensing robot using three FBG fibers with 4 FBG sensors each [109, 110, 111]. Closed loop feedback [112, 113]. Closed loop control with object avoidance for a continuum robot using FBG shape sensing [114].
Xinhua Yi, Linyong Shen, <i>Shanghai University, China</i> (2005)	Different real-time FBG sensors for shape reconstruction using four FBG fibers [115, 116, 117, 118].
Yong-Lae Park, Mark R. Cutkosky, <i>Stanford University, USA</i> (2010)	Real-Time 3D shape estimation of a needle using three FBG fibers[119].
Matthew D. Rogge, <i>NASA Langley Research Center, USA</i> (2012)	Shape sensing using multi-core FBG fibers [120].
Osvaldo Daniel, <i>University of Castilla-La Mancha, Spain</i> (2009)	FBG shape reconstruction for a long single-link robot [121].

Pierre E. Dupont, <i>Boston Children's Hospital, Harvard Medical School, USA</i> (2014)	FBG shape sensing for concentric tube robots [17] and optimizing sensor placement [122].
Rajni V Patel, <i>Western University, Canada</i> (2016)	A helically-wrapped FBG sensor to sense curvature, torsion and force in continuum robots [123, 124].
Robert J. Webster, <i>Vanderbilt University, USA</i> (2016)	Using FBG-based sensors for concentric robots [125].
Russell H. Taylor, Mehran Armand, <i>Johns Hopkins University, USA</i> (2015)	FBG sensor for a 2D continuum robot [126, 18]. They claim that it can be used with larger deflections.
(3) Inertial sensors - problems with drift and size for instruments	
Guang-Zhong Yang, <i>Imperial College London, UK</i> (2013)	Uses inertial sensors to track the position of a snake-like robot [21]. Inertial sensors have problems with drift and the size is too big for instruments.
(4) Cable displacement	
Kaspar Althoefer, <i>King's College London, UK</i> (2013)	Two different shape sensors measuring the displacement of stiff cables to sense the shape with light modulation fiber optic [127, 128].
(5) Hall Sensors	
Cagdas D. Onal, <i>Worcester Polytechnic Institute, USA</i> (2015)	Shape sensor for a soft robot using micro-fabricated hall sensors [129]. The size is about 6x3cm and thus too big for the use in instruments.

P. Dario, G. Megali, <i>Scuola Superiore Sant'Anna,</i> <i>Italy</i> (2000)	A novel mechatronic tool for computer-assisted arthroscopy. They used a stiff passive cable and a hall effect sensor to measure the bending [20].
(6) Light Intensity Modulation	
Conor Walsh, Robert Wood, <i>Harvard University, USA</i> (2017)	A shape sensor using LED and photo-transistor in each joint developed for Endobot [130]. The size is more than 1cm which is too big for the use in instruments.
(7) Shape Memory Alloy (SMA)	
Günter Niemeyer, <i>Stanford University, USA</i> (2008)	Used laser-machined SMA springs for shape sensing. SMA springs are placed at each joint [131]. SMA sensors have a strong hysteresis.
(8) Computer Vision: X-Ray	
Joachim Hornegger, <i>Friedrich-Alexander-University</i> <i>Erlangen-Nuremberg, Germany</i> (2012)	Uses fluoroscopic images to reconstruct the shape of a catheter [132].

Table 2.3: Shape sensing used in surgical robotics.

Research Group	Research
(1) Bending Sensor - Different techniques, size is problematic	
Ali Abbas, <i>Colorado State University, USA</i> (2016)	A coiled thread sensor [133].
Alon Wolf, <i>Technion Israel Institute of</i> <i>Technology, Israel</i> (2013)	PVDF Sensor [134] array built with 4 sensors in line [135].

Lucia Beccai, <i>Scuola Superiore Sant'Anna,</i> <i>Italy</i> (2015)	Revealing bending and force in a soft body through a plant root inspired approach. Two textile electrodes with a dielectric layer in between. Bending in form of stretching can be measured [136]. Size because of textiles is too big for instruments.
Cecilia Laschi, <i>University in Pisa, Italy</i> (2012)	Electrolycra textile used to measure bending in form of stretching. Multiple sensors used to measure at different positions [137]. Because of textile, the size is too big for instruments.
Kaspar Althoefer, <i>King's College London, UK</i> (2015)	Change in resistance of electro-conductive yarn used to shape sensing [138, 139]. Size is multiple millimeters thick, thus its too big for instruments.
Robert J. Wood, <i>Harvard University, USA</i> (2011)	PDMS foil with micro channels filled with conductive liquid EGaIn. Micro channels get squeezed while bending. It can be used to measure angles. Size is about 1.3mm and 20mm long [140]. Same method used for different sensors, such as soft artificial skin [141], curvature sensors [142], soft tactile sensor arrays [143, 144], and soft tactile keypad [145]. Size is generally too big for instruments.
(2) Flex Sensor - Varies resistance regarding deflection, size too big for instruments	
Bheemesh Gudur, <i>Halakatti College of Engineering</i> <i>and Technology, India</i> (2012)	Uses a flex sensor for gloves to control a robotic arm [146].

P. D Abd Aziz, <i>Universiti Kuala Lumpur British Malaysian Institute, Malaysia</i> (2014)	Uses flex force sensor for a glove to control a robotic arm [22].
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(3) Strain Sensor

Jennifer A. Lewis, <i>Harvard, USA</i> (2015)	A stretchable strain sensor with a diameter of 1.5mm using multicore-shell fiber printing [147].
Kenji Hata, <i>National Institute of Advanced Industrial Science and Technol- ogy (AIST), Japan</i> (2011)	A stretchable carbon nanotube strain sensor with a width of 1mm [148].
Oluremi Olatunbosun, <i>University of Birmingham, UK</i> (2016)	A flexible capacitive strain sensor for vehicle tyres [149]. Size is about 1cm but could probably be reduced.
Rebecca K. Kramer, <i>Purdue University, USA</i> (2017)	Strain sensor built in flexible, stretchable PMDS [150]. It has a strain circuit imprinted. Kramer belonged to R.J. Wood and the work is based on the work in his group.
Robert J. Wood, Vincent Duchaine, <i>Harvard University, USA</i> (2013)	A stretchable and bendable strain sensor based on ionic and metal liquids [151] with a thickness of 3mm. A printing method of adding strain sensors to stretchable elastomers [152].

(4) Highly Stretchable Elastomers

Samia Nefti-Meziani, Kaspar Al- thoefer, <i>University of Salford, UK</i> (2015)	Stretchable sensor with a channel filled with eGain [153].
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Stéphanie P. Lacour, <i>University of Cambridge, UK</i> (2009)	A pressure sensitive sensor. Two electrodes inside of flexible PMDS above each other with a distance of 0.5mm. Under pressure distance changes and resistivity changes, too [154].
--	--

Table 2.4: Sensing techniques possibly usable in shape sensing.

2.3.1 Fiber Optical Sensing and Fiber Bragg Grating

Fiber optical sensing (FOS) is a method used for shape and force sensing. The sensor is based on optical fibers. A light source is emitting a form of light (often laser or multi-wavelength light). Typically the light source is an LED or a laser. The sensing is typically done by modulating light, through intensity, frequency and phase. Taffoni *et al.* [85] categorised these sensors into two groups:

- (i) *Intrinsic Sensors*. The optical fiber is the sensing element by changing the properties of the fiber, e.g., through bending.
- (ii) *Extrinsic Sensors*. The optical fiber is only the carrier for the light which is modulated at the measuring point.

FOS allows the component (emitting source, light sensor), which is usually too big for the instruments, to be placed in the proximal end in order to keep the size of the sensor small. Another big advantage is that FOS is in general magnetic resonance imaging (MRI) compatible due to its immunity from electromagnetic interferences. Furthermore, FOS is mostly decoupled from the actuation and the system. The more sensing is decoupled from the actuation and the more the sensed value is placed towards the output of the system, the more accurate it will sense. Several reviews and survey publications cover FOS [38, 85, 155].

In the following, two different principles of FOS are discussed:

- *Light Intensity Modulation (LIM)*. Sensing of bending or force is extrinsically done by changing the light intensity.
- *Fiber Bragg Grating (FBG)*. Sensing is done intrinsically within the optical fiber. Multiple sensors can be embedded in one fiber.

Light Intensity Modulation

Light Intensity Modulation (LIM) based FOS sensing techniques measure extrinsically by sending light through an optical fiber to the measuring point. The light is reflected by an optical mirror. Afterwards it is transported back by one or more fibers. The sensor on the proximal end is measuring the change of light intensity. According to [38], this type of sensors is temperature independent and does not require complex or expensive components. Unfortunately, they are affected by unintended intensity losses through fiber bending [85]. Fiber-optic reflectance measurements can be deployed in a variety of formats using small, low cost components (e.g., unmodified fibers, laser or light emitting diodes, and phototransistors or other single channel detectors) and relatively simple fabrication procedures. Thus, they are well suited for the use in small scale snake-like robots [37].

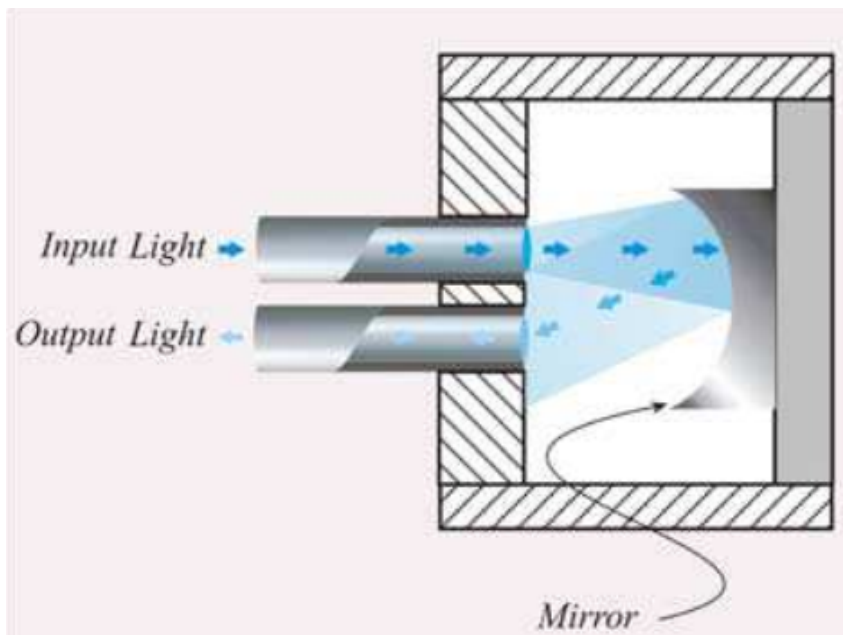


Figure 2.16: The principle of LIM-based sensing is shown: The light intensity is modulated by a displacement of the mirror and the light is reflected back into a second fiber. (Source: [15]) ©

In [15] Silvestri *et al.* describe different types of LIM-based techniques. One of the most common one is shown in Figure 2.16 where the light is emitted from one fiber, the intensity is changed by a displacement of a mirror, and the light is then reflected back into a second fiber. The modulation can be done by rotating the mirror for shape sensing or changing the distance for force sensing.

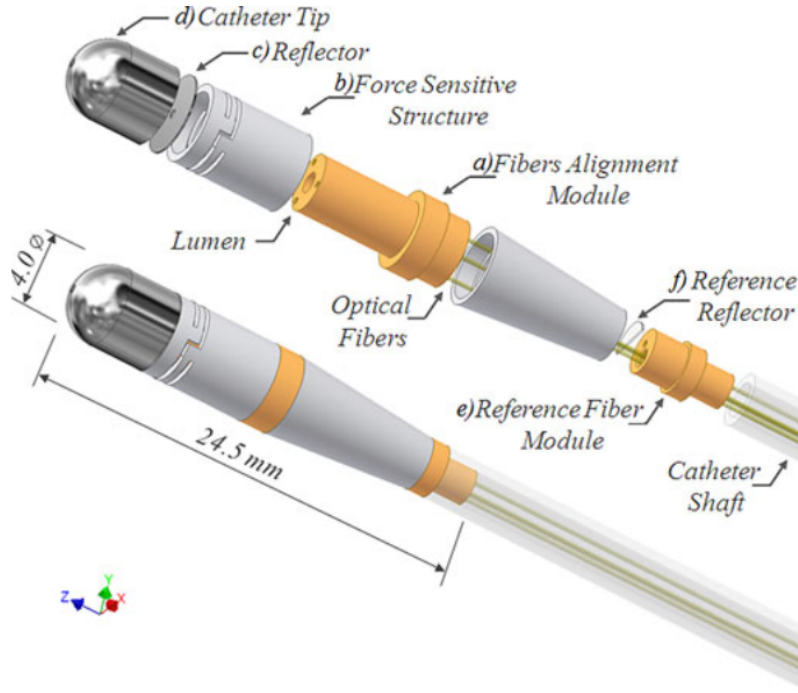


Figure 2.17: An LIM-based force-sensitive tip developed by Polygerinos *et al.*, which is MRI-compatible. This is a proof that shape sensing can be done with an LIM-based optical fiber approach. (Source: [16]) © 2011 IEEE

Polygerinos *et al.* [16] developed a force-sensitive tip based on light intensity modulation fiber optical sensing. Although it is used for force sensing, the same principle applies for angle measurement. Figure 2.17 shows the architecture of the instrument. It has one light emitting fiber in the center and three receiving fibers located in 120 degrees around the center fiber (a). A reflector (c) at the tip reflects the light back from the emitting fiber to the receiving fibers. A force sensitive structure (b) displaces the reflector (c) when the tip (d) is pressed, which leads to the intensity modulation. A reference reflector (f) and the reference fiber module (e) compensate for losses through fiber bending.

Fiber Bragg Grating

Fiber Bragg grating (FBG) is the second important principle of FOS. It uses gratings in a fiber to reflect light back. This reflection is highly sensible to strain, bending, and thermal characteristics. These gratings reflect only a narrow range of wavelengths, allowing multiplexing with multiple gratings with different wavelengths along a single fiber. The principle of the shift in wavelength is shown in Figure 2.18 and is described in detail in [15]. Silvestri *et al.* also describe the fabrication process of FBGs and their application in medicine.

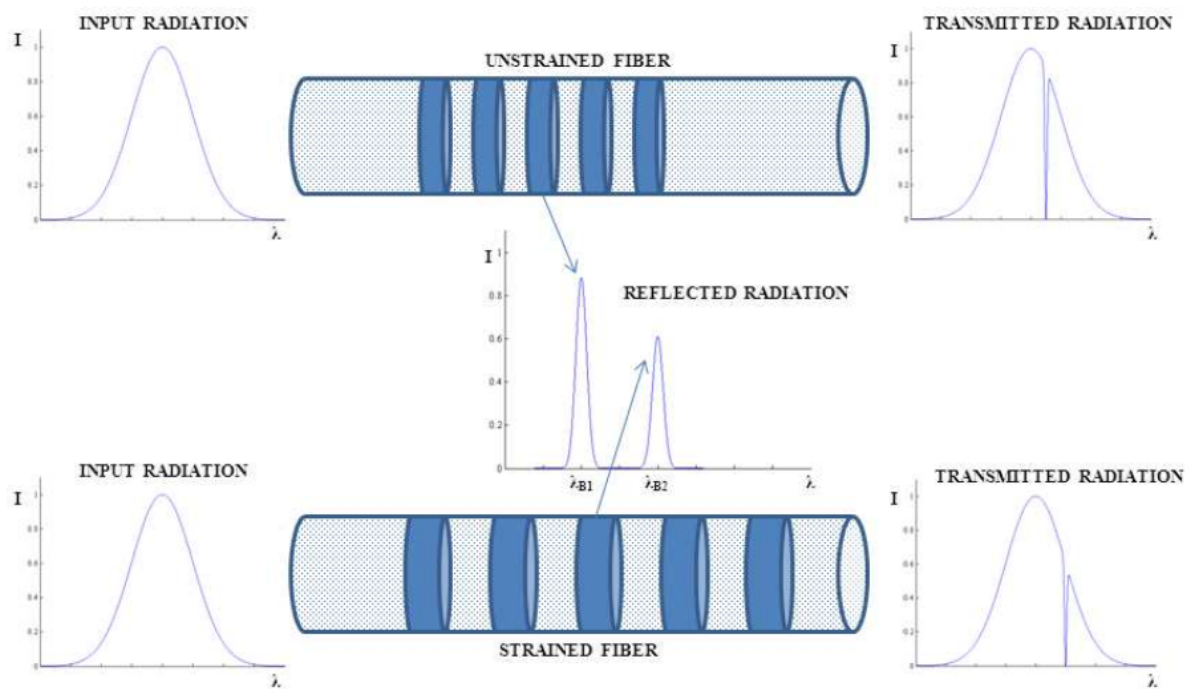


Figure 2.18: Silvestri *et al.* describe the principle of FBGs in detail. This figure shows the shift in wavelengths in an FBG caused by strain in the fiber. (Source: [15]) ©

While FBGs are capable of providing precise shape sensing in three dimensions, expensive spectrally resolved detectors are usually required. Furthermore, if commercially available devices are not suitable for a given task, the fabrication of the FBG sensors can be complex and challenging.

In [156] Luna Innovations Incorporated, which was lately bought by Intuitive Surgical Operations Inc., patented the use of FBGs as shape sensing devices for medical devices, with one or multiple cores.

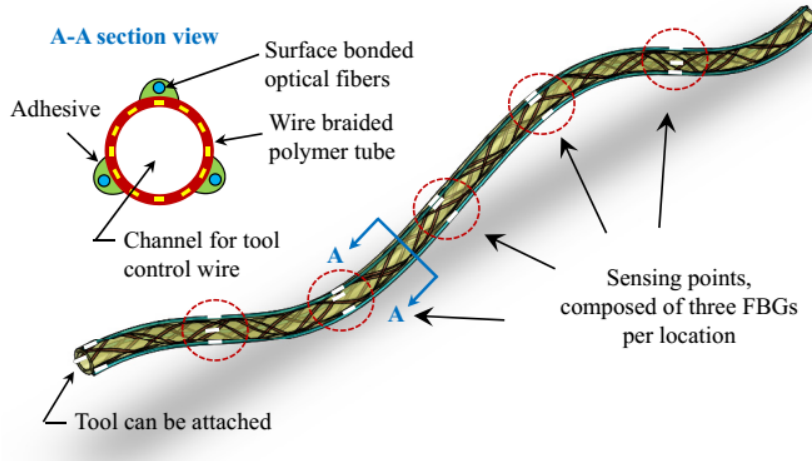


Figure 2.19: The principle of a cable with attached FBG fibers measuring 2D movements in different sensing points. (Source: [17]) © 2014 IEEE

In [17] Ryu and Dupont used FBGs to sense the shape of concentric tube robots. A wire with three surface mounted FBGs distributed in 120 degrees was described. Along the length of it several FBG sensing points were distributed. The setup is shown in Figure 2.19. This is the common setup of an FBG wire measuring two dimensional bending in several sensing points. This paper analyses the use of a polymer as a wire. They encountered different effects, which are discussed.

In [18] Liu *et al.* propose a shape sensor for a 35mm long dexterous continuum manipulator (DCM). Figure 2.20 shows the design of the DCM in (a) and the alignment of the sensing points in (b). The DCM is tendon driven and can bend planar in one dimension. For shape sensing it got two FBGs integrated and each of them has three sensing points. In the shape reconstruction only planar bending was considered. Clothoids, of which the curvature is linear in arc length, were used to fit a curve with the FBG measurements. For the evaluation the robot configuration was influenced by an obstacle. In the case where the robot bends uniformly the reconstructed shape perfectly matches the robot. But in two other cases, where the shape is externally influenced by an obstacle, the shape reconstruction missed the robots shape significantly.

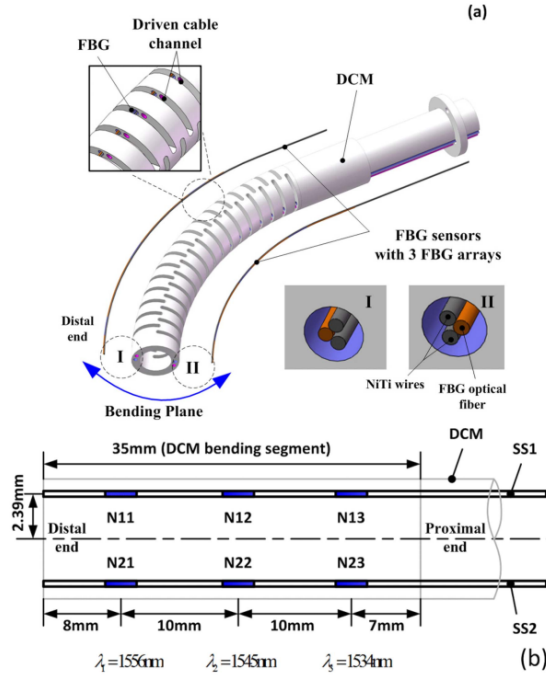


Figure 2.20: The dexterous continuum manipulator (DCM) developed by Liu *et al.* (a) shows the robot which can bend planar with two FBG fibers for measuring the shape. (b) shows the distribution of the FBG sensing points within the two fibers. (Source: [18])
 © 2015 IEEE

2.3.2 Electromagnetic Tracking

After FBG sensors, for shape sensing electromagnetic (EM) tracking is the second most common method to track the tip or multiple points of a snake-like robot, which can be used for shape reconstruction. EM tracking relies on measuring the intensity of magnetic fields with electromagnetic sensors. A base station generates an alternating electromagnetic field. To measure multiple directions the same number of magnetic coils are needed. The advantage of this method is that it is easy to set up and to read. There are good commercial systems available which are basically ready to use. The drawbacks of this method are:

- that an external device is needed which is placed next to the patient,
- that it influences devices which are sensitive to magnetic distortion,
- that the sensor is heavily influenced by other magnetic, electronic devices or metal structures,

- and finally that the sensor drifts over time and has to be re-calibrated somehow.

Most publications tackle one of the mentioned drawbacks of the system.

Song *et al.* [19] use an EM tracking system to track the elements of a continuum robot to sense the shape of it. The robot has three EM sensors embedded, which are sensed by an external EM tracker. It uses six coils to get six dimensional measurements. Two sensors define the part in between. Figure 2.21 shows the setup of the system with the external EM tracker below the robot (left) and the placement of the sensors along the robot (right).

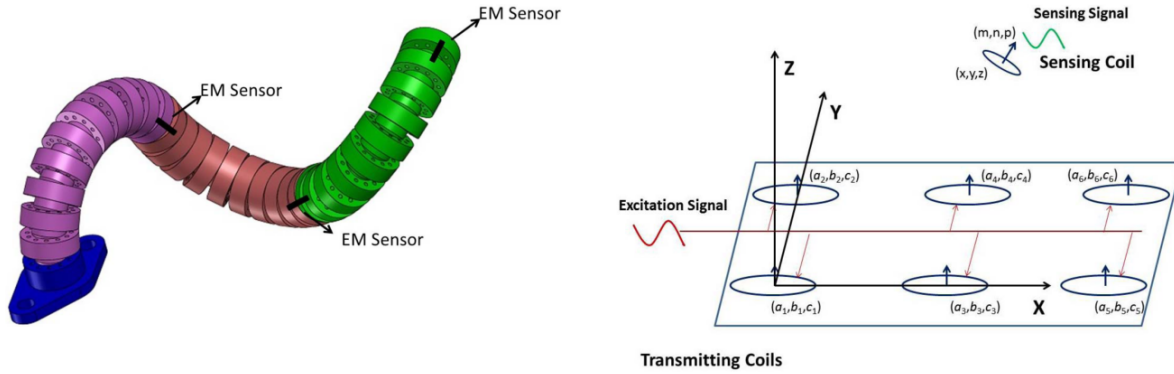


Figure 2.21: Left: Arrangement of the system with an electromagnetic tracker underneath of the robot. Right: The placement of the sensors along the robot. (Source: [19])
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There are commercial systems for EM tracking available on the market. In [106] Sadjadi *et al.* use the commercial system Ascension trakSTAR to gain the data from the EM tracking system. To overcome the noise of the environment they use a SLAM algorithm to map the distortion.

2.3.3 Hall Sensors

In the article [20] two new types of sensors are described, a bending sensor and a contact sensor. Instead of placing a sensor at the tip, Dario *et al.* decided to place the sensor, which is in this case a hall sensor, in the proximal end. Figure 2.22 shows the mechanical schematics. A passive steel cable is connected to the tip of the instrument on one end

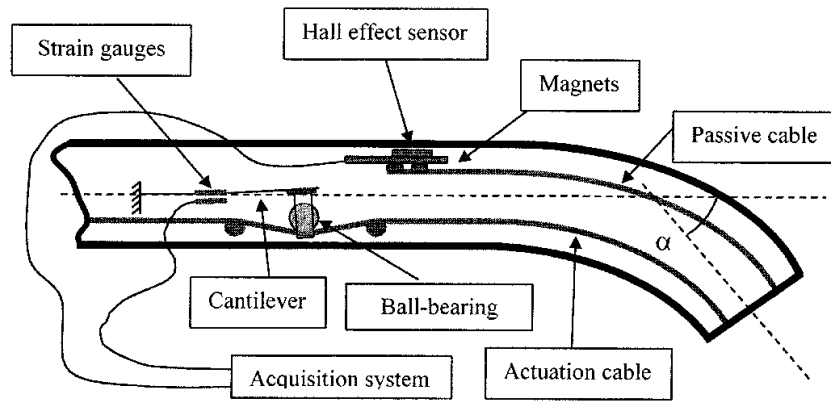


Figure 2.22: Mechanical schematics of a positioning sensor using a hall sensor proposed by Dario *et al.* (Source: [20]) © 2000 IEEE

and to a magnet on the other end. This magnet can move back and forth which is sensed by a hall sensor. The output value of the hall sensor correlates to the bending angle of the instrument. As a result the bending of the tool in one direction can be measured. The design principle cannot be extended easily to multiple degrees of freedom, especially redundant degrees of freedom. Further, it is a quite indirect way to measure the shape. The measurement can be affected by several external effects on the way from the tip to the sensor and it is additionally effected by elongation and backlash of the steel cable. The paper additionally introduces a way of measuring the contact force on the whole surface of the tip. This is done by measuring the tension of one of the driving cables with a cantilever instrumented with strain gauges. If the tension of the cable is increased, the cantilever is pushed upwards. This movement is measured by the strain gauges. This is an interesting approach although strain gauges are said to drift over time.

Zhang *et al.* [21] also suggested the use of inertial sensors to track the shape of a robot, see Figure 2.23. A prototype of a robot with 2 DOF demonstrated the concept. The inertial sensors are used with a filter to derive the angle. But the disadvantage is that drift still is a remaining issue.

2.3.4 Flex Sensors

A flex sensor is a resistance-varying strip sensor that increases its resistance when it is bent. It is consisting of two alternating elements: Carbon and flexible substrate. Syed *et al.*

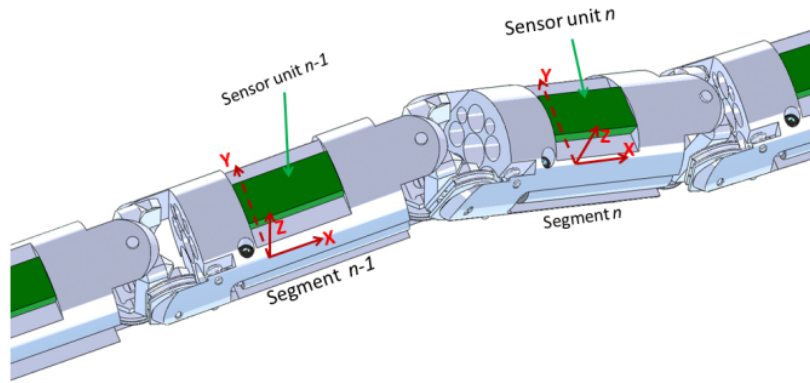


Figure 2.23: Zhang *et al.* use inertial sensors (green) to track the shape. (Source: [21])
© 2013 IEEE

[146] had a glove equipped with a flex sensor. With this flex sensor they were able to measure the movement of a finger and controlled a robot arm accordingly. They received a quite linear voltage output according to the deflection of the sensor to a maximum angle of 73 degrees.

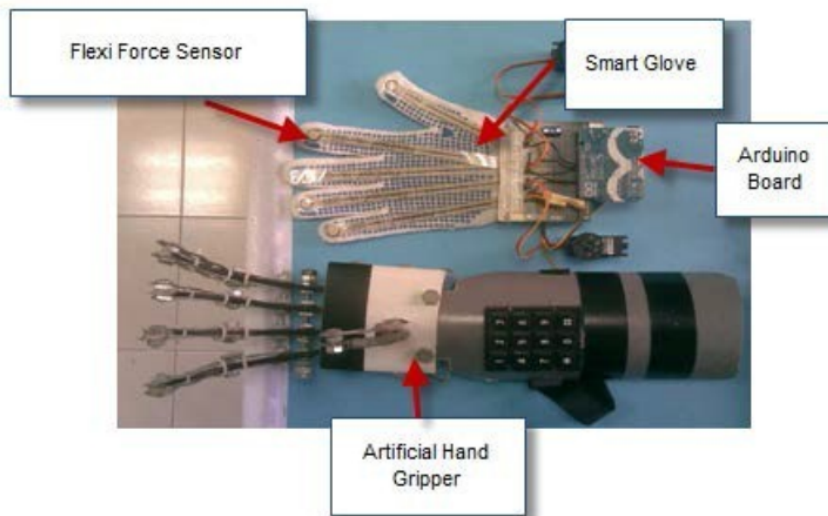


Figure 2.24: The Smart Glove developed by Miqdad *et al.* has a flex sensor in each finger to control an artificial robot hand. (Source: [22]) © 2014 IEEE

In [22] Miqdad *et al.* use flex sensors in each finger of a glove, called Smart Glove, to control a five-fingered artificial robot hand. On each finger tip, flexi-force sensors were attached. With these force sensors, the pressure force between the finger tip and an external surface could be measured. Figure 2.24 shows the glove and the robot. The paper states that the resistance of the sensor depends on the bending direction. Flex sensors seem to be too

big in size to be applied to small instruments, although the demonstrations seem to be promising.

2.4 Control Algorithms

The control and kinematics of the instruments are important for successfully doing surgical tasks. Generally, the surgeon uses a user interface comparable to the omega.7 haptic devices (Force Dimension, Nyon, Switzerland). The position of the user input is typically used as the position of the end-effector so that the surgeon can directly control the end-effector position. To let the robot follow these input positions, an input position has to be transformed to motor values. To solve this transformation some kind of inverse kinematics (IK) is needed. In Section 2.4.1 some publications regarding IK are highlighted. These motor values are then transferred to the motor controllers. Since the robot is tendon-actuated, multiple effects decrease the joint controllability. Solutions to these problems are reviewed in Section 2.4.3.

2.4.1 Inverse Kinematics

Common methods for calculating inverse kinematics are Jacobian pseudo inverse [157] and Damped least-squares [158].

In [23] Leibrandt *et al.* presented a way of modeling the instrument kinematics for an instrument robot, as developed in this thesis. Figure 2.25 sketches the kinematics of the robot. They present how to calculate the forward kinematics (which is the transformation from motor values to end-effector position) and further describe how to calculate the inverse kinematics (end-effector position to motor-values) with consideration of the joint limits of the robot using Jacobian matrices. Tang *et al.* presented a kinematic model of a snake-like robot during rectilinear motion in [159], which was applied on a custom made system equipped with a “one-direction wheel”.

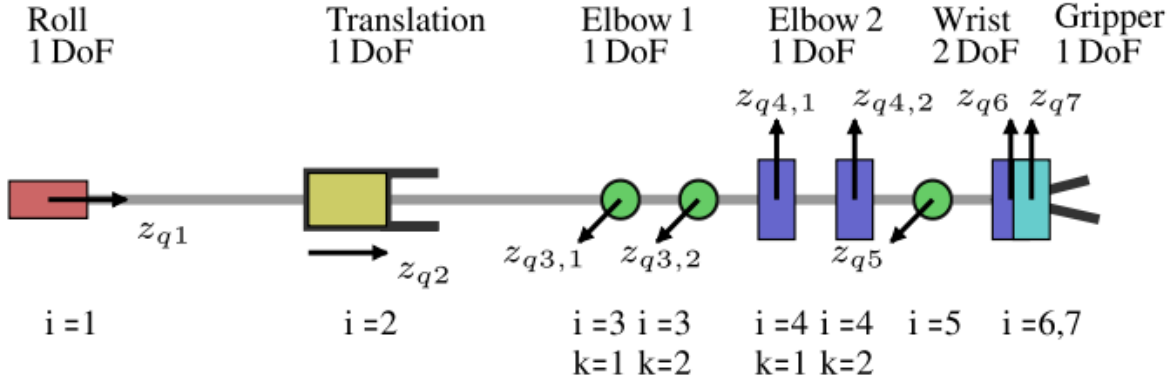


Figure 2.25: Kinematics of the robot used in [14]. Leibrandt *et al.* developed the inverse kinematics for it. (Source: [23]) © 2017 IEEE

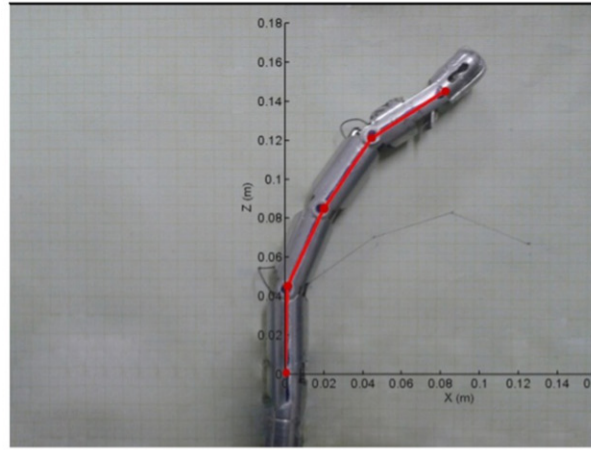


Figure 2.26: A 2-dimensional snake-like robot used to demonstrate a geometric approach of inverse kinematics. (Source: [24]) © 2013 Elsevier

Sardana *et al.* [24] presented a geometric approach to solve inverse kinematics. They claim to find a single optimal solution and to be able to switch between the solutions depending on the path and environment. The algorithm is demonstrated on a 2-dimensional snake-like robot with multiple links, shown in Figure 2.26. Parker *et al.* [160] proposed a genetic algorithm to solve inverse kinematics allowing to specify additional constraints. After 30 generations a good solution was found. They suggest that GAs are suitable for offline programming of a robot.

Y-shape robot control, meaning solving the inverse kinematics for a master-positioning robot and two attached arms, is a new emerging field. Chikhaoui *et al.* [161] propose a Jacobian based solver for these kind of robots.

2.4.2 Use of Neural Networks to Solve Inverse Kinematics

The use of neural networks to solve inverse kinematics has been previously addressed for robotics application. In [162] Godage *et al.* presented kinematics for a multi-section continuum arm, which is based on a center-spine using dual quaternions (DQ). They claim DQ's have higher accuracy than homogeneous transformation matrices (HTM) and are numerically stable. Their DQ kinematics have no singularities like Euler angle based inverse kinematics.

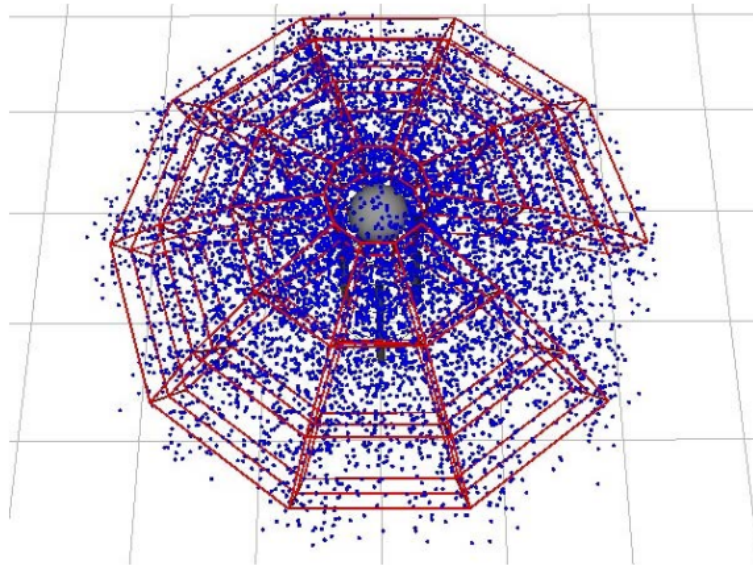


Figure 2.27: Rolf *et al.* used machine learning to train the inverse kinematics. The picture shows a tenth of the training set which was used. (Source: [25]) © 2014 IEEE

An interesting solution is presented by Rolf *et al.* in [25]. It is an approach to learn the inverse kinematics of snake-like robot arms. Figure 2.27 shows a tenth of the training set used for learning the inverse kinematics. They claim to have overcome the high dimensionality, restrictive, unknown actuation ranges, and non-stationary system behavior with a recent exploration scheme called online goal babbling. They evaluate the method in real-world experiments on the non-stationary robot.

Duleba *et al.* [163] published a comparative study of five Jacobian based methods to solve inverse kinematics, the Jacobian transpose, Jacobian pseudo-inverse, two approximation methods and a modified Levenberg-Marquardt method. They found the Levenberg-Marquardt method to be the best and fastest method.

The method shown in [164] uses Damped least-squares (DLS) to train pairs of calculated joint values and task space coordinates. But this introduced the disadvantages of DLS, such as joint limit constraints. Using reinforcement learning can overcome this limitation [165, 166]. The problem of reaching a target is known as the *Reacher Problem*. Usually, a 2D-Reacher is used to evaluate a new algorithm.

2.4.3 Robot Control and Compensation

During the control of a tendon-driven robot with joint angles, there are many undesirable non-linear problems. Suh *et al.* [80] described the coupling effect for the rolling-based joint. They also suggest solutions using gears, ribbons, and central elastic fixtures. Tendon-sheath actuation systems have been widely used in designing the robots. Wu *et al.* investigated the tendon-sheath problems in [167], such as hysteresis, dead zone, backlash and direction dependent behavior. They developed a mathematical model to compensate for these problems. The Tendon viscoelasticity and friction effects are modeled with a *LuGre dynamic model* in [168, 169] with joint side load cells. Xu *et al.* [170] proposed recursive linear estimation using the actuators' positions and external measurement of the end-effector to estimate backlash and a correction factor for elastic characteristics. Simaan *et al.* [171] proposed an actuation compensation method with superelastic push-pull backbones. This approach was then extended by the characterization of motion transmission loss and coupling by using Fourier series, and feedforward actuation compensation by using the static model of the robot [170].

2.5 Conclusion

In research the mechanical design of small instruments for surgical robotics is widely explored. Only minor changes are proposed in recent conferences. Two different designs have been established, rigid links and continuum robots based on a back-spine. The

construction of these instruments is mainly based on existing methods. A special focus lays on rotation and wrists, where still some research gaps can be found.

Shape sensing for small instruments is mostly an open research topic with no good solution, besides FBGs. FBGs showed to be a robust and precise solution. Other solutions have not been established yet, although there are some ideas and prototypes published. To integrate these new approaches of shape sensing into the instruments will be a challenging task.

The control of the instruments is a crucial part. Much work has been done in research in this field. But still there are some gaps open for further improvement. An effective consideration of joint limits into inverse kinematics solvers is one of these open areas. Another open point is Backlash and crosstalk compensation. Both enable a more precise control.

Considering the limitations discussed in this chapter, the aim of the research presented in this thesis was to develop robot arms with diameters below $\varnothing 4\text{mm}$ that were suitable for integration with the *i²Snake* global positioning robot for advanced applications in minimally invasive surgery. The following chapters discuss the mechanical design and fabrication of the robotic instruments (Chapter 3), a task-oriented design optimisation using a genetic algorithm (Chapter 4), the integration of a shape sensing mechanism into a robot joint based on light intensity modulation (Chapter 5), and the development of a control architecture based on reinforcement learning inverse-kinematics (Chapter 6).

Chapter 3

Mechanical Design of the Instruments for a Snake-like Robot

In the scope of this thesis, a snake-like robot is considered for use in Natural Orifice Transluminal Endoscopic Surgery (NOTES). The *i²Snake* robot is a flexible fully actuated endoscope with a diameter of 16mm, which is build by another PhD student in this project [34]. It has a camera and two lights at its head and two channels for instruments. These channels are approximately 5mm in diameter along the whole body of the *i²Snake* robot. Through these channels two instruments can be inserted and exchanged. The instruments stick out of the snake head and can be observed through the camera. The *i²Snake* robot acts a master positioning system. Once it has been positioned within the body, the instruments can be used for surgery.

Within this thesis the instruments for the *i²Snake* robot were designed. These instruments are tendon driven rigid-link robots controlled by antagonistic wires. Because the instruments are inserted through the channels of the *i²Snake* robot, the tendons need to be led through a flexible body to the proximal end. This flexible body makes it impossible to use backend rotation transmitted over a stiff shaft. Because of that a distal-roll included in a gripper was developed. Further a common problem is slip in the joints and tendon slack because of the nonlinearities introduced through hinge joints. The slip is solved using rolling gear joints, which also highly reduce the nonlinearities. At last, the

size of the robotic instruments arms are reduced to a diameter of $\varnothing 4\text{mm}$ and then further reduced to a diameter of $\varnothing 3\text{mm}$. The work developed here was published by Andreas Schmitz *et al.* in [26] and [27].

This chapter first gives an overview over the system in Section 3.1, then describes the flexible instrument shaft needed to guide the wires through the *i²Snake* channels in Section 3.2, and explains the instrument actuation unit in Section 3.3. Then the instrument with a diameter of $\varnothing 4\text{mm}$ is shown in Section 3.4.1 and the $\varnothing 3\text{mm}$ -instrument in Section 3.4.2. The rolling gear joint is presented in Section 3.6, and a gripper with a distal-roll in Section 3.5. All further joints used for these instruments are then described in Section 3.7. Finally an evaluation and the conclusion are given in Section 3.8 and Section 3.9.

3.1 System Overview

The work presented in this chapter reports developed of flexible robotic instruments that can be inserted through the instrument channels of the *i²Snake* robot. These instruments are tendon driven. The tendons are antagonistic, which means that one wire pulls in one direction and the other wire pulls it in the other direction. That means, to actuate a joint two wires are used. The instrument consists of the instrument arm, a flexible tail, and a control unit. A schematic view of the overall system is shown in Figure 3.1 and a second iteration in Figure 3.2. The instrument arm operates a gripper or other instruments which are used for surgery, such as knives and scissors. The arm is connected to a flexible tail, which allows for passage of the tendons that are required for controlling the instrument through the snake-like robot. After the flexible tail leaves the snake robot, which is connected to an actuation unit. This unit reorders the tendons and connects them to the motors. Two instruments were built, each with different characteristics. The first instrument, described in Section 3.4.1, has a diameter of 4mm and has 6 degrees of freedom (DOF) plus an additional DOF for the Gripper. It is constructed out of hinge joints, described in Section 3.7.1, where the distal part is sliding on top of a round surface. Further, it has a ball joint (Section 3.7.2), and a 4mm-gripper with rolling capabilities,

see Section 3.5. The schematics of the instrument are similar to the one of a human arm. The second instrument, described in Section 3.4.2, has a diameter of 3mm and has 4 DOF consisting of gear joints (Section 3.6), a gripper, and translation. Gear joints, where two gears are rolling on top of each other, have the advantage of negligible slip and are thus more controllable. Due to its smaller diameter, this instrument can only have 4 joints. To achieve this, the design of this instrument was optimised using a genetic algorithm, seen in Chapter 4. The material parameters of the instrument components are shown in Table 3.1.

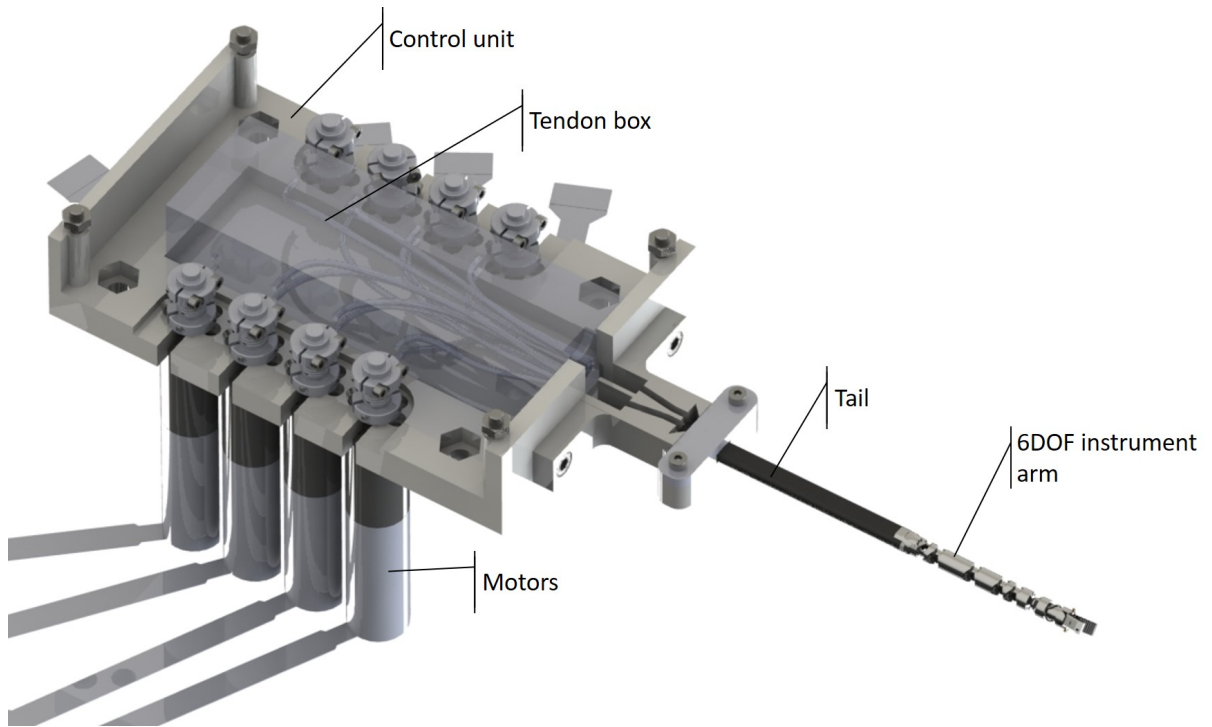


Figure 3.1: Schematic view of the overall system layout, in its first version. All tendons from the instrument arm are guided through the tail, the tendon box to the motors. The tendons are connected to spools, called capstans. Two tendons of a joint are actuated by a single capstan. (Source: [26]) © 2019 IEEE

3.2 Flexible Instrument Shaft

The flexible tail consists of two multi-lumen catheters (Polytetrafluoroethylene (PTFE), $\varnothing 1.6\text{mm}$), with 7 holes each, as shown in Figure 3.3. Each catheter is embedded in a stainless-steel coil cable (ID:1.7, OD:2.15, ASAHI INTECC, Amsterdam, Netherlands) to

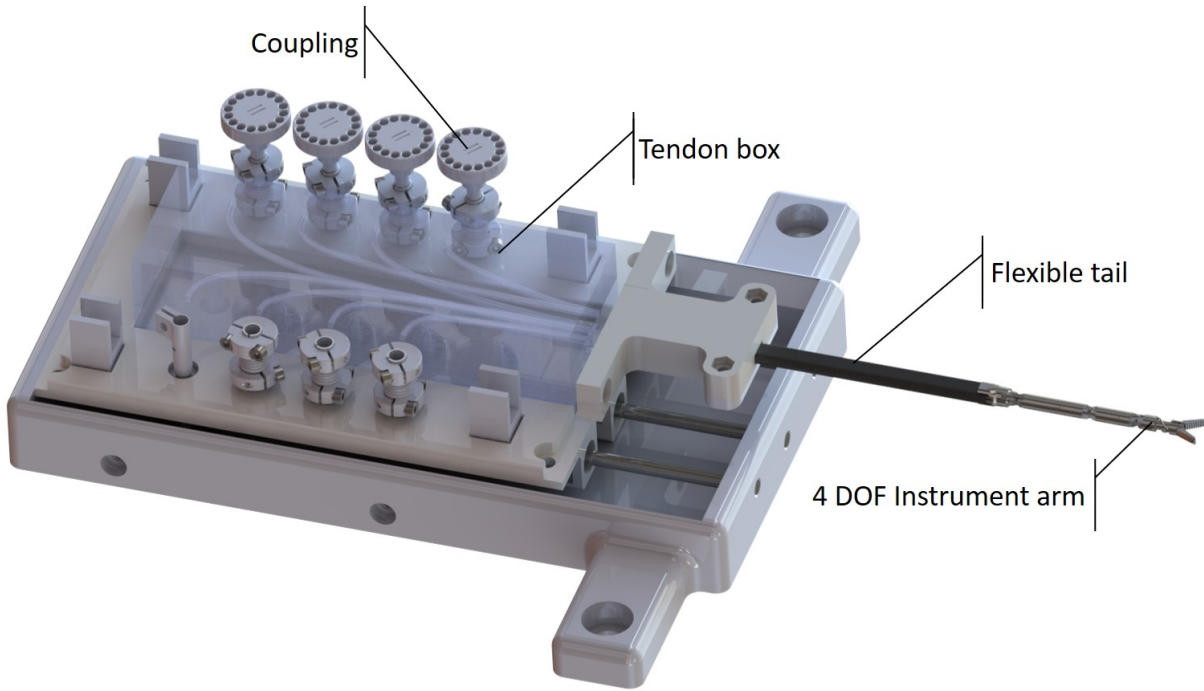


Figure 3.2: The second version of the tendon control unit of the flexible instrument. The main improvement is the addition of a prismatic joint in the actuation unit. This enables the instrument to translate further and increase the workspace. (Source: [27])
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improve the force transmission to the distal end. It has to be glued inside the coil cable at both ends. Since the multi-lumen catheter is manufactured out of PTFE, a primer (Loctite Primer 770) has to be used to make the tube glueable. This stops the catheter from rolling inside the coil cable. To prevent the two coil cables from being tangled with each other, they are surrounded by heat-shrink tubes (thickness: 0.00635mm, Nordson Medical, Westlake, Ohio, US). Then, both cables are bound together with another heat-shrink tube. The flexible tail will be about one meter long, since it will bend with the snake robot and reach deep inside of the human body.

3.3 Instrument Actuation Unit

The instrument is connected via the tail to the actuation unit. This unit can be seen in Figure 3.1 and the second iteration in Figure 3.2. The second iteration was designed to embed a prismatic motion which is described in Section 3.7.4.

Part	Instrument		
	Description	Size	Material
Arm	Instrument arm	Ø 3mm	SS
	Number of teeth	14	SS
Tendons	Tendons for joints	Ø 0.33mm (7*19)	SS 316
	Tendon for gripper	Ø 0.30mm (7*19)	SS 316
3mm gripper	Nitinol wire	Ø 0.305mm	NiTi alloy
Tail	Heat shrink	0.00635mm thick	-
	Multi-lumen catheter	ID: 0.5mm OD: 1.6mm	PTFE
Coil cable	Coil cable for the 3mm gripper	ID: 0.4mm OD: 0.9mm	SS 316
	Coil cable for the tail	ID: 1.7mm OD: 2.15mm	SS 316
	Coil cable for the tendon box	ID: 0.4mm OD: 0.9mm	SS 316

Table 3.1: Parameters of instrument components

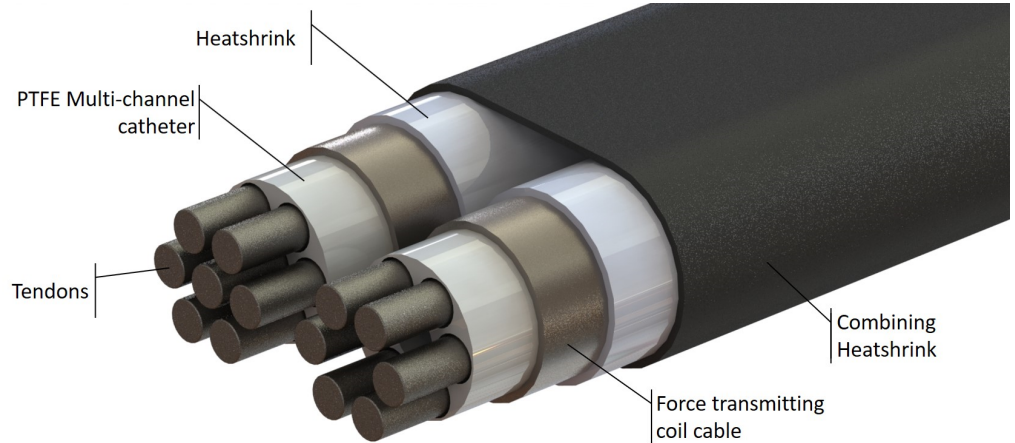


Figure 3.3: Schematic view of the flexible tail. (Source: [26]) © 2019 IEEE

Since the instrument is tendon driven, these tendons are passed from the instrument through the tail to the actuation unit and coupled to the capstans, which are connected to a motor.

Two tendons are needed to drive a joint. To save the number of motors both tendons of a joint are coupled to one motor. This coupling can introduce tendon slack if the tendon length change is different on each of the two tendons while moving the joint. This leads to nonlinearities in the tendon length change depending on the type of joint, e.g., hinges have

nonlinearities while gear joints do not. It is important to note that the coupling cannot compensate for these nonlinearities. The tendon alignment is defined by the joints and needs to be reordered using a 3D-printed tendon box. The tendon box is a manifold with channels inside the box guiding the tendons to the right motor. This box makes it easy to assemble and to put the tendons in order. The tendon box is printed either with an Ultra 3SP (EnvisionTEC, Gladbeck, Germany) or a Form2 (Formlabs, Somerville, MA, US) using scan, spin, and selectively photocure resins. Since the printing material is liquid in places where it should not be printed, it can be easily removed from the channels. Coil cable tubes are placed inside the channels, which can help reduce friction and prevent the tendons from being cut off by sharp edges, allowing them to pass through the narrow, tortuous spaces. All tendons are driven by motors from Maxon Motors AG (Switzerland) and controlled by a digital positioning controller (EPOS2 Module 36/2, Maxon Motors AG).

On the instrument side, the tendons are welded inside of the links in a hole using a laser that strikes the tendon from the outside. The laser welder (SWMP 6002, ROFIN) shoots several times on the side of the joint, where the tendon is in the hole and the wall is thin. This is a quick and easy way to weld the tendon inside the hole. The drawback compared to stoppers seems to be the strength of the connection as shown in Section 3.8.1. This connection can exert 4N at the end-effector before breaking, which is enough for surgical tasks.

In the case of the tendons in the gear joints of the 3mm instrument, the end of the tendons are held in place by stoppers that can be placed between the cutouts of joints, making it able to withstand more tension. One disadvantage of this is that the stoppers take up some space, which can lead to design difficulties in confined environments. In the case of this instrument arm the stoppers fit into the cutouts of the joints.

3.4 Instrument Design

Two instruments were built, one with an outer diameter of 4mm and one for which the diameter was decreased to 3mm.

3.4.1 Instrument Design in 4mm

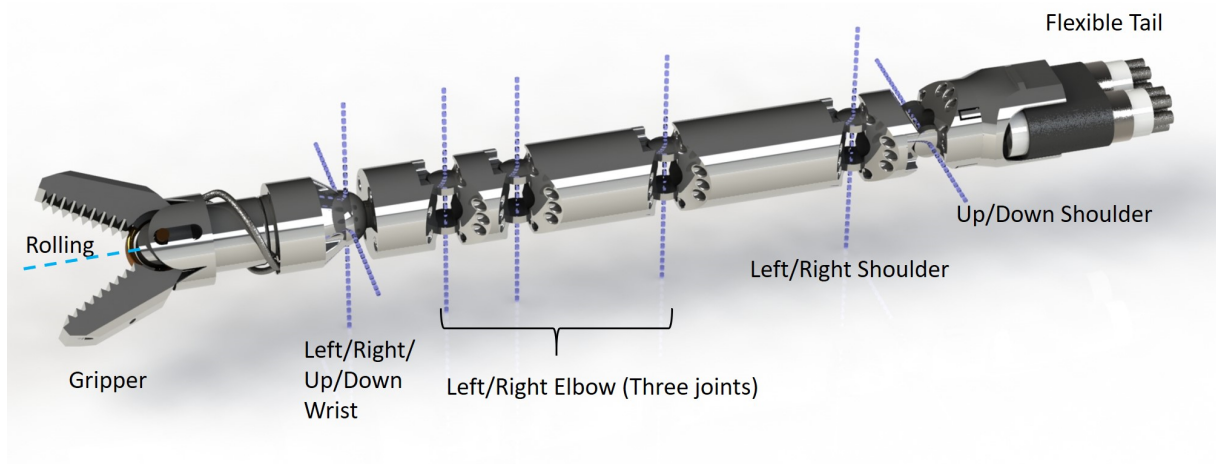


Figure 3.4: Schematic view of the developed instrument arm for a snake-like robot. The rotation axes are highlighted. (Source: [26]) © 2019 IEEE

The 4mm instrument has a length of 42mm and 6 DOF plus the gripper (see Figure 3.4). It is actuated using tendons (OD:0.30mm, Mat:SS 316, ASAHI INTECC, Amsterdam, Netherlands). As a tendon can only be pulled and not pushed, two antagonistically actuated tendons are required for a single DOF to be controlled in both directions. For the gripper one additional tendon for the open/close motion is required. In total, 13 resulting tendons are guided through all other joints and the flexible tail to the proximal end. Both tendons of each DOF are attached to a capstan to move in opposite directions. This saves a motor for each DOF but cannot compensate for the non-linearity introduced by the hinges. All tendons are pretensioned to stiffen the instrument. The tendons have a diameter of 0.33mm.

The instrument layout is based on the human arm. The idea behind that is, that since the robot is controlled by a human using its hands via a master controller, the instrument

can follow the same trajectories as the users hand. In this case, all possible positions can be reached. As seen in Figure 3.4, the first joint moves the arm up and down. The second joint moves the arm away from the center. Like the human arm it also could move towards the center in rare cases. Together these two joints form the shoulder, although the axial rotation is missing. The third joint corresponds to the elbow and moves the robot arm back to the center. This is a combined DOF which consists of three joints to increase the bending angle. The tendons are only fixed on the last link and move all hinges. The increased bending angle is required for this joint to ensure that the instrument is able to reach the center even if the first two joints turn the arm away from the center. Together with the shoulder and elbow, the arm can triangulate to use the workspace with more dexterity, do not block the camera, and collide less likely. A ball joint just before the gripper enables the wrist to move the gripper up or down and left or right. Although a ball joint is less stable than two alternating joints, it was chosen to allow the wrist to be as near as possible to the end-effector. In the end, the ball joint showed some disadvantages, which are further discussed in Section 3.7.2, though it is possible to improve the handling with better production qualities. To enable rolling, a roll joint is incorporated in the gripper, as described in Section 3.5.

3.4.2 Instrument Design in 3mm

The instrument described in this section has a diameter of 3mm and a length of 42mm with 4 DOF, an additional prismatic joint, and a gripper. It is one of two instruments used in this thesis and shown in Figure 3.5.

The 3mm instrument described here was optimised using a genetic algorithm. The optimisation process is described in Chapter 4. The instrument is composed of an instrument arm, a tendon control unit, and an actuation unit. The overall setup is shown in Figure 3.2. The instrument arm is connected to a flexible tail. The flexible tail and the instrument arm pass through the channel of the snake robot. The actuation unit actuates the tendon control unit.



Figure 3.5: Flexible 3mm instrument prototype for snake-like robots. The instrument was 3D printed in stainless steel and uses tendons for actuation. (Source: [27]) © 2020 IEEE

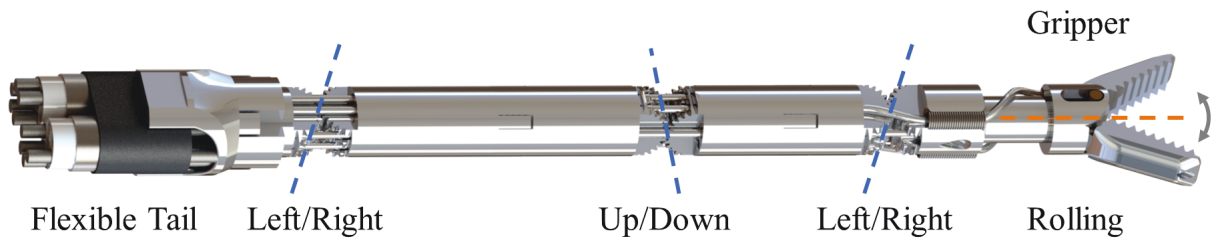


Figure 3.6: Schematic view of the flexible arm. This prototype is 3mm in diameter and has a length of 42mm with 4 DOF. (Source: [27]) © 2020 IEEE

A genetic algorithm combined with recorded suturing and anatomical data were used to design a pair of robotic instruments with 4 hinge joints under strict mechanical constraints. It is actuated using stainless steel tendons ($\varnothing 0.33\text{mm}$, ASAHI INTECC, Amsterdam, Netherlands). Since the control of a single DOF with one motor implies non-linearities for most types of joints, the precision was improved by optimizing the design and calculating the compensation of tendon length. The instrument joints are actuated by 8 tendons corresponding to 4 motors. For the gripper, one additional tendon is required for the open/close movement. A total of 9 resulting tendons are guided through the joints and the flexible tail. All tendons are pre-tensioned to stiffen the instrument. For the translation motion, the tendon control unit can be translated on the guide rail through a rack and pinion mechanism. In total 6 motors actuate the full arm. The instrument arm layout

is shown in Figure 3.6, the photo of the arm is shown in Figure 3.5. The first joint is the prismatic joint moving the whole arm out of the i^2Snake head. The second joint can move the arm left and right and move the arm away from the center. The third joint can move the arm up and down. The fourth joint moves the robot arm back to the center. All these joints work together to get the instrument to a target position. A roll joint is additionally included just before the gripper to enable rolling.

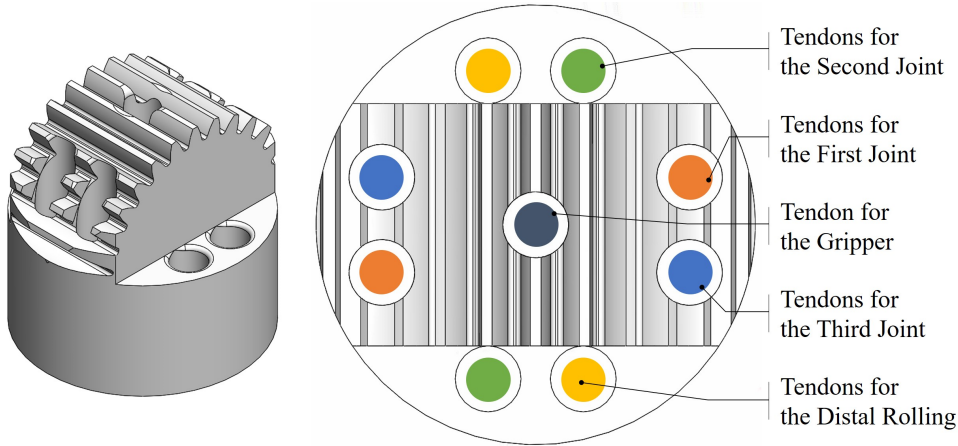


Figure 3.7: The tendons layout of the base link. The compact design enables a miniaturised instrument arm. (Source: [27]) © 2020 IEEE

The tendon layout is shown in Figure 3.7. Each joint is actuated by two tendons. To make the joint motion stable, the two tendons are arranged to pass the center of the link cylinder. The tendons for a joint are placed diagonally to each other. This helps to even out the load to the joints, e.g. imagine the last joint has both tendons to the left, pre-tensioning bend the second last joint.

3.5 Gripper with Rolling Capabilities

In Natural Orifice Transluminal Endoscopic Surgery (NOTES), rolling the tip of the instrument is an essential movement and greatly improves dexterity [1]. Usually, in single-port applications the tendons are guided through rigid shafts. To roll the instrument's end-effector, this shaft is rotated as presented by Shang *et al.* [14] and Shin *et al.* [81]. However, since snake-like robots are articulated and the instruments pass through it, this shaft must be flexible and shaft-wise rotation cannot be applied to it. Further, the

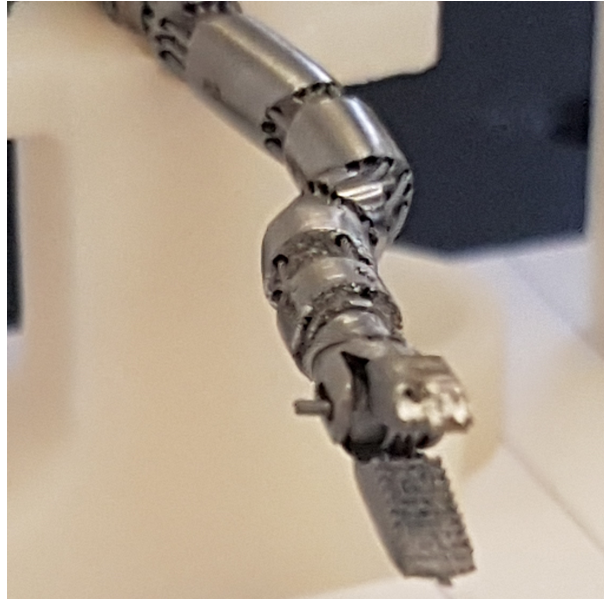


Figure 3.8: Photograph of the surgical instrument prototype developed for a snake-like robot. (Source: [26]) © 2019 IEEE

commonly used backend rolling method is known to have limited precision. The lack of accuracy is because when the backend rotates, all joints need to rotate as well. The rotation of all joints will accumulate all backlash.

Thus, to be able to rotate the end-effector this section suggests a gripper with rolling capabilities, as shown in Figure 3.8. The main advantage of rolling at the tip is that the roll joint can be used for stable in-place rolling. The evaluation showed that the distal-roll gripper can rotate about 165° and is capable of applying forces up to 6.5N.

3.5.1 Mechanical Design

In principle the roll rotation is realised by two parts rotating against each other. This is achieved by two tendons going around a cylindrical center, see Figure 3.9. All links are 3D printed in metal using Mlab cusing 200R (Concept Laser GmbH, Lichtenfels, Germany). After metal printing the surface is rough and irregular. It is crucial that the cylinder is polished so that the friction is low enough and the tendons can slide over it smoothly. A pin centers the two links. Once one of the tendons is pulled and the other is released the change in the tension turns the upper part. The bottom part has a printed distance plate which can easily be polished so that the upper part can move freely. The tendon coming

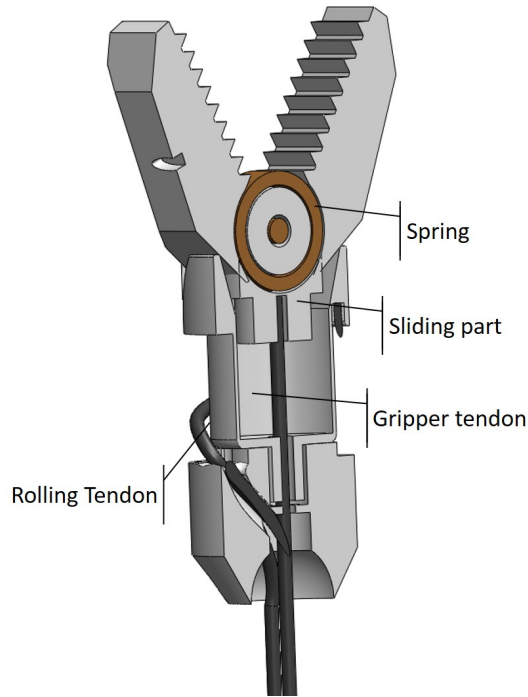


Figure 3.9: The mechanics of the gripper with rolling motion shown in a sectional view. It consists of a rolling part. The gripper closes by sliding inside the hull. (Source: [26])
 © 2019 IEEE

from the gripper passes through the rotating part. Because the rolling tendons are fixed at one side, all the pulling force is applied to the same side of the gripper. Therefore, while rolling the pin, the center cannot keep the joint straight so that it will bend sideways. However, the tendon of the gripper passes through the rolling joint and by keeping it at tension it will give the joint more stability. By design the roll joint can rotate up to 180° . Because of the high rotation angle, the gripper needs to be adapted. If the gripper had multiple tendons (e.g. four), these tendons would twist and twine. Therefore, the developed gripper only needs one tendon to close the jaws while a spring opens them once the tension in the tendon is released. The tendon is attached to a sliding part at which a spring is attached. The jaws are attached to the spring. Little etched guidelines hold the spring in place and align the jaws with the spring. While pulling the tendon, the jaws slide into the gripper's hull, which forces them to close. The jaws have a flat surface that fit to the flat surfaces from the gripper's hull. Before using the flat surfaces a design was tested that had round surfaces for the jaws as well as the hull. While closing the gripper by moving it inside, the round surfaces made it tilt to one side. Using the flat surfaces solved this problem. It is important that these flat surfaces at the jaws are polished.

Because the jaws were polished manually and as they are too small to hold them, they were printed with a holding structure. The gripper is designed to use the space from the roll joint to slide into. This way the gripper and the roll joint together are smaller than they would be separately. The tendons driving the roll motion have channels which guide them to the center channel. All three tendons join there and can then pass through the ball joint that serves as a wrist directly after the gripper.

3.5.2 Geometry of the Roll Joint

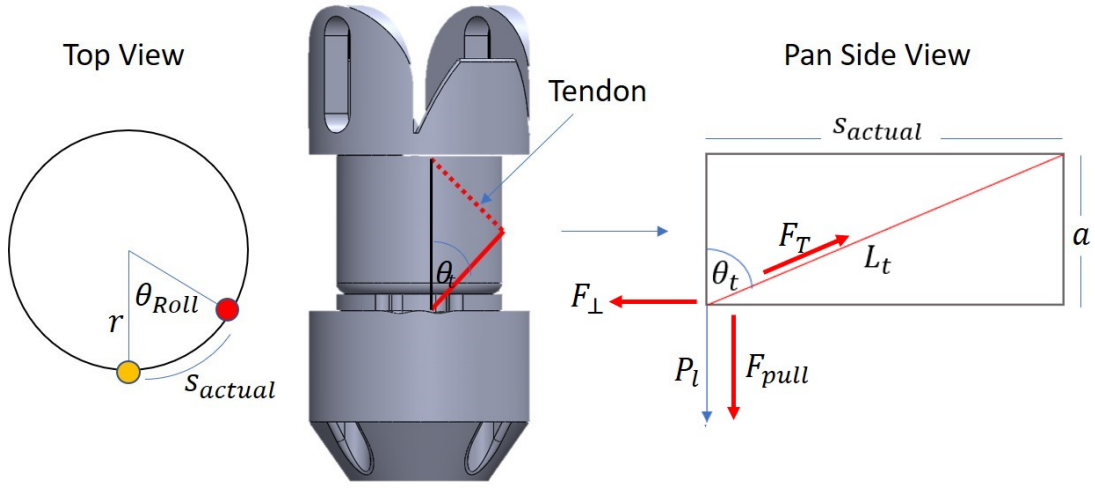


Figure 3.10: The geometry of the roll joint at the gripper. (Source: [26]) © 2019 IEEE

The geometry of the roll joint is shown in Figure 3.10. The roll joint is controlled by pulling tendon in the direction of P_l to rotate the instrument by the angle Θ_{Roll} . In order to calculate the angle, the geometry of the roll joint needs to be analysed. The angle of the roll joint Θ_{Roll} is calculated from the actual perimeter s_{actual} which is shown in equation 3.1.

$$\Theta_{Roll} = \frac{s_{actual}}{\pi \cdot r} \cdot 180^\circ \quad (3.1)$$

The actual perimeter is dependent on the actual tendon length L_t which is varied by the pulling tendon's length as shown in equation 3.2.

$$L_t = L_{max} - P_l \quad (3.2)$$

The maximum actual tendon length is calculated by the following equation 3.3

$$L_{max} = \sqrt{(\pi r)^2 + a^2} \quad (3.3)$$

where r is the radius of the roll joint and the roll joint has the height a . The tendon angle Θ_t is calculated as shown in equation 3.4.

$$\Theta_t = \cos^{-1}\left(\frac{a}{L_t}\right) \quad (3.4)$$

The actual perimeter is calculated in equation 3.5.

$$s_{actual} = \sqrt{L_t^2 + a^2} \quad (3.5)$$

The lateral force $F_{\perp}$ and rolling joint radius r are used to consider the rolling torque $\tau_{rolling}$ in equation 3.6

$$\tau_{rolling} = F_{\perp} \cdot r \quad (3.6)$$

where the lateral force is calculated by tendon angle θ_t and rolling-joint tendon force F_T in equation 3.7, which again is dependent on pulling force F_{pull} and tendon angle in equation 3.8.

$$F_{\perp} = F_T \sin(\theta_t) \quad (3.7)$$

$$F_T = \frac{F_{pull}}{\cos(\theta_t)} \quad (3.8)$$

Then the spring force F_{spring} at the tip is calculated following equation 3.12.

$$F_{spring} = \frac{\tau_{spring}}{L_{grip}} \quad (3.12)$$

Second, the pulling force F_{pull} at the gripper tip can be considered as the following equation 3.13.

$$F_{pull} = \frac{\tau_{pull}}{L_{grip}} \quad (3.13)$$

The normal force at the hinge F_a and the distance from the center of pulling to the hinge d are used to consider the pulling torque τ_{pull} in equations 3.14 and 3.15.

$$\tau_{pull} = F_a \cdot d \quad (3.14)$$

$$d = \sqrt{c^2 + e^2} \quad (3.15)$$

The normal force at the hinge F_a is determined by the tendon force F_{tendon} in equation 3.16.

$$F_a = \frac{F_{tendon}}{2 \cdot \sin(\beta)} \quad (3.16)$$

The gripper angle Θ is dependent on the pulling length e and the distance between the center and the hinge c as shown in equation 3.17.

$$\Theta = 90^\circ - \tan^{-1}\left(\frac{e}{c}\right) \quad (3.17)$$

Finally, angles α and β can be calculated following equations 3.18 and 3.19 respectively.

$$\alpha = 180^\circ - \theta \quad (3.18)$$

$$\beta = 90^\circ - \alpha \quad (3.19)$$

Integrating all formulas into (3.10) calculates the expected gripping force in N :

$$F_{grip} = \frac{\frac{\frac{1}{2} \cdot F_{tendon}}{\sin\left(\tan^{-1}\left(\frac{e_i + e_{pull}}{c}\right) - 90^\circ\right)} \cdot \sqrt{c^2 + (e_i + e_{pull})^2} - \frac{K_s}{90^\circ - \tan^{-1}\left(\frac{e_i + e_{pull}}{c}\right)}}{e_{pull} + l_{grip}} \quad (3.20)$$

3.5.4 Rolling Gripper with a 3mm Diameter

To miniaturize the instruments from 4mm to 3mm the gripper needed to be improved. The improved version was used in the 3mm instrument described in Section 3.4.2. It is to be noted that the distal-roll gripper with a diameter of 4mm can rotate to high angles of around 165° . Based on this design, a smaller flexible instrument was developed to be used in the 3mm instrument. It can be used in a snake robot of a smaller diameter to reach narrower natural lumen. However, a 90° rolling motion is sufficient for surgical applications.

The 3mm rolling gripper is based on the same principle as the 4mm rolling gripper, i.e., that two parts are rotating against each other, which realizes the roll motion. Figure 3.12 shows the gripper with a diameter of $\varnothing 3\text{mm}$. The rotation is achieved by two tendons going around a central cylinder. After metal printing, the surface is rough and irregular. It is crucial that the cylinder is polished so that the friction is low enough for the tendons to slide over it smoothly. A pin of the distal-roll is inserted into the hole of the link as a rotating shaft. Once one tendon is pulled and the other is released, the change in the tension causes the upper part to rotate. The bottom surface of the cylinder and the top surface of the link need to be polished so that the cylindrical part can move freely over the link. When the tendons come out of the link, they will go around the cylinder so that it will have a large pulling angle and friction. To reduce the friction, two coil cables are mounted to the link to make the rolling tendons move smoothly.

In the design of the 4mm rolling gripper the size limitation is given by the size of the embedded torsion spring. It was not possible to find a smaller torsion spring than with an outer diameter of 3mm. This makes the use of the torsion spring in the 3mm rolling gripper impossible. Instead, a Nitinol wire (Memory Corporation, A SAES Group company) is

used as a spring. Therefore, the developed gripper only needs one tendon to close the jaws and the spring opens itself once the tension in the tendon is released. The Nitinol wire is attached to the jaws and the sliding part where the tendon is attached to. A hole in each jaw holds the wire in place. Similar to the 4mm version of the gripper, when the tendon is pulled, the jaws slide into the gripper's hull, which forces them to close. The jaws have a flat surface that fits to the flat surfaces of the gripper's hull. These flat surfaces at the jaws are polished to make the motion smooth. The sliding part of the gripper is designed to make use of the space from the cylinder of the roll joint to slide into.

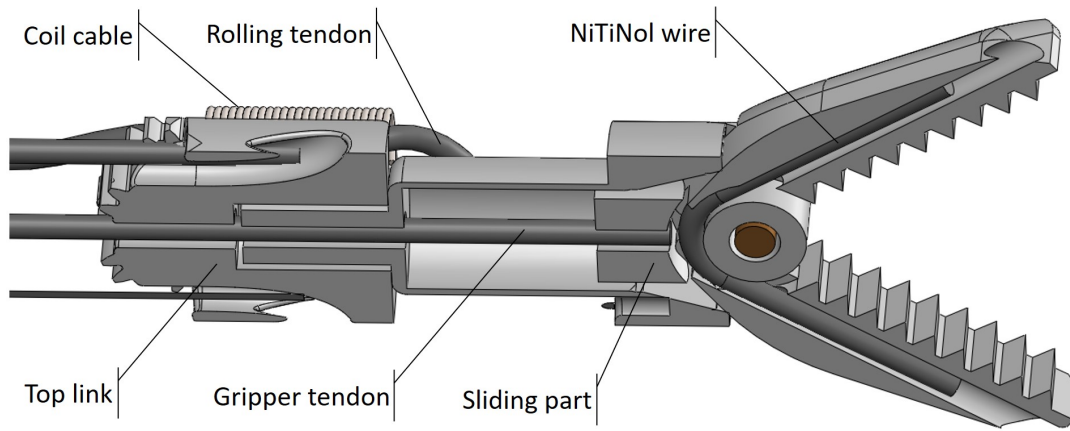


Figure 3.12: The developed gripper with rolling capabilities. A Nitinol wire is used as a spring to open the gripper. (Source: [27]) © 2020 IEEE

To measure the roll angle the instrument was recorded from the front. The gripper was rolled to both extreme positions and the maximum angle was measured. The roll joint can rotate approximately 90° .

3.6 Gear Joint Design

In this section a rolling gear joint is presented which removes any slip during operation. It is designed to be used in the 3mm-instrument, see 3.4.2, but can also be used for the 4mm-instrument, see 3.4.1. Tendon-driven flexible instruments are known to suffer from actuation coupling, slack, and backlash, which diminish the accuracy of the kinematic model. This section presents a static model for the gear joint to account for cross-coupling

and slacking effects between subsequent joints. In the evaluation, the actuated joints have achieved good repetitive motion and the compensations are validated experimentally.

The principle of the rolling gear joint is to have two round surfaces rolling against each other. The main advantage of a rolling joint is that the change in tendon length to move the joint is equal on both sides. This makes it perfectly suitable for being actuated by one motor for both tendons. The general disadvantage of these rolling surfaces is slip. The slip can happen to both sides, along the rotation axis and perpendicular to the rotation axis. Further, the slip can result in a rolling motion. To remove any slip a gear was embedded into the joint. Each link of the gear joint has a diameter of 3mm. The gear joint is shown in Figure 3.13. It has a central hole ($\varnothing 0.5\text{mm}$) for the central tendon and 8 holes for additional tendons ($\varnothing 0.45\text{mm}$). All links are 3D metal printed using an Mlab cusing (Concept Laser GmbH, Lichtenfels, Germany). It is to be noted that the links are split into two half parts. This split design ensures good printing quality of the gear teeth and enables small backlash. The primary purpose of using the gear design is to enable stable rolling. They prevent slip and stabilize the rolling motion like spur gears. Consequently, the gears help joint behaviors become more accurate and more predictable. The joint is able to bend to an angle of up to 90° . On the sides of the link, the gear joints have cutouts for the tendons, which prevent the tendons from scratching and sharp bending at large angles.

The calculations done in Section 6.2.2 recommend to use two cutouts to entirely remove the nonlinearities from the control, which means that the change in tendon length is the same for both tendons while moving the joint. The first cutout is on the side, which is included in the design. The second one would have been for the tendons passing through the gear. This was not possible, because the cutout led to small gear parts on both sides of the cutout. The joint became very unstable, because the gears could slip inside of each other or bend away. But since the same tendons sometimes change from the side channels to the gear channels or vice versa, when the instrument changes its bending direction, the tendon slack has improved considerably.

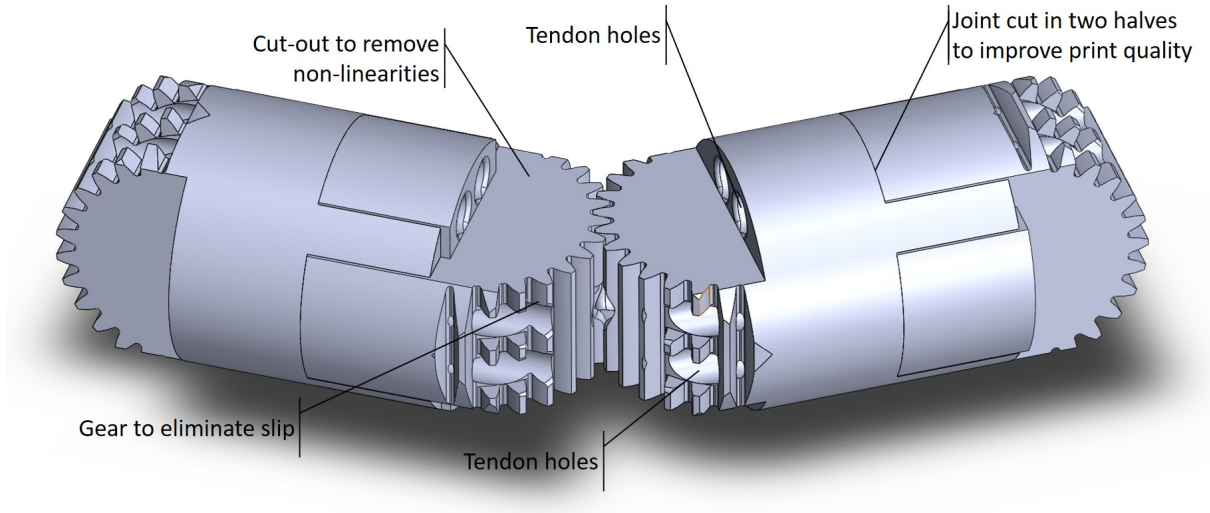


Figure 3.13: The rolling gear joint has two surfaces rolling against each other. The cutouts on the sides improve the control with one motor, because it reduces the nonlinearities. The slip on the surface is removed by using the gear.

3.7 Further Joint Designs

Several joints have been designed for use in the two instruments presented in this thesis, each of which are described in this chapter. The gear joint described in Section 3.6 and the distal-roll, see Section 3.5, are major contributions and were therefore presented as their own sections in this chapter, including an evaluation of their feasibility. Below, a series of additional joint/link designs are discussed, which were also investigated as part of this work, albeit in less detail. This includes a hinge joint in Section 3.7.1, a ball joint in Section 3.7.2, a gimbal joint in Section 3.7.3 and a mechanism for translation in Section 3.7.4.

3.7.1 Hinge Joint

The first joint design was based on the design made by Shang *et al.* [14]. Each link is a cylinder with a diameter of 4mm, see Figure 3.14. The design underwent an evolution starting from the joint in Figure 3.14(a) which finally led to joint (b). The basic principle is the same in both joints. Both have a central channel ($\varnothing 1.7\text{mm}$) for the central multi-lumen catheter. This central channel can accommodate up to seven tendons for later

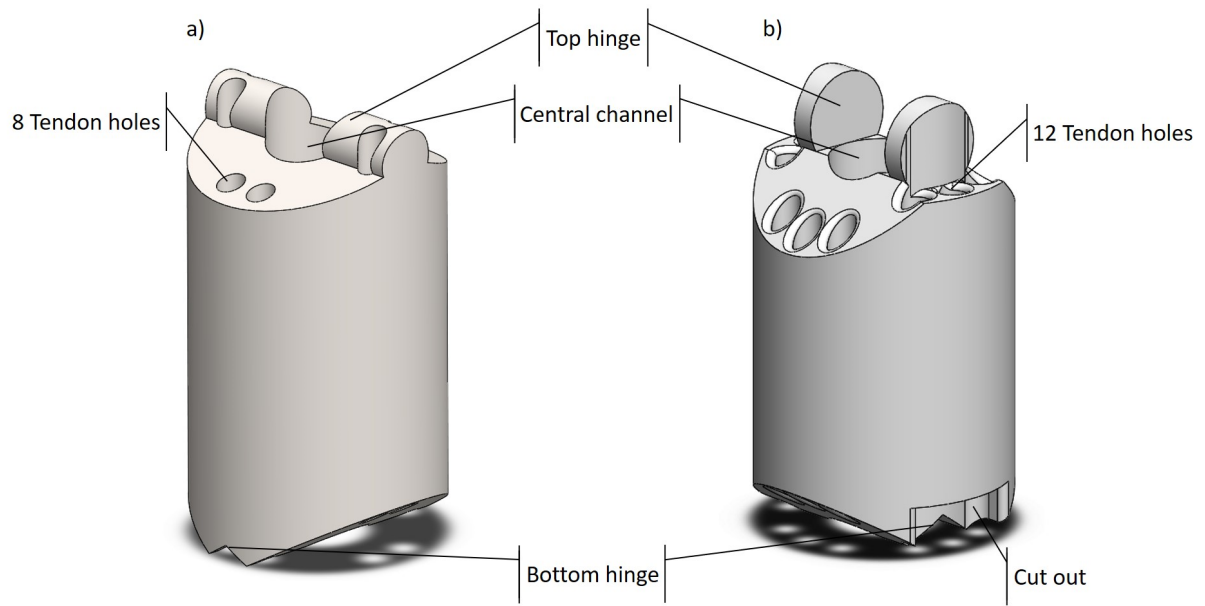


Figure 3.14: a) The first version of the hinge joint based on the design made by Shang *et al.* [14]. b) The improved second version of the hinge joint, which is used in the 4mm instrument described in Section 3.4.1. The Top hinge is round, but the bottom hinge is a triangle to reduce the contact point size. The joint has a high bending angle of 75° because of the big round part and the beveled sides. (Source: [26]) © 2019 IEEE

joints, such as the rolling gripper described in Section 3.5. A head is needed to integrate the tendons from the central channel to the tendon channels for the joints. The improved design (b) of this link increased the number of tendons it can accommodate from 8 tendons in (a) to 12 tendons in (b). The holes for tendons have a diameter of $\varnothing 0.45\text{mm}$. Together with the seven tendons from the central channel the link is able to guide 19 tendons through the arm. The links have two types of hinges. On the top they have a circular hinge. In (b) both hinges were significantly increased. The circular hinge has a diameter of $\varnothing 1.5\text{mm}$. The increased sizes of both hinges of the link ensure a good printing quality and enable a high bending angle of 70° . On the sides of the circular hinge the joint is sloped by 40° . On the bottom side of the link there is a 1.22mm triangular hinge. In this size the hinge can be easily printed. The sides next to the hinge have a slope of 33° . Because of these slopes the joint is able to bend to an angle of up to 75° . On both sides the hinges have cutouts for the tendons. This is necessary to prevent the tendons from scratching and sharp bending at high angles. Together with these cutouts the tendons which are passing through the joint can use a distance of 1.86mm to bend between two

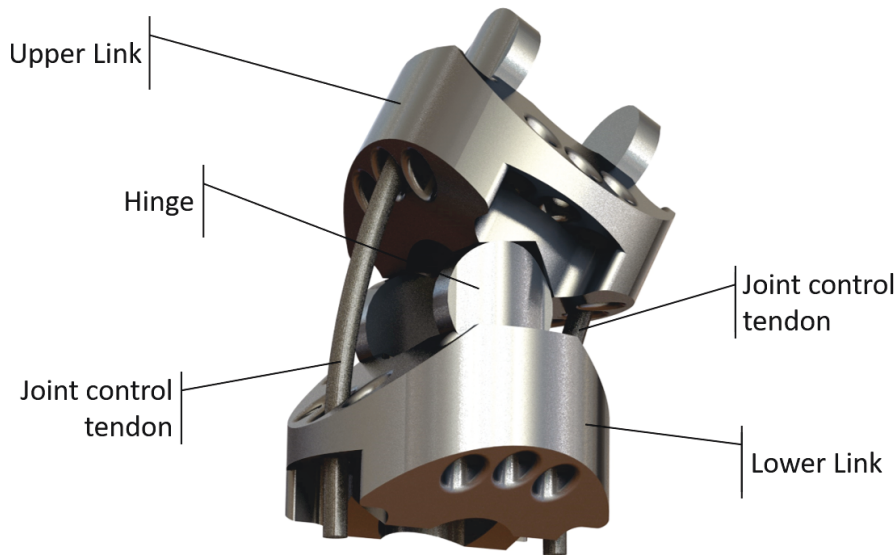


Figure 3.15: The complete hinge joint consisting of an upper and a lower link. The tendons used to control this joint are visualized. The remaining tendon holes are used to pass through tendons for the next joints or the gripper.

links. The complete hinge joint consisting of two links is shown in Figure 3.15. The links are held together by the tension of the tendons passing through the joint.

3.7.2 Ball Joint

The ball joint consists of two links, see Figure 3.16. The upper link has a hemisphere shaped opening. This opening fits to the sphere of the lower link. Four tendons control the ball joint to bend it in 2 dimensions. They are guided through the proximal part of the ball joint and are welded into the distal part. In theory three tendons at 120° are sufficient to control a 2 DOF joint, but every of these tendons needs to have its own motor. Further, in this instrument design the tendons need to be routed through the symmetrically placed tendon holes. Because it uses four tendons, the tendons of the opposite side are controlled together by one motor.

Three tendons, the two used for the rolling rotation and the one to close the gripper, are passed through the ball joint. A wide channel is going through these two parts. The opening in the ball is designed in such a way that the tendons fit through in every possible angle. The multi-lumen catheter which contains the three tendons and proceeds through

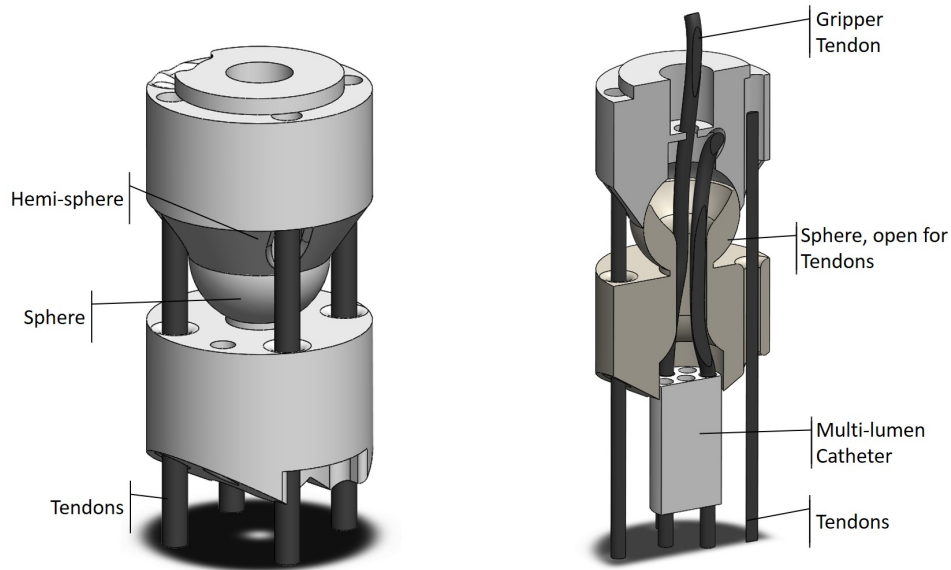


Figure 3.16: Schematic view and sectional view of the developed ball joint, which can bend in two directions (2D joint). (Source: [26]) © 2019 IEEE

the central channel of all other joints ends in the lower part of the ball joint. In this part the three tendons leave the multi-lumen catheter and enter the gripper. The two tendons for the rolling motion are guided to the rolling surface. Both tendons are kept near to each other to maximise the rolling motion distance.

During operation it was recognised that manufacturing the ball joint introduced some disadvantages. The ball joint needed less force rotating around the center when it was fully bent sideways than when it was moving over the center and passing over a straight position. Obviously, the joint needs less force in a bent position than in the straight position. A plausible explanation is that polishing the sphere caused a small deformation, so that it was not a perfect sphere anymore. This introduced the problem that the force needed to move along the side was lower than moving through the center. That means that straightening the joint was barely possible. This problem increased as friction experienced during repeated use of the instrument deformed the sphere further.

3.7.3 Gimbal Joint

The gimbal joint was designed and produced as a prototype in 4mm to be used as a replacement for the ball joint, because it is possible to control more precisely. The joint can bend 45° in two dimensions. It consists of six parts and polishing was necessary on the small middle part. It was initially planned to be used in the 4mm instrument, described in 3.4.1. The joint is shown in Figure 3.17. The basic principle is to use two parts connected by a middle part. This middle part has 4 round bars as rotation points and connections to the other parts. Since this part is embedded in the joint, the top and bottom part is split into half. This way, the middle part can be integrated. It has four tendons to control the bending in 2 dimensions. To assemble this bending tendons, one tendon with double length is pulled through the holes, after that the whole is crimped to lock the tendon in place. The middle part has three tendon holes, two for the rolling motion of the gripper and one to close the gripper. These holes are to guide the tendons through the joint while bending.

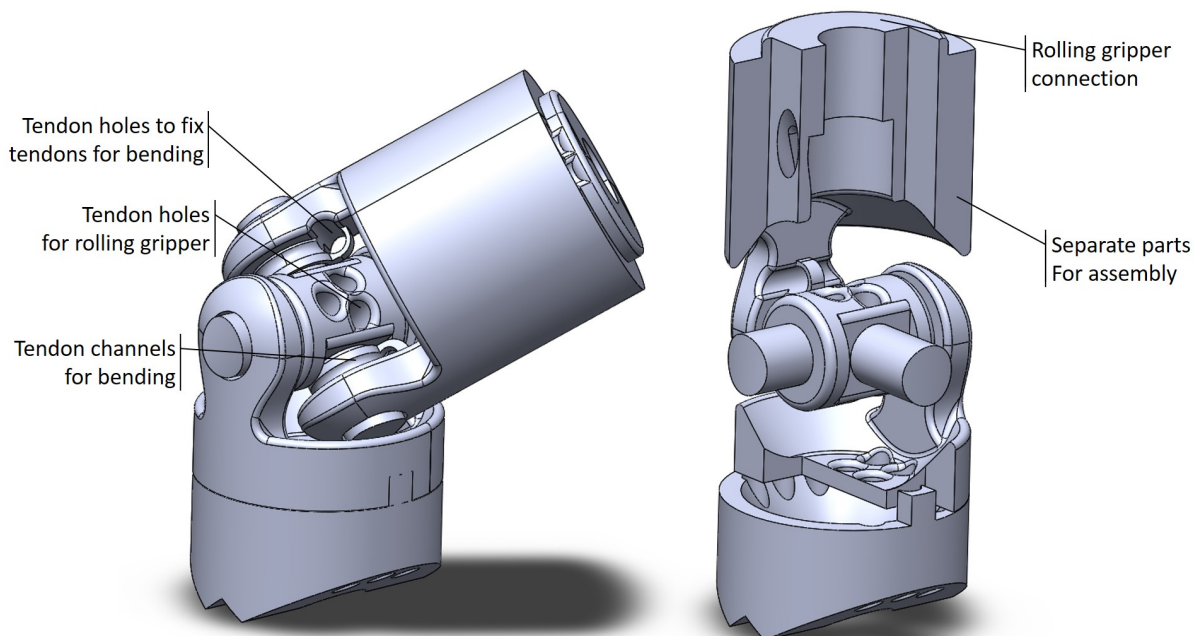


Figure 3.17: The gimbal joint was designed and produced in 4mm to be used in a 4mm instrument. It consists of six parts.

Two prototypes were built and the joint seemed to be stable and easy to control but was then replaced by the ball joint, because the ball joint just consists of 2 parts and was easier to fabricate. Finally after the experiments and the discovery of the disadvantages of the ball joint, the use of the gimbal joint will improve the control of the instrument, although it is much more complex to build.

3.7.4 Translation

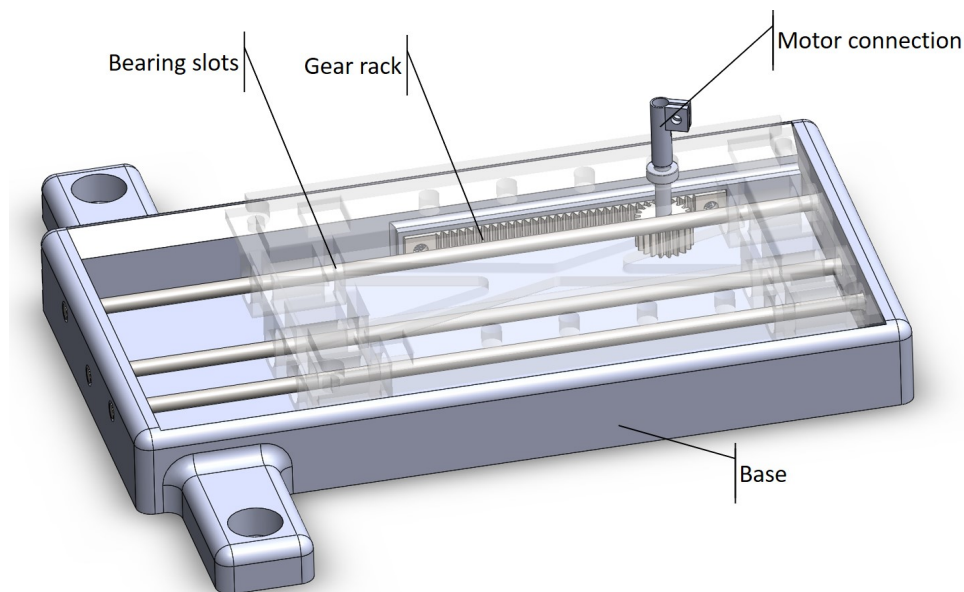


Figure 3.18: The translation mechanism used in the last version of the instrument arm. A gear and a gear rack were used to actuate the prismatic joint.

During optimisation of the instruments design, see Chapter 4, it was found that including a DOF for translation could help to increase the work space of the instruments enormously. Therefore, the second iteration of the instrument actuation unit used a prismatic first joint to translate the instruments forward and backward, shown in Figure 3.18. This enables the arm to extend and retract. The translation is included in the second version of the actuation unit, seen in Figure 3.2. The translation is built by having a sliding part which moves on top of a base part. It is locked in place with rods. The two side rods lock the translating part in place. Because the middle rod is slightly lower than necessary, it puts tension on the rods. This ensures that the translation part is locked in place and does not shake while moving. The actuation is achieved with a gear and a gear rack.

The gear is connected to a motor. When the motor is rotating, the force is translated to a forward-backward motion. Since the gear and the rod were 3D printed, it introduced some backlash. The control program was able to compensate for that. To improve the translation, the rack and gear should have as less play as possible. Another possibility to improve the translation is the use of a high quality zero-backlash lead screw.

3.8 Evaluation

To evaluate the capabilities of the surgical instrument that is presented in this section, three different tests were performed. First, the forces that the gripper is able to apply were measured. Second, the maneuverability and repeatability of the instrument arm were determined. Third, a workspace analysis was performed. Finally, the maneuverability of the gear joint is determined.

3.8.1 Evaluation of the Gripper

Force Estimation

The rolling torque and the gripper force were measured in the testbed shown in Figure 3.19. In both tests a test joint was fixed in a holder and motors pulled the driving tendons. The equations mentioned in Section 3.5.2 are used as a guideline for the design parameters.

To measure the rolling torque a test roll joint was used. It was driven by the two tendons to rotate clockwise. The roll joint in the instrument needs the gripper tension for stability. Therefore, in the test scenario the counterclockwise rotation and center tendon were tensioned to provide the system with stability. To measure the force a tendon was fixed tangential to the rotational joint so that it connects the joint with a force sensor which was fixed in a holder. The motor was driven forward step by step until the system failed. The measured force was $F_{rot} = 6.55N$. The torque is defined as: $\tau_{rot} = r \cdot F$. With a

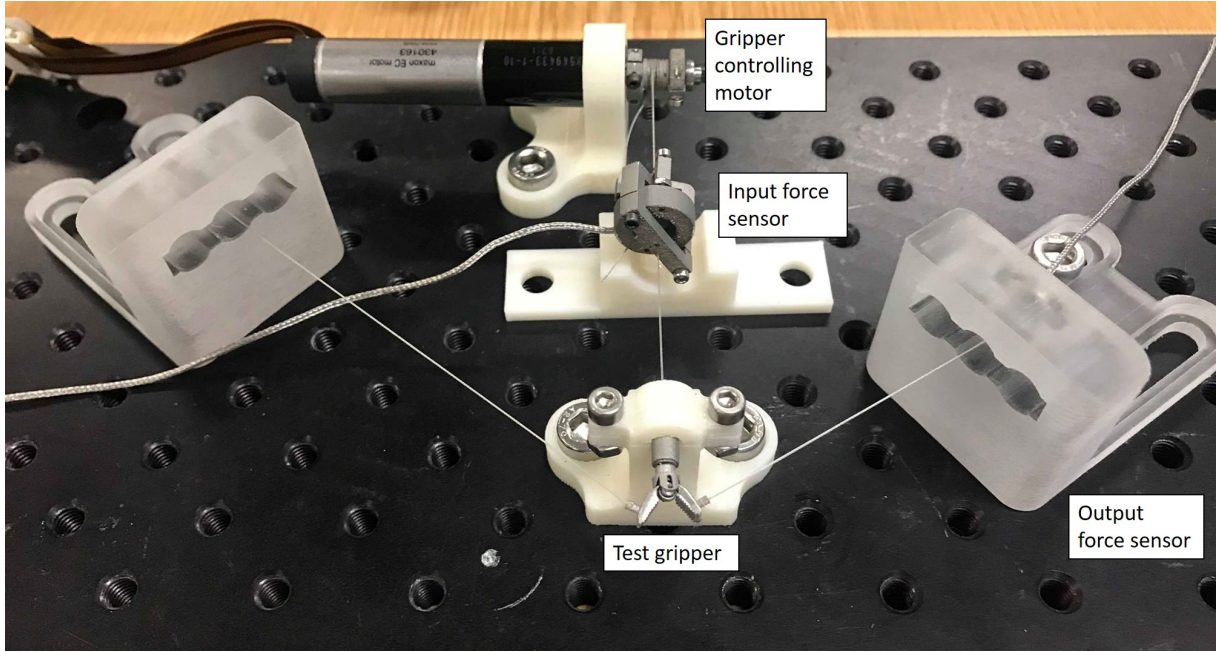


Figure 3.19: Photograph showing the testbed which was used to evaluate the output forces of the gripper. (Source: [26]) © 2019 IEEE

radius of $r = 2mm$ the torque is $\tau_{rot} = 0.0131Nm$. The system failed because the driving tendon broke. The rolling torque is also dependent on the rotation angle and pulling force as in equation 3.6.

Measurement of Gripping Force

The gripping force was also measured using the setup shown in Figure 3.19. The driving tendon was the tendon connected to the sliding part of the gripper. Between the motor and the gripper tendon, a force sensor was placed to measure the input force F_{in} . A tendon connects each jaw of the gripper with a force sensor which measures the output force. When the driving tendon was pulled, the input and output forces were recorded using an amplifier and an Arduino and the values were transmitted to a PC where they were scaled to Newton using a scaling factor that was computed during sensor calibration. The system was driven manually by step increments. The graph shown in Figure 3.20 visualizes the relation between the input force F_{in} and the output force F_{out} . The manual steps can be recognised. Around $tick = 7000$ some anomaly can be seen. This is because the system got stuck and needed to be released. At an output force $F_{out} = 4.2N$ the

system failed. The failure was because the driving tendon slipped out of its hole of the sliding gripper part.

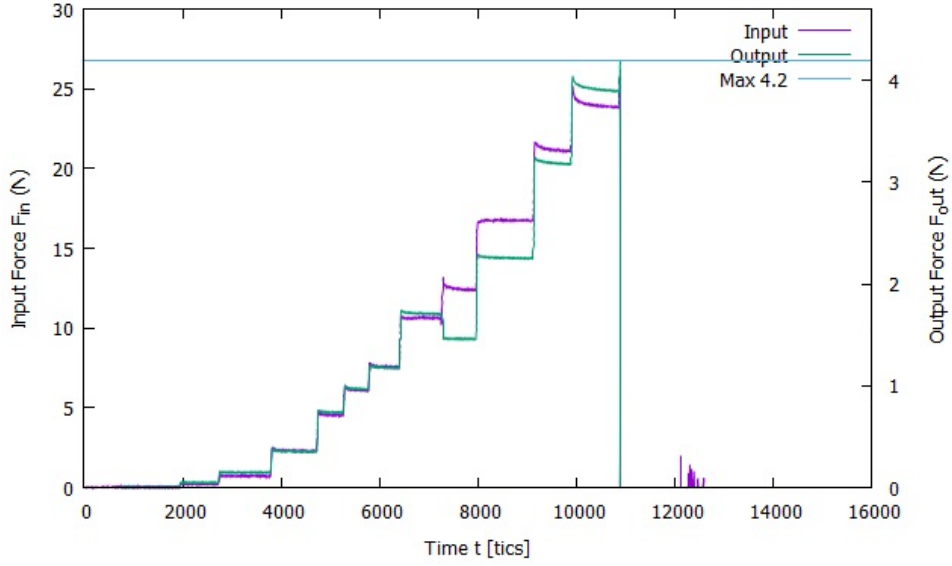


Figure 3.20: Input and output forces of the gripper jaws over time. Input forces are shown in purple and output forces are shown in cyan. (Source: [26]) © 2019 IEEE

The factor between F_{in} and F_{out} can be set to approximately $f = 0.155$ with $F_{out} = F_{in}f$. The maximal torque reached was $\tau_{grip} = 0.0084 Nm$.

3.8.2 Evaluation of 4mm Instrument

The performance of the 4mm instrument is evaluated by determine the maneuverability, repeatability, and workspace.

Determination of Maneuverability

To measure the maneuverability of the instrument arm, the prototype was placed in a test rig. It consists of the motor box, a part of the flexible tail, the instrument and a camera to record the movements, see Figure 3.21.

This setup was used to test repeatability, the real joint bending angles and the rolling angle. To measure repeatability for one joint of the instrument at a time, this joint was

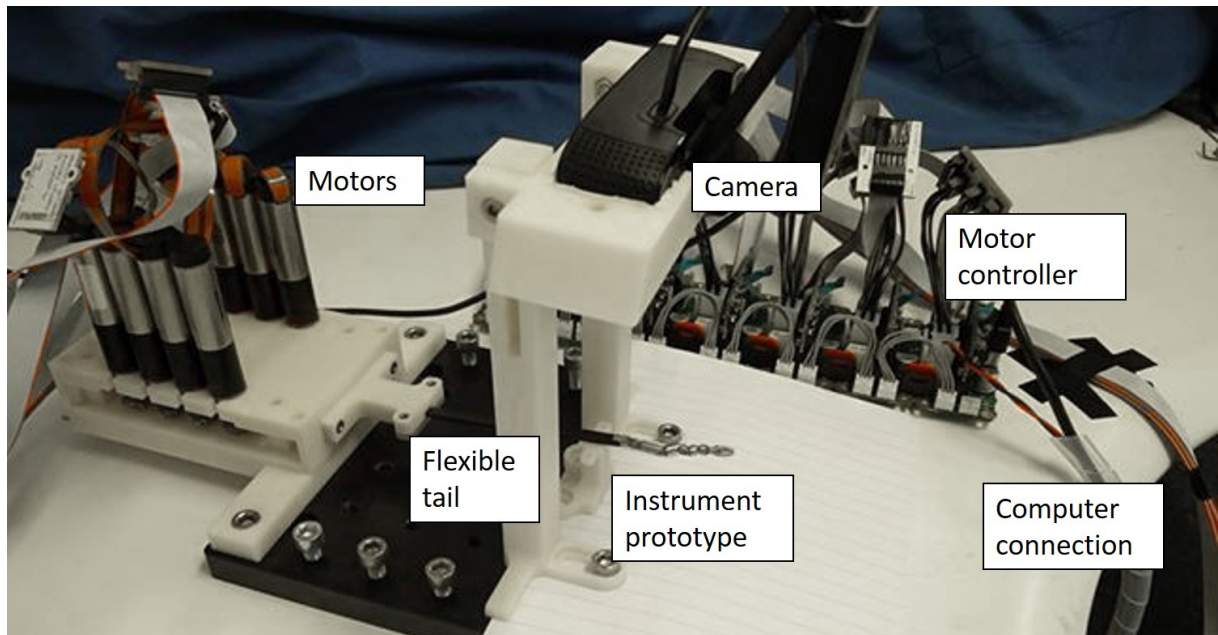


Figure 3.21: The test setup used to evaluate the repeatability and the maximal joint angles. (Source: [26]) © 2019 IEEE

driven by a defined repetitive motion. In the video that was taken the angle was measured manually for each run. For the hinge joints, the maximal difference was less than 2° which includes the error for manual measuring. Regarding the rolling joint, most of the 60 measurement points were inside of a maximal difference of less than 1° .

To measure the maximal joint angles the instrument was moved into an extreme position, and the angles of the joints were measured. Figure 3.22 shows the measurement position. At every joint the instrument can bend by 72° which is also the theoretical mechanical limit as it can be seen in Figure 4.4. The picture also shows the bending capability of the whole instrument.

To measure the roll angle the instrument was recorded from the front. The gripper was rolled to both extreme positions and the angle in between was measured. The result is a roll angle of nearly 165.65° .



Figure 3.22: The measurement position of the instrument to determine the maximal joint angles. (Source: [26]) © 2019 IEEE

Workspace Analysis

For the developed instrument layout, a workspace analysis was calculated. This analysis was developed by Leibbrandt *et al.* [23], [172]. It measures the dexterity of a robot at a certain position for all positions the robot can reach. It is derived from the manipulability measurement and considers joint limits [173]. Using this approach it is possible to compare the workspace of different instruments. The analysis was performed for two different configurations of the instrument presented in this section (see Figure 3.23). Both configurations are the same, except that one has the presented roll rotation capabilities (Fig. 3.23 right) while the other one has not (Figure 3.23 left). The scale of the result is the same in both analyses. It is easy to recognize that the rolling rotation strongly improves the dexterity.

3.8.3 Maneuverability of the 3mm Rolling Tip

In Figure 3.24 (a), the maximal rolling motion of the 3mm rolling tip is demonstrated. Because of the reduced diameter the tendons cannot be guided in an s-shape. This let

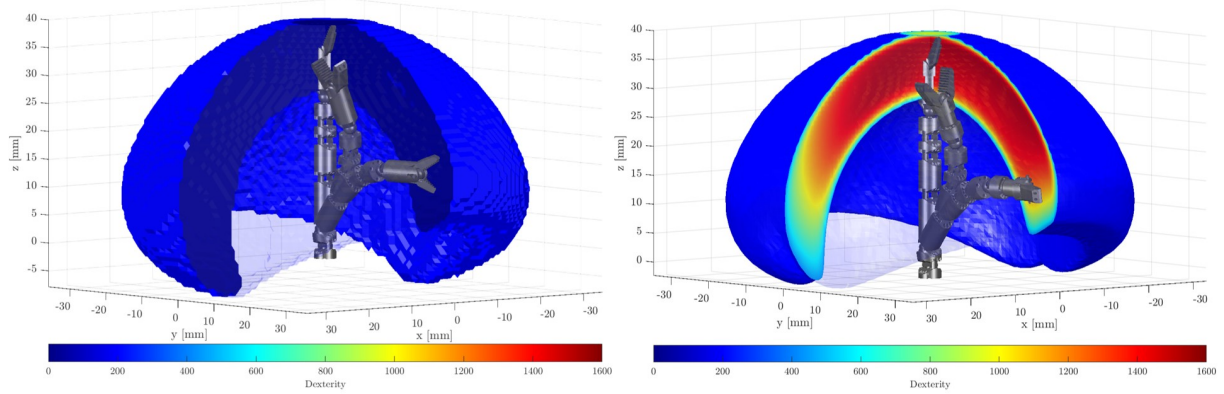


Figure 3.23: Two workspace analyses were made for the same instrument without a prismatic joint, except one has no roll rotation capabilities (left) and one has the roll rotation capabilities presented in this section (right). The colors represent the dexterity of the instrument at the given positions. (Source: [26]) © 2019 IEEE

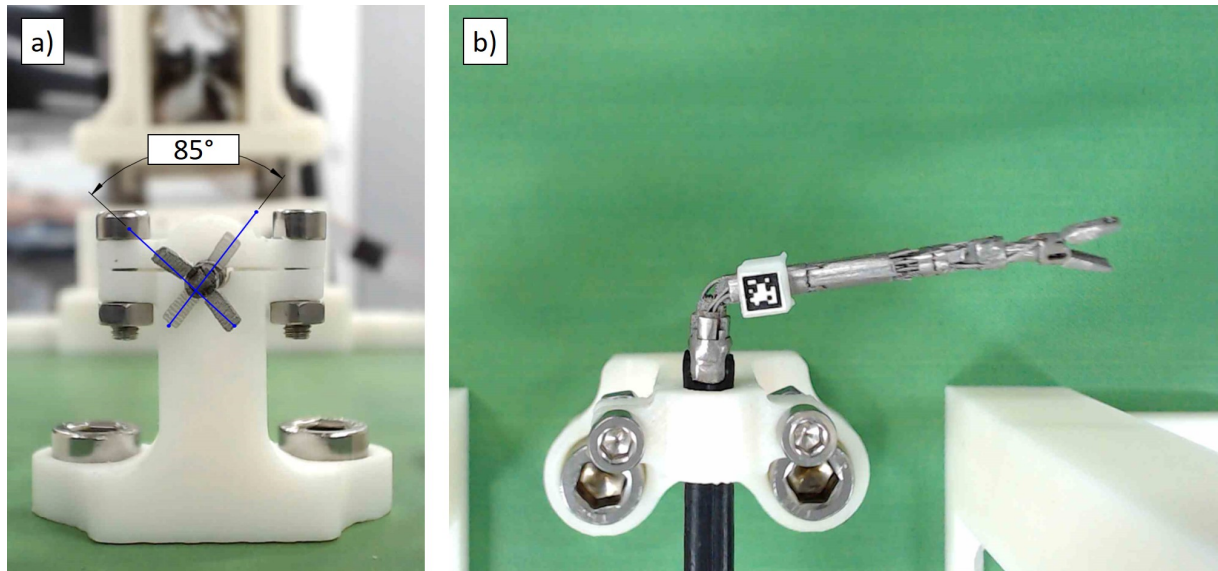


Figure 3.24: Two cameras measure the rolling and bending angle: a) The maximal rolling angle of the 3mm instrument of 85° . b) The measuring the maximum bending angle of each joint of the 3mm instrument.

to a reduced rolling motion of 85° . This is still a good range of motion for most of the surgical applications as demonstrated in Chapter 4.

3.8.4 Maneuverability of the 3mm Gear Joint

To measure the maneuverability of the rolling gear joint, the 3mm instrument prototype was placed in a testbed, see Figure 3.24 (b). It consists of the actuation unit, a part of the

flexible tail, the instrument, as well as a camera which records the movements. To measure the maximal bending angles of joints and the rolling angle of the tip, the instrument was moved into an extreme position, and the angles of the joints were measured. At every rolling gear joint, the instrument can bend up to 82° of a maximum of approximately 90° . For both sides together the range of motion is 164° which makes this joint very flexible, compared to the hinge joint with 72° . The positioning accuracy and repeatability is not tested separately but for the whole arm including compensations in Section 6.5.

3.9 Conclusion

This chapter has presented the design of two new flexible instrument prototypes for endoscopic surgery. The designs include a combination of tendon-based hinge joints and novel joints such as a gripper that is able to perform a roll motion and a gear joint which removes slippage and improves control. The rolling motion of the gripper is achieved via two antagonistic tendons which go around a rotation shaft. The gripper is closed by a single tendon and opened by a spring.

The first instrument prototype is 4mm in diameter and has 6 DOF plus the gripper movement. Some disadvantages result out of the building process and can be solved, e.g., the processing of the ball joint can be improved or the gimbal joint can be used. The evaluation has shown that the movement of a single joint is repeatable and the force is useful with 4.2N. With improvements in the assembly process it will be possible to further increase this force. The possible rotation of the roll joint is comparably high with an angle of 165° . The hinge joints bend up to an angle of 72° . It was shown that the rotation is necessary and strongly improves the dexterity. The main advantage of the roll joint is that it can be used for stable in-place rolling. Leibrandt *et al.* [23] showed that this is a crucial motion and that with the commonly used back-end rolling method this motion cannot be precise. This is because when the back-end rotates, all joints need to adapt. Since the sides of an instrument are not equal, some positions are harder to reach. This leads to imprecise holding of the position and orientation during rolling. Another factor

is that the adaption of all joints is accumulating all backlash. In [23] Leibrandt *et al.* use a lot of calibration and backlash compensation to operate an in-place roll. The proposed rotation has none of these disadvantages by principle, since it is rotating at the tip and all joints remain stationary.

The second instrument reduced the diameter to 3mm and has 4 DOF along with a translation and a gripper. The compact and miniaturised design of the instrument allows surgeons to perform MIS and enable more precise surgery. The instrument includes a translation in the actuation unit which increased the workspace and dexterity. This instrument arm introduces gear joints. It is shown that these joints have less non-linearities while controlling the joint with one motor. The arm is composed of three of these gear joints.

The evaluation showed that each gear joint could bend up to an angle of 82° and the rolling angle was nearly 90° . With improvements in the design and the assembly process, it will be possible to further increase the rolling angle.

As a future work the instrument can be improved by enhancing the building procedure, e.g., use milling to create smoother gears. That should result in lower frictions and therefore in a smaller loss between the input and output force.

Chapter 4

Design Optimisation

Over the last few years, there has been a significant rise in designing small, agile, and flexible medical systems. In the case of endoscopic surgery, existing systems vary significantly from each other. The gold standard for robot arm design is the human arm with its 7 degrees of freedom (DOF) while a typical workspace is composed of 6 dimensions, 3 dimensions for position and 3 dimensions for rotation. Having more controllable DOF than the workspace has dimensions allows for better dexterity, especially during complex manipulation tasks. However, as robots are getting smaller, it is becoming a real challenge to design and assemble these miniature redundant manipulators, so that the outcome is often a simplified system with limited dexterity. In current research the endoscopic instrument designs often use less than 6 DOF and vary significantly from one system to another. The daVinci robot (Intuitive, USA) for instance uses a 3 DOF tool holder with a 3 DOF instrument and a grasper. This allows the operator to intuitively manipulate tissue. Table 4.1 shows the degrees of freedom of multiple systems which can be found in research literature.

All these examples show that there are various types of instrument designs with various amounts of DOF even though the targeted applications are similar. This raises the following question: *Is there a general tool design with a reduced amount of joints that can perform most surgical tasks?* The aim of this section is to study the impact of design and kinematics on endoscopic robotic instrument performance.

System	DOF
STRAS [69]	3 + Grasper
LESS [70]	2 + Grasper
IREP [71]	5 + Grasper
MASTER [72]	5 + Grasper
K-FLEX [174]	4 + Grasper
CYCLOP [175]	5 + Grasper
Chapter 3 4mm Instrument [26]	7 + Grasper

Table 4.1: Degree of Freedom of instruments of different published systems. The grasper is controllable and therefore also a DOF, but since it does not contribute to the positioning of the tip it is listed separately.

To evaluate the performance of a designed tool, tasks from the fundamentals of laparoscopic surgery (FLS) were used, which consist of a set of training tasks for laparoscopic surgeons, and represent a good and valid method to create a library of general surgical motions [176]. This approach, referred to as task based design, has been used for various design optimization problems [177]. Yang and Chen [178] used an evolutionary algorithm to minimise the required amount of DOF of a modular robot based on kinematic performance metrics. Chung *et al.* [179] used a genetic algorithm (GA) to optimise the link length of a modular robot manipulator and the relative manipulability as a metric. Bergeles *et al.* [67] used patient specific data and surgical workspace constraints to optimise the design of a concentric tube robot. Further design optimisations are presented in [178, 179, 180].

Among the existing design optimisation methods, evolutionary algorithms have the advantage of being efficient, simple to implement, and robust to local minima.

This chapter proposes to use task based design to create a pair of endoscopic instruments for the *i²Snake* [74, 30] and to study the impact of kinematics on instrument performance. The objective is to collect data of an operator performing FLS tasks combined with physiological data and to use a GA to search possible instruments. For each design generation, an inverse kinematics solver is used to evaluate the design quality. The distance between the robot tip and desired target is used as a cost metric for the GA. The instruments with the smallest error are used to generate the population of the next generation. The results therefore improve with each generation. Once the best result stalls the search is stopped.

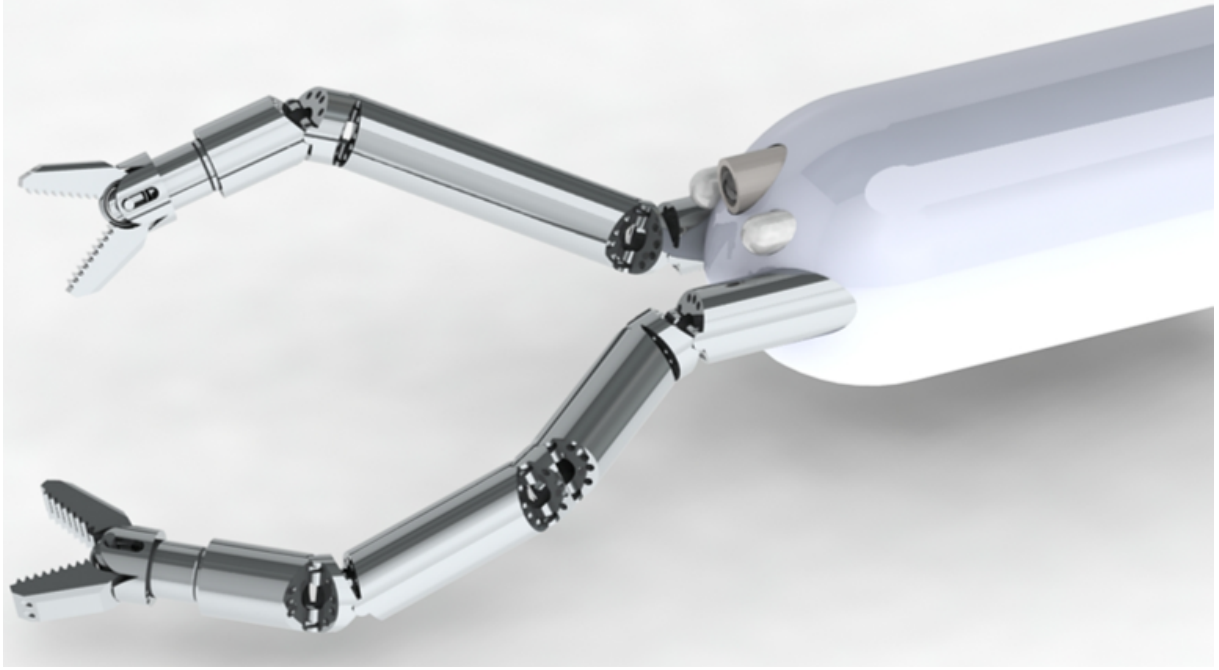


Figure 4.1: Rendering of the i^2Snake endoscopic system with the final set of GA generated endoscopic instruments. At rest position, the instruments can slide in and out the head of the i^2Snake . (Source: [28]) © 2019 IEEE

The final set of 4mm instruments found with the approach proposed in this chapter is shown in Figure 4.1.

The work developed here was published by Andreas Schmitz *et al.* in [28] and [29].

This chapter is structured as follows: Section 4.1 introduces the methods for data collection and Section 4.2 the robot kinematics. Section 4.3 defines the used GA and Section 4.4 presents the results as well as a discussion. Section 4.5 presents a focus on simple instruments, because complex instruments were not possible to build with a diameter of $\varnothing 3\text{mm}$. Finally the conclusion is found in Section 4.6.

4.1 Data Collection and Processing

In order to collect clinically relevant motion data, we used one of the FLS tasks considered to be the most challenging, especially when considering endoscopic application: suturing and knot tying [176]. The demonstration was done manually rather than with a

robotic device to alleviate the potential impact of the kinematics of the robot used. The data acquisition was performed by a right-handed non-medical PhD student with some experience in suturing and knot tying. It is arguable that data from a novice operator could affect the overall results, but in practice, novice users tend to make more arbitrary movements than expert surgeons leading to more complex trajectories. In this case, data from a novice may actually be more robust than data from an expert.

Additional factors such as the width, length, and orientation of the wound, the direction of suture, etc., were not considered at this stage, but it can be expected that having a larger dataset would result in a more polyvalent tool design at the cost of higher computation times. However, existing manual surgical instruments are usually optimised for one specific task, e.g., grasping forceps, biopsy forceps, or dissecting forceps, so it seems logical to collect separate datasets for specific instruments. To generate a tool that fits to all tasks, the optimisation needs to be done with the whole dataset.

The data collection was done using an Ascension trakSTAR (Ascension Technology, NDI, USA) electromagnetic (EM) tracker equipped with three sensors (Root mean square (RMS) error of 1.4mm, 100Hz recording frequency). Non-magnetic tools were used to perform the task in order to avoid ferromagnetic noise on the tracker. The left instrument was a forceps equipped with one miniature EM sensor at the tip. The right instrument was a needle grasper also equipped with a miniature EM sensor at the tip. The suturing and knot tying was performed using a silicone phantom as shown in Figure 4.2. The third EM sensor was placed below the phantom to locate the exact task location. The task consisted of the following steps: inserting a suturing needle on the right side of the wound, coming out on the left side, pulling the thread with the forceps and grasper, rolling the thread around the grasper twice using the forceps, catching the thread's other end with the grasper, and finally tying the knot by pulling on both ends of the thread.

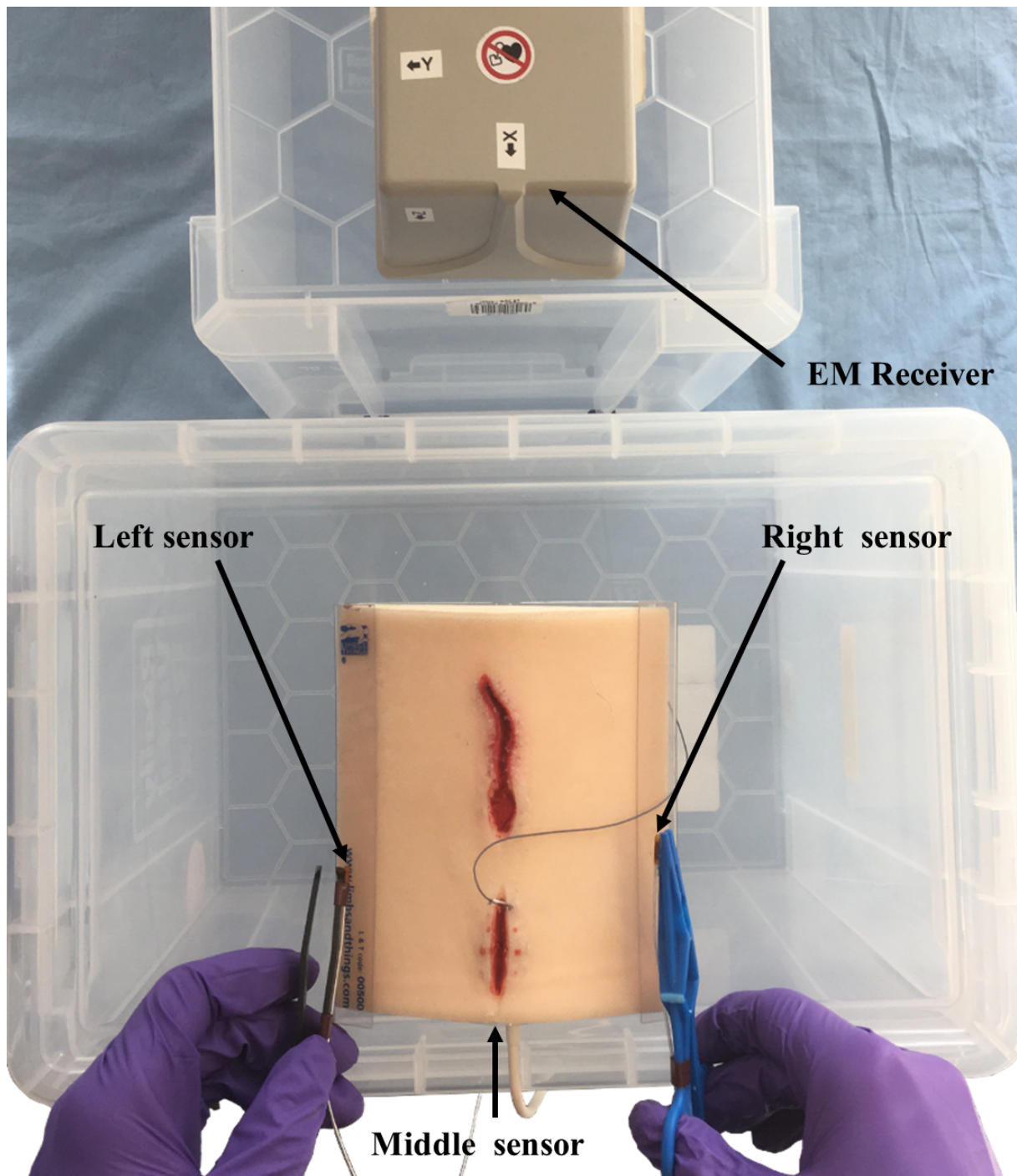


Figure 4.2: Suturing and knot tying task. As the operator moves the instruments, the EM sensors located on each instrument are tracked and the trajectory is saved. The middle sensor is used to know the task location. (Source: [28]) © 2019 IEEE

4.1.1 Data Processing

As the demonstrations were performed in a large workspace (human arm scale) and relative to the EM tracker reference frame, the first step of data processing consists of

transforming all the trajectory points relative to the third sensor position and changing the orientation so that it matches a global reference frame. This can be done using the following equations:

$${}^F p_i = p_i - s_z \quad (4.1)$$

$${}^F R_i = R_g \cdot R_i \quad (4.2)$$

where p_i is the trajectory's 3D position at index i , ${}^F p_i$ is the new point in the new frame F, s_z is the third sensor's 3D position used as the new origin, R_i is the trajectory point orientation matrix at index i , ${}^F R_i$ is the new orientation in the new frame F, and R_g is the rotation matrix allowing for rotation of R_i into a desired global orientation.

4.1.2 Data Downsampling

The next step consists of downsampling the data. As the data is recorded at 100Hz, the recorded files contain many redundant points. Moreover, the larger the dataset, the more time the GA will need to find a result. The data size can be significantly reduced by using geometric downsampling. Each time the instrument moves more than a desired threshold Δ_p , the point is saved, and all intermediate points are discarded. This is also applied to the orientation; if the tool moves more than a desired angle Δ_R , the orientation is saved and the rest is discarded. While the data points are being parsed, the downsampling algorithm also looks for extrema and adds them to the smaller dataset *dwnData*. The downsampling process considers the data from the left and right sensors individually. However, to keep

Algorithm 1 Data Downsampling

```

1: procedure SAMPLING( $\Delta_p, \Delta_R$ )
2:    $dwnData_0 = data_0, x = 0$  ▷ Save first data
3:   for  $i = 0; i < \text{DataSize}; i++$  do
4:     for  $s = 0; s < 2; s++$  do ▷ for each sensor
5:        $\delta_p = \text{getPositionDelta}(p_i, p_x)$ 
6:        $\delta_R = \text{getOrientationDelta}(R_i, R_x)$ 
7:       if  $\delta_p \geq \Delta_p$  or  $\delta_R \geq \Delta_R$  or  $\text{newExtremum}(p_i, R_i)$  then
8:          $dwnData_{x+} = \text{SaveAllSensors}(i), x++$ 
9:   return  $dwnData$ 

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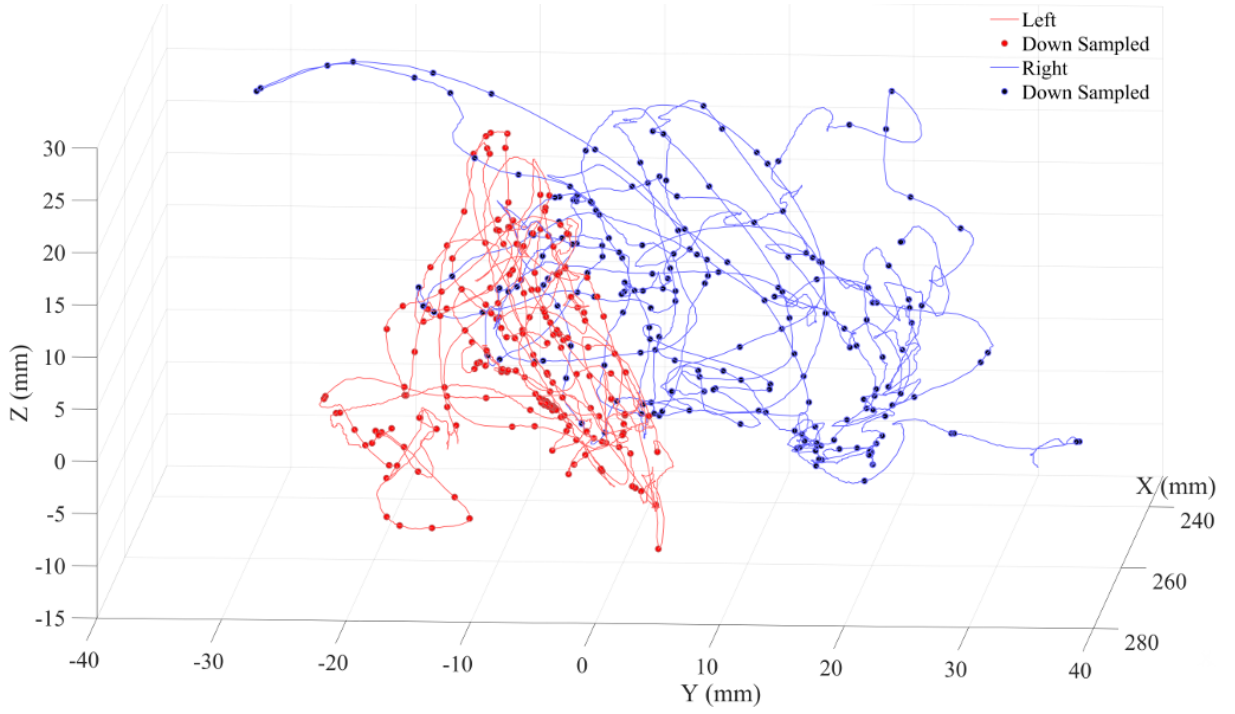


Figure 4.3: Example of EM recorded data and the resulting down-sampled data points with a $\{10\text{mm}, 10^\circ\}$ sampling resolution. The algorithm also picks the extrema regardless of the resolution. In the case shown above, the data size was reduced from 5385 to 214 points. (Source: [28]) © 2019 IEEE

the tool interaction synchronised, each time a point of either instrument is saved, the data of the opposite instrument is saved as well. This process ensures both the left and right instrument data are still synchronised and of the same length. The entire process is summarised in Algorithm 1 and an example can be found in Figure 4.3. It is important to note that the data downsampling step is done purely to save computation time during the GA search, and that it could be completely discarded as time allows. Finally, the tool performance is calculated on the entire trajectory as described in Section 4.4.2

4.1.3 Data Scaling

As the tasks were done by hand, the motion data must be scaled down to be used for endoscopic application. According to the literature, the average diameter of a human colon or duodenum is 50mm [181]. Therefore, the recorded data should be scaled so that the motion amplitude is confined in a 50mm volume. In order to keep the data aspect

ratio, the x , y , or z amplitude should be scaled with the same ratio. Therefore the data scaling process consists of finding the x , y , or z axis with the largest amplitude and calculating the ratio to reach the desired scaled volume. Then, all the trajectory points are scaled one by one with the same ratio.

Together with the data down sampling a data set was created in which all data points are within a working space of 50mm.

4.2 Robotic Instruments Kinematics

In order to find an optimal set of instruments, a given instrument must be evaluated based on its capabilities to reach the target positions. To do so, the forward kinematics (FK) and inverse kinematics (IK) need to be calculated. The FK receives the joint values, e.g., angles, and calculates the instrument's tip position and rotation. IK inverts this process and calculates the joint values out of a given tip position and rotation.

The FK and the IK solver were implemented in C++ using the multi-threaded EndoRob library for articulated endoscopic and snake-like robots [182].

4.2.1 Forward Kinematics

During the search, the GA evaluates 150,000 different instrument designs while knowing each instrument's position and orientation in 3D space. This was done using the modified Denavit-Hartenberg (DH) convention (further described in Section 4.3.5) as in typical robotics textbooks [157]. However, different instrument designs will lead to different tip orientations. This happens when the algorithm adds a new joint with a change in the joint orientation. Due to the DH-convention this leads to a 90° rotation in the tip. This is a problem when trying to follow the recorded trajectories as some points might become unreachable because of this offset. To overcome this problem, a tool matrix is automatically computed when creating a new robot object within the GA. All the recorded

trajectory points were transformed so that the orientation of the first point is moved to the origin. Therefore the robot's orientation at rest should also be identity and the tool matrix can be computed as

$$R_{tool} = R_{traj} \cdot R_{tip}^T \quad (4.3)$$

$$R_{tool} = R_{tip}^T \text{ (when } R_{traj} = I \text{)} \quad (4.4)$$

with R_{tool} being the tool rotation matrix, R_{traj} the rotation matrix of the first point of the trajectory, and R_{tip}^T is the instrument tip matrix at rest configuration, computed using forward kinematics.

4.2.2 Inverse Kinematics

Since the generated designs are unknown in advance, it is not possible to have an explicit algebraic form of the inverse kinematics. Moreover, as the instrument designs can vary from an under-actuated design with a small number of DOF to hyper-redundant architectures, the best method to perform IK is to use a Jacobian based iterative approach. In this work, the Levenberg-Marquardt, also called damped least square (DLS), method was used [158]:

$$\|J\Delta\theta - \vec{e}\|^2 + \lambda^2 \|\Delta\theta\|^2 \quad (4.5)$$

where J ($6 \times n$) is the geometric Jacobian of the instrument computed using the modified DH convention. $\Delta\theta$ is the joint angle variation, $\vec{e}$ is the error between the desired and current robot position and orientation, and λ is the damping parameter < 1 . The iterative equation can then be formulated as follows:

$$\theta_{i+1} = \theta_i + J^T(JJ^T + \lambda^2 I)^{-1} \vec{e} \quad (4.6)$$

which is solved using singular value decomposition (SVD) [158]:

$$J^T(JJ^T + \lambda^2 I)^{-1} = VEU^T \quad (4.7)$$

with U and V being the matrices from the SVD, and E a diagonal matrix as follows:

$$e_{i,i} = \frac{\sigma_i}{\sigma_i^2 + \lambda^2} \quad (4.8)$$

with $e(i, i)$ are the components of E for each index i, j , σ_i being the singular value of J at index i . Using equation 4.6 for the IK of an instrument offers a generic solver that can work for all the generated designs and is therefore well suited for the GA.

4.2.3 Joint Limit Consideration

To ensure that the generated instruments are mechanically feasible, joint limits must be carefully considered, especially with tendon-driven robots, because a large joint angle would result in a sharp bend and lead to tendon damage, due to kinking and scratching. To ensure that the solver's solutions stay bounded within joint limits, this work uses an approach similar to the one proposed in [183], which modifies the Jacobian to disable joints in limits. It monitors the joint variation and sets the corresponding column of the Jacobian to $\vec{0}$ when the joint would reach its limit; this works well during teleoperation, where the data is continuous and most of the points can be reached. However, in the case of GA, some designs will not be able to reach the first trajectory point without running into joint limits and the method proposed in [183] would then affect the convergence. So instead of applying the Jacobian based joint limit all the time, the proposed approach lets the solver converge to a solution first and then clamps the joints in limit together with the Jacobian column modification to ensure the returned joint vector is within the joint limits. However, when limiting the joint angles, it is possible that the target position cannot be reached from a specific starting position (local minima). To avoid this problem, the inverse kinematics was also run from random joint configurations and only the best result was kept.

4.3 Genetic Algorithm

The GA is used to automatically design surgical instruments that can fulfill a desired task. The goal of the GA is to find an instrument design that can follow the trajectory of the suturing and knot tying task, while keeping the amount of joints to a minimum.

4.3.1 Surgical Instruments Definition

The instruments which should be optimised with the idea presented here are two surgical instruments which are robotic arms consisting of a gripper and multiple joints, including a translation and a distal-roll at the gripper, as described in Chapter 3. Except for the translation, all joints are steered with tendons which are guided through a flexible body. All links between the joints are rigid and the lengths can vary. These instruments are deployed from a larger robot: the *i²Snake* system [34, 26], which is used as a master positioning system. Hence, they need to have a longitudinal arrangement to fit inside the channels. An arm is defined through the length of each link, the orientation of the joint, and if it uses the translation and distal roll.

4.3.2 Joint Characteristics

The GA search space must be constrained to adapt to the desired mechanical properties, the manufacturing limitations, and the various desired instrument properties. These constraints are:

- The robotic arm can consist of a number of joints, which are between 1 and 10. Ten joints were considered as sufficient.
- Three types of joints were allowed during the search: The first joint can be revolute or prismatic as the whole instrument can slide in and out of the *i²Snake*. The final joint can be revolute or of “distal-roll” type as presented in [26].

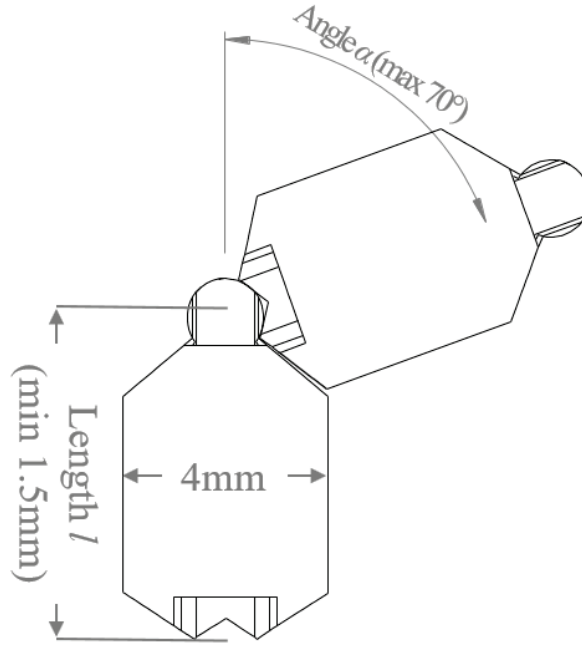


Figure 4.4: Generic link with aligned top and bottom articulation as the one used by the GA. Link parameters include width, joint range, length, and articulation placement (parallel or orthogonal). (Source: [28]) © 2019 IEEE

- All the remaining joints are revolute as shown in Figure 4.4. They have a diameter of 4mm and have a minimal length of 1.5mm, which is the manufacturing limitation for this type of joint, and a maximal length of 20mm. The diameter is not used during the optimization process, since it does not have any effect on the workspace or dexterity of the robot.
- One link can have two hinges in the same direction (parallel arrangement), and thus keep the motion direction, or it can have two hinges rotated by 90° , and thus change the motion direction (orthogonal arrangement).

The algorithm can freely choose to use any possible configuration. Different arrangement angles could also be used during the search, but this would result in more complex manufacturing as the tendon routing and tendon channels would not align. As the algorithm uses the DH convention, other joint types could also be implemented (*e.g.*, a ball joint) but are harder to manufacture and therefore are beyond the scope of this optimisation.

4.3.3 Properties of Genetic Algorithms

Genetic algorithms (GA) are a group of optimisation algorithms [184], which have the following advantages: they do not rely on a gradient and can handle non continuous cost functions. GA use multiple individuals per iteration, so they are well-suited for parallel processing and thus they can process big search spaces quicker than gradient based optimisation algorithms. They use multiple starting positions (often thousands), so they are less affected by local minima compared to gradient searches. GA are often used for multi-objective optimisation because they can keep several non-dominated optimal solutions and process the non-dominated optimal front afterwards manually. Finally, they are easy to implement because of their individual-based concept and several libraries are available. The algorithm used in this thesis is based on [185].

One disadvantage of GA is that they are normally not capable of running in real-time. Hence, GA are well suited for design optimisation problems where real-time capabilities are not required.

4.3.4 Genetic Algorithm Implementation

A GA uses individuals which form a population. An individual has genes which define it. These can be any binary representation of an object, or an array of numbers. In this case, each individual represents an instrument configuration with the genes describing that configuration in terms of the number, type and orientation of joints, the link lengths, whether translation is used, and the master position of the instrument.

A GA workflow is typically as follows:

- **Initialise population.** The first generation is randomly initialised within the defined search space.
- **Evaluating individuals.** All individuals in the current generation are evaluated using an evaluation or cost function. This is called the "fitness" of the individual.

- **Sorting individuals.** The individuals are sorted by their fitness value.
- **Optimisation Stalled.** If the fitness value has not improved for a predefined number of generations (here 10) the optimisation has stalled and the algorithm stops.
- **Crossover.** A fraction of the population (here 0.7) will be created by performing a crossover operation on two parents. These two parents are selected randomly with a likelihood distribution given as

$$likelihood(i \in P) = \frac{\frac{1}{\sqrt{k_i+1}}}{\sum_{j \in P} \frac{1}{\sqrt{k_j+1}}} \quad (4.9)$$

for an individual i in the population P with the ranking k_x in the sorted population starting from 0 for the best solution, where k_x is the individual in the population P at position x . For this learning purpose, two crossover operations were defined, see Section 4.3.6.

- **Mutation.** After a new individual is created it has a likelihood (here 0.4) to mutate. The different mutation operators are further described in Section 4.3.7.
- **Selection.** The newly created individuals and the previous generation are sorted together. The first best elite (here 10%) is transferred to the new generation. The rest is filled by randomly selecting individuals with a likelihood of $likelihood(i)$ of equation 4.9 for an individual i .

Algorithm 2 Genetic Algorithm

```

1: procedure GA
2:   Initialize(Population)
3:   Evaluate(Population)
4:   Rank(Population)
5:   while Best not stalled do
6:     Crossover(Population)
7:     Mutation(Population)
8:     Evaluate(Population)
9:     Rank(Population)
10:    Select(Population)

```

Algorithm 2 shows how these operations are used to evolve the population over each iteration, by using the crossover and mutation operators and then selecting the fittest individuals. The algorithm continues until the results do not improve when compared to the previous generations.

4.3.5 Gene Definition

To save on computation time and reduce the search space, the instruments were optimised individually. The genes for an instrument consist of the following members:

- **Number of joints.** The algorithm can adjust the amount of joints in one arm. This value is randomly initialised within a range of 1 to 10.
- **Uses Translation.** The algorithm can decide to use the translation as the first joint.
- **Uses distal-roll.** The last joint can be the distal-roll.
- **Joints.** Each joint consists of the following parameters:
 - **Orientation.** A binary value specifies if the joint is parallel or orthogonal. This is done by setting $\alpha = 0$ or $\alpha = \frac{\pi}{2}$ in the DH table.
 - **Length.** The length of the link is changed by setting the value of a in the Denavit–Hartenberg (DH) table. This value is randomly initialised within a range between 1.5mm and 20mm.
- **i^2 Snake position (x,y,z).** The snake-like master positioning system is brought into position at the beginning of a suturing task, and it is not possible for the user to change this while doing the suturing. Thus, this position should hold for the whole procedure. Because the head position enables different instrument designs, e.g., long or short instruments, it is important for the algorithm to be able to change this position.

4.3.6 Crossover Operators

To create new individuals, two parents were selected using the likelihood distribution given in equation 4.9. These two individuals were then used to create a new individual. Two crossover operators were implemented:

- **Averaging operator.** The averaging operator took two parents and created a new individual by choosing the joint count between the limits of both parents. The length of a joint was chosen between the limits of the lengths of that joint of both parents. Precisely, given two parents p_1 and p_2 , a random value $r \in [0, 1]$, and the number of joints c^i for the individual i , the number of joints for the new individual n is determined as:

$$c^n = r \cdot c^{p_1} + (1 - r) \cdot c^{p_2} \quad (4.10)$$

Given the length l_j^i for joint j of an individual i , the operator then defines the lengths of the joints for the new individual n with:

$$\forall l_j^n : l_j^n = r_j \cdot l_j^{p_1} + (1 - r) \cdot l_j^{p_2}, r_j \in [0, 1] \quad (4.11)$$

for all the joints that exist in both parents. The orientation of each joint is chosen randomly from the orientation of that joint of both parents. The length of joints only existing for one of the parents are set to the length of that parent, and the same applies to the orientation.

- **Cross-point operator.** The cross-point operator chooses a random joint number within maximal joints and splits the two parents into halves. Then, it switches the parts and chooses one of them as the resulting new individual, as shown in Figure 4.5. For two parent individuals p_1 and p_2 and their number of joints c^{p_1} and c^{p_2} , the minimal number of joints of both individuals is $c_m = \min(c^{p_1}, c^{p_2})$ and the cross-point is chosen

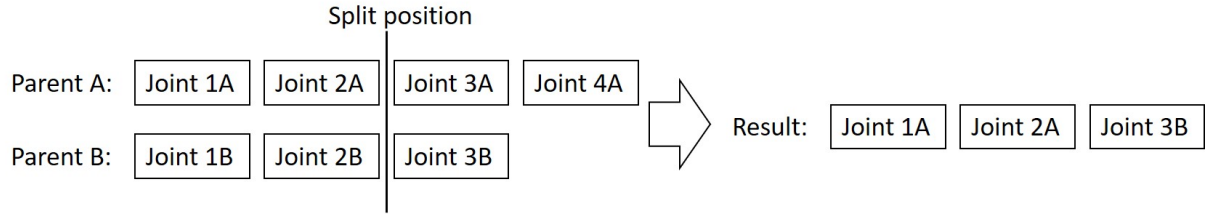


Figure 4.5: The cross-point operator splits the two parents, swaps the second half and selects one of the results.

randomly as $x \in [0, c_m]$. Given the length l_j^i for joint j of an individual i and a random value $b \in \{0, 1\}$ (either 0 or 1) the resulting individual is defined as follows:

$$c^n = b \cdot c^{p1} + (1 - b) \cdot c^{p2} \quad (4.12)$$

$$\forall j \in [0..c^n] \in \mathbb{N} : l_j^i = \begin{cases} l_j^{p1}, & \text{if } i < x, b = 0. \\ l_j^{p2}, & \text{if } i > x, b = 0. \\ l_j^{p2}, & \text{if } i < x, b = 1. \\ l_j^{p1}, & \text{if } i > x, b = 1. \end{cases} \quad (4.13)$$

4.3.7 Mutation Operators

The mutation operators are used to alter a new individual after crossover. It introduces randomness into the search. This ensures that the search can always continue and is able to find the best solution even when it starts with poor estimates in the beginning. There are generally two tasks the mutation operators need to fulfill: do a nearby search and extend the search. In the first case, the near neighborhood of an individual is searched and in the second, larger changes are made to the individual to allow the search to be extended.

- **New individuals.** This operator introduces an entirely new individual which replaces the crossover individual. This was used to introduce fresh new search points.

- **Length mutation.** This mutation changes the length of all joints by relatively small values. This enables the algorithm to search in the neighborhood of the current position. For an individual i , the length l_j^i of all joints j is changed as follows:

$$l_j'^i = l_j^i + r_j, r_j \in [-0.5, 0.5] \quad (4.14)$$

- **Joint split.** When adding an entirely new joint with a new length, the problem appears that the new instrument is in most cases too long for the tasks. Thus, it was recognisable that the GA reduced the number of joints more often than it increased the number of joints, which only happened rarely. This led to small numbers of joints and high errors in distances even when the number of joints was not penalised. To reduce this effect, the joint split operator was added which splits an existing link into two links with a new joint in the middle. The total length of the instrument stays unchanged which is important to solve the problem.

The split point is chosen randomly in between the chosen link. The choice of which links are split is determined randomly as well. This process is summarised in Algorithm 3.

Each time a new operator was introduced during the development process, it was verified that the GA used it to create at least one new best individual over its iterations and ensured that the operator helped to find a good solution.

Algorithm 3 Split Joints

```

1: procedure SPLIT JOINTS ▷ R()=Random  $r \in [0, 1]$ 
2:   for  $R() \cdot (MaxSplits - 1) + 1$  do ▷  $l$ =Length
3:     repeat ▷ Select a joint
4:       select  $j \in Joints$ 
5:     until  $l_j > 2 \cdot l_{min}$ 
6:      $l_{new} = R() \cdot (l_j - 2 \cdot l_{min}) + l_{min}$  ▷ Split joint
7:      $l_j = l_j - l_{new}$ 
8:      $Orientation_{new} = R() > \frac{1}{2}$ 
9:     InsertNewJoint( $Orientation_{new}, l_{new}$ )

```

4.3.8 Evaluation Function

To evaluate each individual, the genes of that individual are translated into a DH table. The IK solver presented in Section 4.2 was used to evaluate the reachability of the individuals. To avoid local minima and sub-optimal IK solutions, the IK solver was executed 20 times with random joint values used as initialisation for each task point.

Since the evaluation depends on the three criteria position error, orientation error, and number of joints, an evaluation function weighting the different parameters and hence allowing to alter the outcome of the search was implemented. With the set of all target points N with $|N|$ number of points, the error in position $e_{pos}(j)$ for target point $j \in N$, the error in orientation $e_{ori}(j)$, and balance factors for orientation f_{ori} and for the number of joints f_{count} , the total cost $c_{total}(i)$ is defined as follows:

$$c_{total}(i) = \sum_{j \in N} (e_{pos}(j) + e_{ori}(j) \cdot f_{ori})^2 + |N| \cdot f_{count} \quad (4.15)$$

If not specified differently, the two parameters are chosen as $f_{ori} = 5.0$ and $f_{count} = 1.0$. These values roughly equalise the importance of the rotational and positional error.

4.3.9 Parallel Implementation

To use the full computational power of the CPU, the GA was implemented using parallelization. The main loop of the GA runs in the main thread. A collection is created with a pre-defined number of threads. During evaluation, each individual is assigned to a thread as long as there are free threads available. If there is no free thread available, no new individuals start their evaluation until a thread finishes. Thus, the size of the thread collection defines the number of parallel running evaluations. The number of used threads varied depending on the used computer.

4.4 Search for Optimal Instruments

Four searches have been performed, an overall optimal instrument, an instrument without distal roll, a simple instrument, and an instrument without a prismatic joint. The simple instrument is further investigated in Section 4.5.

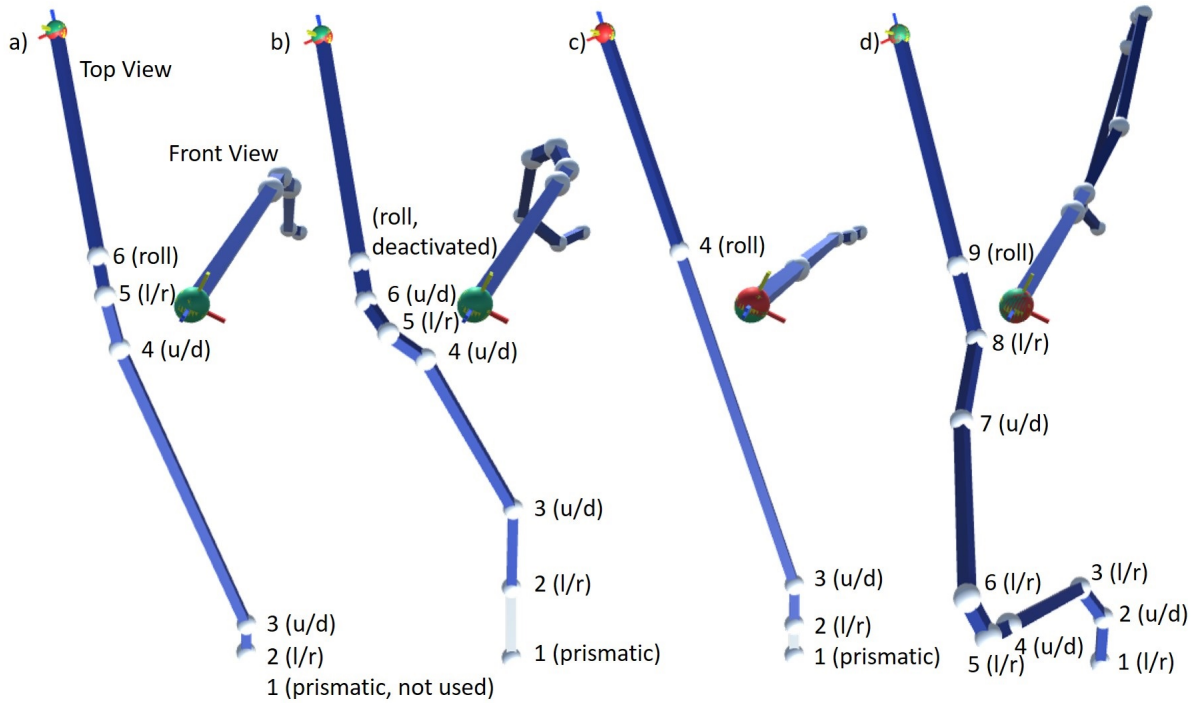


Figure 4.6: Right arm results for the proposed GA search strategies: a) Best instrument, b) No distal roll, c) Simplest instrument, d) No prismatic joint. The resulting instruments can all follow the trajectory and their used number of joints ranged from 4 to 9 DOF. The joints are annotated. “u/d” means up/down hinge joint. “l/r” means left/right hinge joint. (Source: [28]) © 2019 IEEE

4.4.1 Kinematic Solver Performance

To allow efficient design and computation of multiple instruments in parallel, a multi-threaded solver was implemented in C++. The implemented solver was characterised in terms of running frequency. For 100,000 randomly generated target points, it took an average of 1.8ms to converge to a solution for two 8 DOF robotic instruments (50,000 targets each). This represents a running frequency of 555Hz, which is quick enough for the GA or even for real-time teleoperation of the instrument arms.

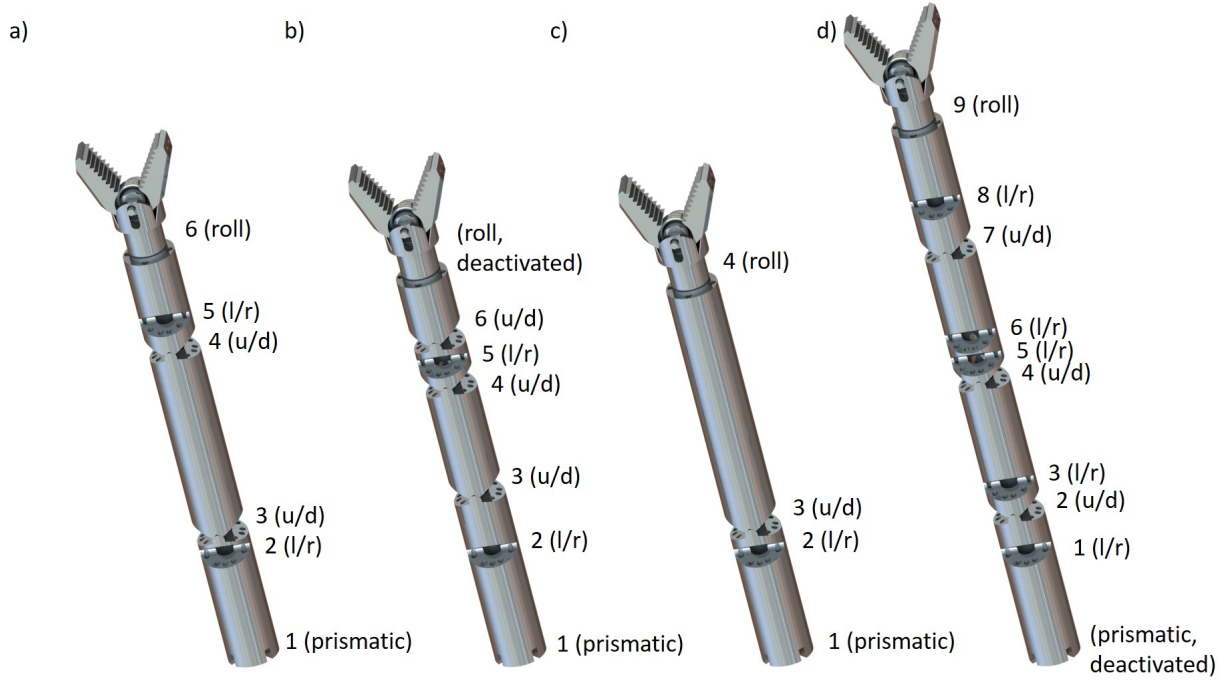


Figure 4.7: A rendering of the resulting instruments, (a) best instrument, b) No distal roll, c) Simplest instrument, d) No prismatic joint. The joints are annotated in the same way as in Figure 4.6.

4.4.2 Genetic Algorithm Search Parameters

Several GA search strategies were performed on the suturing data. The data was down-sampled with the following parameters $\{\Delta_p=40\text{mm}, \Delta_r=40^\circ\}$ resulting in 40 points (20 per instrument). On average, it took 3 hours and 46 minutes on a high-performance laptop with an i7-8750H CPU to generate 150,000 designs varying from 2 DOF to 10 DOF. The evaluation of the individuals was running on 12 threads plus one main thread.

The GA parameters (e.g., crossover ratio = 0.7 or mutation ratio = 0.4) were experimentally set to improve the computation time. Changing these values had little effect on the outcome of the search and mainly affected the time to find the optimal design as long as they are . The cost function parameters (i.e., the joint cost factor and the orientation cost factor) define the outcome of a search and can be manually tuned. The simplest tool shows an interesting configuration of these factors and was further investigated in Section 4.5. The following types of searches were performed:

- **Free search with focus on orientation.** Any joint configuration (following the constraints) is allowed.
- **No distal roll.** The GA was not allowed to use the distal roll tip.
- **Simplest instrument.** A higher weight was given to the number of joints.
- **No prismatic.** The GA was not allowed to use a prismatic joint.

It is important to note that although the dataset was significantly reduced for the GA search, the evaluation of each generated tool shown in Figures 4.6 and 4.7 and Table 4.2 was performed on the entire suturing dataset. The results show that extracting key feature points and using them for the GA is beneficial to reduce the computation time while it does not reduce the validity of the results compared to using the entire trajectory.

4.4.3 Free Search

The result of the free search is shown in Figure 4.6 a) and is summarised in Table 4.2. The resulting instrument uses a prismatic joint and a distal roll. The instrument performed well on the entire trajectory with an average position error of 0.0058mm and an average orientation error of 1.59°. It is notable that the algorithm created a distal wrist with roll, pitch, and yaw motion with nearly minimal joint lengths in between. On the proximal end it found a positioning system with translation, up/down, and left/right motion.

	DOF	Position Error [mm]	Orientation Error [°]
Best instrument	6	0.0058	1.59
No distal roll	7	0.0094	5.84
Simplest instrument	4	0.0097	15.49
No prismatic	9	0.1746	0.60
Left tool	8	0.0171	0.36

Table 4.2: GA Search Results

4.4.4 No Distal Roll

The results without the distal roll are shown in Figure 4.6 b) and in Table 4.2. To compensate for the lack of roll motion, the GA had to increase the instrument complexity to 7 DOF. The resulting instrument performed well in positioning with an average error of 0.0094mm, but the orientation error is larger with an average of 5.84°. The resulting instrument could probably be used by a surgeon, but the manufacturing complexity makes it less interesting to use. This instrument is moving all its joints to reach the desired orientation.

4.4.5 Simplest Instrument

This search focused on the joint count. In this special case the two optimization factors differ from the default ones. They were $f_{count} = 1.0$ and $f_{ori} = 1.0$. This way, the algorithm does not focus so much on the orientation error. The resulting instrument reaches an acceptable error and is shown in Figure 4.6 c) and in Table 4.2. This tool design with 4 DOF is capable of accomplishing the recorded task with an average error of 0.0097mm and 15.49°. Although the orientation error is important, an experienced surgeon teleoperating the instruments might still be able to complete the suturing and knot tying task (laparoscopic surgeons can perform suturing with rigid and non-wristed instruments) and will be investigated further.

4.4.6 No Prismatic Joint

This search was performed to evaluate the necessity to have a prismatic joint as it can be difficult to control when the *i²Snake* is in complex tortuous shapes. As an example, the human arm does not have a prismatic joint, but it is still able to perform complex tasks. According to the result, not having a prismatic joint will automatically result in higher DOF to get an acceptable position and orientation error. As shown in Figure 4.6 d) and Table 4.2, the best instrument without a prismatic joint resulted in an average positioning

error of 0.17mm and an average orientation error of 0.6° using 9 DOF. Instruments with such a high number of joints are complex to manufacture.

4.4.7 Left Tool

The left instrument of the pair was also generated using the same parameters used for the best instrument from the free search (see Section 4.4.3). A rendering of the overall result for the 4mm instrument is shown in Figure 4.1. The results are shown in Table 4.2. The left instrument has 8 DOF, including translation and distal-roll. The instrument reached an average position error of 0.0171mm and an average error in orientation of 0.36° . The left and right arms got different designs because they need to match different trajectories for the left and right hand.

4.5 Search for Simple Instruments

To build an instrument with a diameter of 3mm, a simple instrument design is required. In the section above, complex to simple instruments were discussed. In this section, the simple instruments are investigated further.

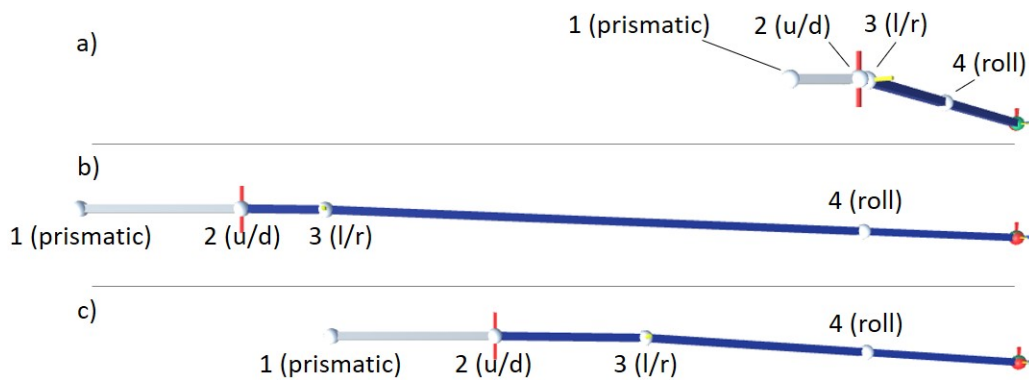


Figure 4.8: Different optimisation results of the simple left instrument: (a) pre-defined starting position, (b) one instrument with optimised position, (c) dual instruments optimisation. “u/d” means up/down hinge joint. “l/r” means left/right hinge joint. (Source: [29])

The objective was to optimise for simple and robust instruments, so that they can be built rapidly and efficiently. The maximal number of hinges was limited to 2, which results in

	Position Error [mm]	Orientation Error [°]	Length [mm]
Default position	0.971	45.8	10.22
Optimised position	0.005	13.8	46.23
Both instruments together	0.013	19.5	24.85

Table 4.3: Result of the optimisation of the 3mm instrument for the whole dataset: error in position, error in orientation, and the total length.

4 DOF, two hinges, one proximal prismatic joint, and a distal roll. The total length of the instruments was not limited. Multiple different optimisations were calculated using various parameters which are discussed here. The resulting error values in orientation and position can be seen in Table 4.3.

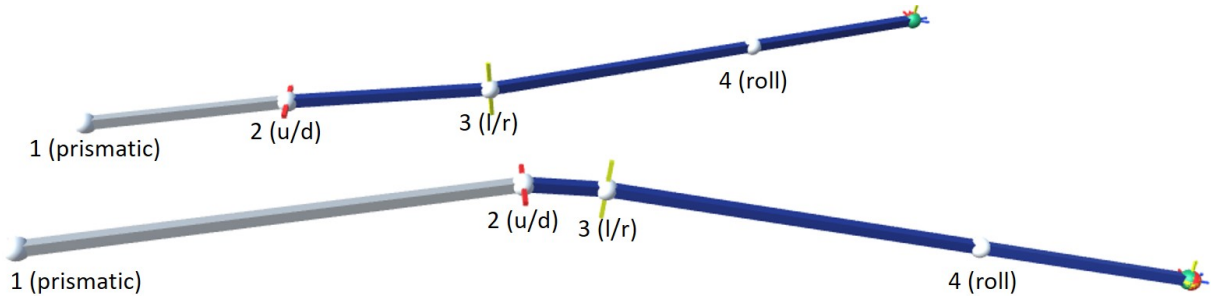


Figure 4.9: Final result: Both left (upper) and right (lower) instruments optimised together, which is the result (c) in Figure 4.8. The starting position was chosen by the GA. The white part is the prismatic joint and the axes in the hinges show the bending axes. The red joints are moving up/down and the yellow joints are moving left/right. (Source: [29])

- (a) First the *i²Snake* position was pre-defined, and the left instrument was optimised. Since the instruments are independent from each other, the optimisation can be done separately. The result is shown in Figure 4.8 (a). The error values especially in orientation are too large to be usable.
- (b) The GA was enabled to choose the tip position of the *i²Snake* system itself. In practice, the *i²Snake* is first positioned, and then only the instruments are deployed to do the surgery. Thus, it is reasonable to let the GA define the position and use this position for all data points. This means that the system does not change position during the operation. It can be seen in Figure 4.8 (b) that the total length was increased significantly by the GA. This design achieved the best results in position

and orientation error. The reason is that the workspace is significantly increased by increasing the length and keeping the number of joints and maximal joint bending angles constant.

- (c) Since the design of the instrument depends on the tip position of the i^2Snake as a starting position, the optimisation of each instrument is not independent anymore. As a result, both arms were optimised together using one starting position but independent arm designs. The final result can be seen in Figure 4.9. It is recognisable that the total length of the instruments are reduced, but the error in orientation increased slightly. Because the GA now needs to balance for both tasks, this outcome was expected.

The final result shown in Figure 4.9 was used to build the 3mm instrument discussed in Section 3.4.2.

4.6 Conclusion

This chapter investigated the automated design of a pair of robotic endoscopic instruments and studied the impact of the kinematics on the tool capabilities. The workflow consisted of using a GA to perform a task based design under constraints. The novelties of the proposed framework include large-scale data collection together with a data processing algorithm for downsampling and downscaling, the automated design generation of bi-manual endoscopic robotic tools using a GA and finally the study of the impact of kinematics on tool performance. Because it uses the DH convention, the presented method can be adapted to most articulated robots.

First, four different instrument architectures were discussed based on the GA output for the search of an optimal instrument. The four architectures were: free search, no prismatic joint, no distal roll and simplest instrument. The free search and the simplest instrument results are both capable of following the trajectory. The results also show the importance

of having a prismatic joint to reduce the errors with a small number of DOF. Having a distal roll further reduces the orientation errors.

After that, the search for a specific simple instrument that could be manufactured with a 3mm diameter, was performed and discussed. To find such a simple instrument, multiple searches have been performed. First, the starting position was pre-defined, but letting the GA find the optimal starting position resulted in better instrument design. The total length of the instruments has a significant influence on the result. Longer instruments seem to perform better for the desired task. In a real environment, the length of the instruments is limited by the available space within the *i²Snake*. This needs to be considered in future GA implementations, as well as using different types of joints such as flexible or continuum.

For this optimisation a suturing task done by one person was recorded. The future work will aim to further optimise the design by using larger datasets with different sizes and shapes of wounds, more different tasks, multiple different users, and by considering obstacles.

This method aims at optimising the instrument joint arrangement for a predefined task. It uses given joint limits, such as minimal size, maximal size and maximal bending angle but cannot change the joint design itself. Further, instrument collision could occur but is currently not considered, though it could be added in future versions. Since force considerations are not part of the optimisation, some resulting instruments have a long instrument design. It needs to be tested if enough force can be exerted through the instrument to perform the required tasks.

Chapter 5

Shape Sensing Using Optical Fibers

The instruments of the snake-like robot are controlled by changing the tension in the tendons to match the desired position of the master interface being used by the practitioner. This is achieved by calculating the motor values with inverse kinematics (IK). The resulting position is only well defined within a certain range, due to tendon stretching, backlash and other inaccuracies. Further, external forces like boundaries can influence the actuated instruments. Many systems currently being used in research are not capable of recognising that the instrument is not doing what the control system is expecting the instrument to do, so it is up to the user to close the loop. To provide a data-based and objective method of closing the control system loop, shape sensing is needed to precisely know the position and orientation of the instruments and their end-effectors. Ideally, shape sensors used for robotic MIS need to be small enough to be integrated into the tools of a snake-like robot without increasing the tool size or reducing the flexibility.

Shape sensing has to be decoupled from the actuation and the system as far as possible. For example, if the shape is sensed by measuring the motion of the tendons, the values are correlated to the movement of the motors. These values do not provide any information about errors in the tendons. If the tendons elongate, for instance, the system will still measure that the robot is doing what it is expected to do, even if this is not the case.

There are multiple methods to achieve accurate shape sensing, which is discussed in detail in Section 2.3. There are Flex Sensors, Electromagnetic (EM) Tracking, Fiber Optical Sensing (FOS), Fiber Bragg Grating (FBG), Imaging, and some more.

In this chapter, a fiber optic shape sensing approach is presented. This method was developed in the scope of this thesis and was published in [30] and [31].

5.1 Shape Sensing System

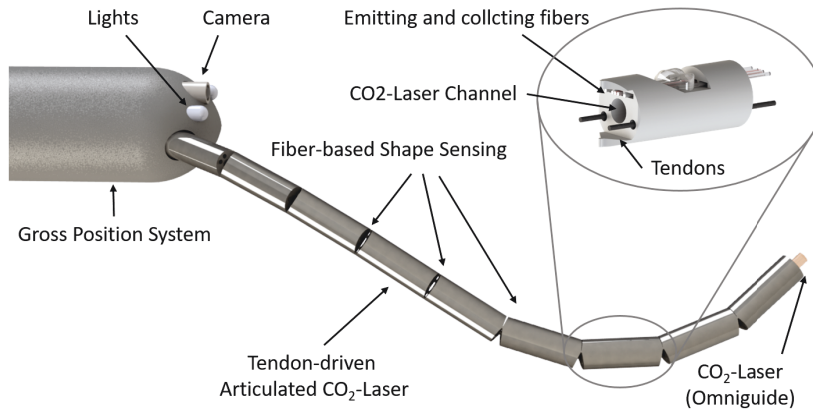


Figure 5.1: A positioning system equipped with a shape sensing, tendon driven robot. The idea is that the robot uses optical fibers to measure the angle of each joint and a CO₂-laser fiber is delivered through the central working channel. (Source: [30]) © 2017 IEEE

A prototype of a two-link robot with a built-in fiber-optic shape sensor was developed and manufactured that can deliver and control the position of a CO₂-laser fiber for soft tissue ablation. In this approach, the shape sensing is based on optical reflectance and Light Intensity Modulation. In this chapter proof-of-concept results are presented demonstrating successful shape sensing (i.e., measurement of the angular displacement of the upper link of the robot relative to the lower link) in real time with a mean measurement error of only 0.7°. The prototype, two-link robot has an outer diameter of 4mm and a 1.5mm central working channel for the delivery of a CO₂-laser fiber or transport of further tendons to control a gripper. The robot also contains 0.6mm channels for tendon actuation of the individual links. A conceptual image of a robot using this shape sensing system can be seen in Figure 5.1.

5.1.1 Optical Setup

In order to provide shape sensing, i.e., measurement of the bend angle of a robot joint, five optical fibers are incorporated into the lower link of the joint. These fibers are positioned at the end of the lower link pointing towards the base of the upper link (see Figure 5.2). The base of the upper, metallic link of the joint is highly reflective at visible wavelengths. The fibers are aligned in a horizontal plane perpendicular to the joint's rotation axis. The central fiber is used to deliver light from a super-continuum laser (Fianium WL-SC-400-4, NKT Photonics A/S, Birkerød, Denmark) while the outer fibers collect the light reflected back from the upper link of the robot joint. As the bend angle is adjusted, the amount of light coupled into each of the four collecting fibers changes, and this effect provides the underlying basis for the shape sensing.

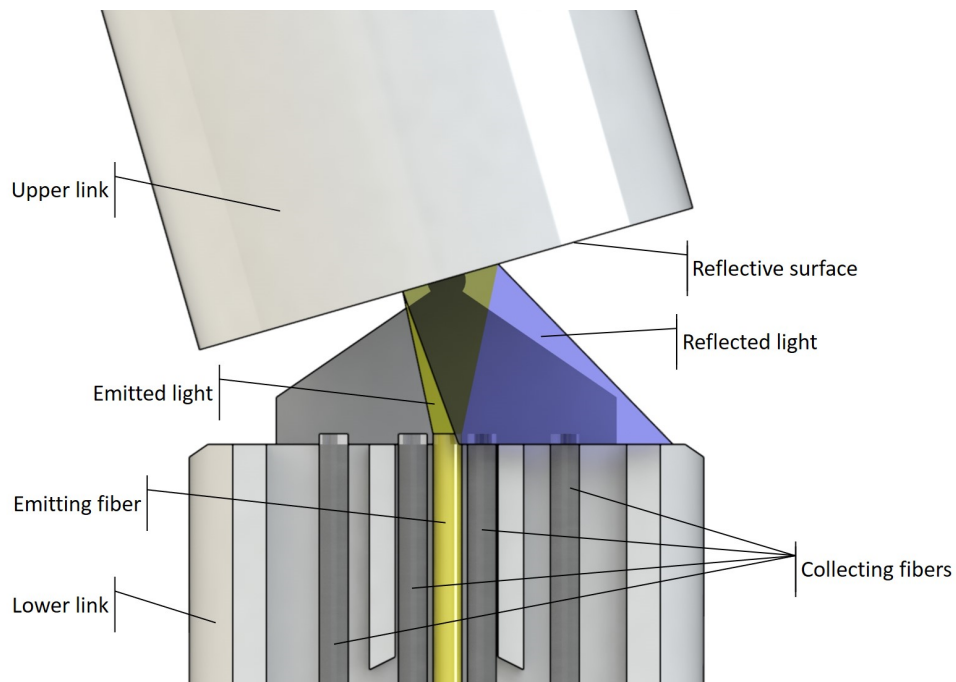


Figure 5.2: Optical sensing concept. The light is emitted out of the emitting fiber (yellow) and reflected back by the surface of the upper link. The reflected light (blue) is then collected by the four other fibers depending on the angle of the joint.

To extract the shape sensing signal from the optical fibers, a compact optical system was developed that couples light into the delivery fiber and directs the collected light onto photo-transistors for detection. The layout of this system is shown in Figure 5.3. The output from the super-continuum laser is collimated and focused into the delivery multi

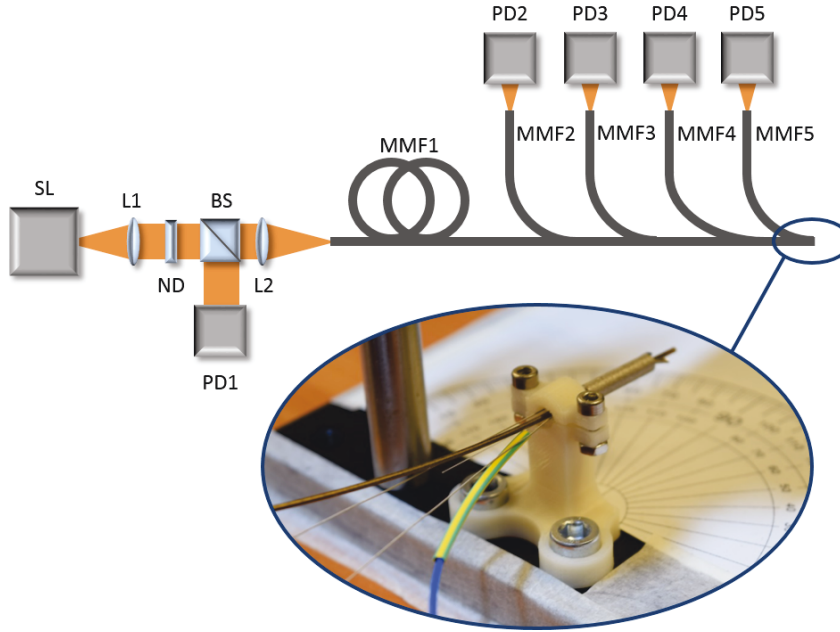


Figure 5.3: Optical setup used for the shape sensor in the base of the single-joint robot. Inset is a photograph of the robot showing the sensing optical fibers, tendons and CO₂-laser fiber entering at the base of the device. Abbreviations: SL — super-continuum laser; L — lens; ND — neutral density filter; BS — 50/50 beam splitter; PD — photo-transistor; MMF — Multi mode optical fiber. (Source: [30]) © 2017 IEEE

mode optical fiber (MMF1) using a pair of lenses. A variable neutral density (ND) filter is placed in the beam path in order to permit control of the optical power without affecting the spectral features of the beam, and a 50/50 beam splitter directs half of the input light onto a photo-transistor to allow measurement of the laser power. This input measurement is included to allow a correction of the variations in the laser power. The proximal end of the delivery fiber is mounted in a 3-axis alignment stage, such that the coupling into the fiber can be optimised. The proximal ends of the four collection fibers (MMF2-5) are mounted in front of photo-transistors for detection.

Multi mode optical fibers with core diameters of 200 μm and total diameters (core + cladding) of 225 μm (FP200URT, Thorlabs, Inc.) are used in the robot joint. These fibers have a high numerical aperture (NA) of 0.5. The NA defines the divergence (and collection) angle θ of the light emitted from (and collected by) the fibers as:

$$\theta = \arcsin(\text{NA}/n) \quad (5.1)$$

where n is the refractive index of the surrounding medium ($n \approx 1$ in this case, as the surrounding medium was air). Thus, for the fibers used in these experiments, $\theta \approx 30^\circ$.

Considering this divergence/collection angle, the lower link of the robot joint is designed with a cutaway at which the fibers are fixed, such that they have a distance of approximately 1.42mm to the reflective surface of the upper link. The three central fibers are positioned directly adjacent to one another (i.e., with the cores separated only by the fiber claddings) in a single rectangular hole in the center of the base link in the final design, seen in Figure 5.4 (h). The outer two fibers are placed 1mm further away from the central fiber in two additional rectangular holes. This configuration ensures that sufficient light is collected by the optical fibers to provide shape sensing over a 35° range of bend angles. Importantly, this range is larger than the maximum bend angle of the CO₂-laser fiber, meaning that shape sensing is achieved over the complete extent of the robot's motion.

5.1.2 Sensors

Two different sensors (photo-transistors) are used for light detection: two Everlight Side-looker Phototransistors (PT928-6B-F) and two Kingbright Ambient Light Photo Sensors (KPS-3227SP1C). These sensors react to light by opening and allowing a current to flow. The analog-to-digital converter (ADC) of a PSOC micro-controller measures the output voltage for each photo-transistor on the pins between V_{ssa} ($= 0V$) and V_{dda} ($= 5V$). The photo-transistor current is transformed into voltage using a resistor, which specifies the dynamic range of the sensor. Since the light intensity at the photo-transistors is relatively low, 33 k Ω resistors, particularly for the two outer collection fibers, are used. This resistance was adjusted and optimised in order to obtain the highest possible signal while maintaining safe photo-transistor current values.

The PSOC micro-controller reads the sensors data due to its range of embedded components, such as the ADC_SAR, multiplexer and RS485. The ADC is used to convert the analog signal into a 12 bit digital signal. After analog-to-digital conversion the RS485 sends the measured data to a PC, where it is processed and recorded.

5.1.3 Evolved Link Designs

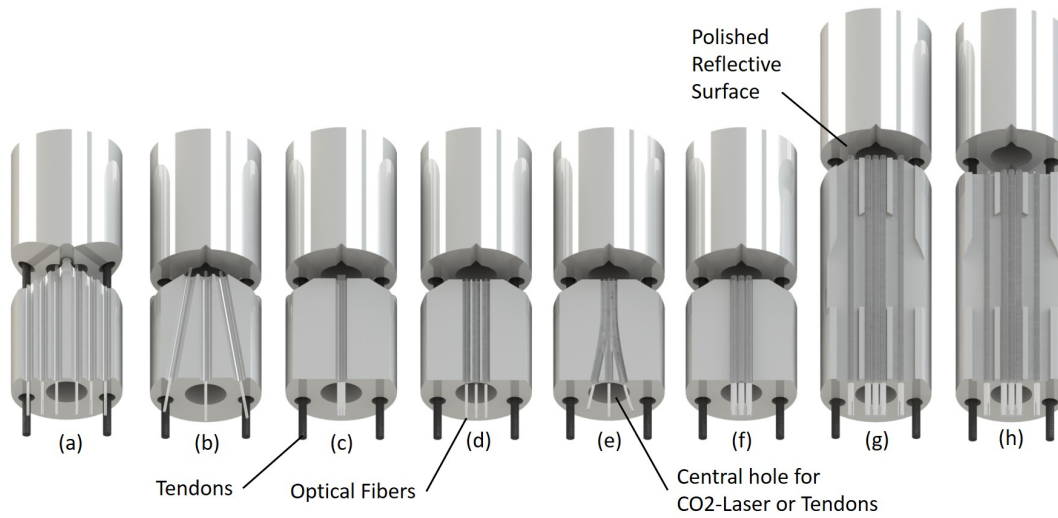


Figure 5.4: The evolution of link designs. Images illustrating the evolution of the design of the first link of the robot. All fibers are aligned in channels next to the central hole. (a) shows the earliest prototype, (h) shows the final version, and (b-g) represent intermediate designs. (Source: [31])

Several joint designs were considered and analysed to find the best trade-off between accuracy, joint range and amount of required fibers. In this section the evolution of these designs is presented and the relative merits of each are discussed. Figure 5.4 shows the different design steps. All the proposed designs share some required key features. In the center of the link there is a core channel through the full length of the instrument that is used to deliver a CO₂-laser fiber for soft tissue ablation or to contain tendons to control further joints or a gripper. On the sides of the core are two channels for tendons to actuate the joint. The design phase presented in Figure 5.4 showing a section view is described below:

- a) The first design was using a link with an angled surface as it had worked well in preliminary experiments in a larger scale (1 cm diameter) robot. However, in the 4mm diameter robot the reflected light was not efficiently collected by the detection fibers. Three optical fibers were positioned on either side with each fiber placed in a separate hole. The middle fiber on each side acted as the light source. The opposite

link of the joint had the same V-shape as shown in the figure. This design was able to detect light for a small range of angles but it had the following flaws: Due to the angle of the opposite side the light was reflected away from the joint at quite sharp angles and was not efficiently collected by the fibers. Further, the heights of the fibers were different in this design, which also acted to limit the range of angles over which light was collected. Therefore, only a very small joint angle range was measurable.

- b) The second design had a flat surface on the upper link of the joint and a flat cutout on the lower link. The flat surface on the opposite link improved the range of detection of the reflected light. The design had three fiber channels which were located on the flat part. Because the fibers had a specific angle range in which they were able to collect light, the collecting fiber channels were angled to enhance the level of the received light signal, using light pathway simulation using ray tracing in SolidWorks (Dassault Systèmes, France). However, experimentally this design did not improve the collection efficiency due to manufacturing limitations. When placing all three fibers in the central channel an improvement in the light collection was observed. The biggest improvement was gained by having a flat surface on both sides and by all fibers being at the same height.
- c) In this design a single hole was used for all three fibers. This led to further assembling difficulties such as fiber alignment and twisting fibers. If the fibers cross, they come out with an undefined angle. It was required that all fibers were parallel and that the emitting fiber was positioned in the center.
- d) In this design three smaller holes were used to better align the fibers. This resulted in the need to change the manufacturing process to obtain smaller tolerances. The printing process was switched from a metal selective laser melting technology printer (Mlab cusing, ConceptLaser, Germany) to a scan spin and selectively photocure technology printer (Ultra HD, EnvisionTEC, Germany). However, the resulting smallest feasible holes were still too large to ensure a tight fit and a good alignment of the fibers.

- e)* Design *e)* aimed to tackle the same problem as *d)*. One large hole was divided into three smaller holes. The idea was to insert the central fiber first and then insert the left and right fibers using the additional outer channels. These were guided along the central fiber. Unfortunately, the minimum achievable channel size was too large and led to fiber overlapping in the channel. It was not possible to fix them properly in place.
- f)* In design *f)* the fiber was changed from a multi mode fiber with 50 μ m core diameter (Thorlabs Inc, USA) to a multi mode fiber with 200 μ m core diameter (Thorlabs Inc, USA), which provided considerable advantages. It has a stronger jacket and thus is more robust while bending. The hole size had to be increased to fit the new fiber. These fibers had no overlap problems and perfectly fit into the minimum sized holes. This simplified the assembly. The fibers were aligned at the same height, protruding from the surface slightly. With this design a good distinctive coverage of a small angular range was achieved.
- g)* To improve the angular range one fiber at each side (two fibers in total) was added. This increased the measurable range by providing light collection (via the two additional fibers) at higher joint bending angles than in the previous design. An opening to the side of the joint was also added, which provided access to the fibers and made it possible to align the fibers more accurately and fix them in position.
- h)* It was discovered that positioning the upper part of the robot joint slightly further away from the optical fibers increased the range of measurable angles. Thus, in the final design the distance between the optical fibers and the upper reflective surface is increased.

Using the final design *h)* it is possible to measure angles accurately. The design of the final link that is used for shape sensing is shown in detail in Figure 5.5. This figure shows the important features of the design including the optical fibers used for shape sensing, the tendons used for angle control, the central hole for delivery of the CO₂-laser fiber, the joint hinge, and the window used to secure the sensing fibers. This optimised

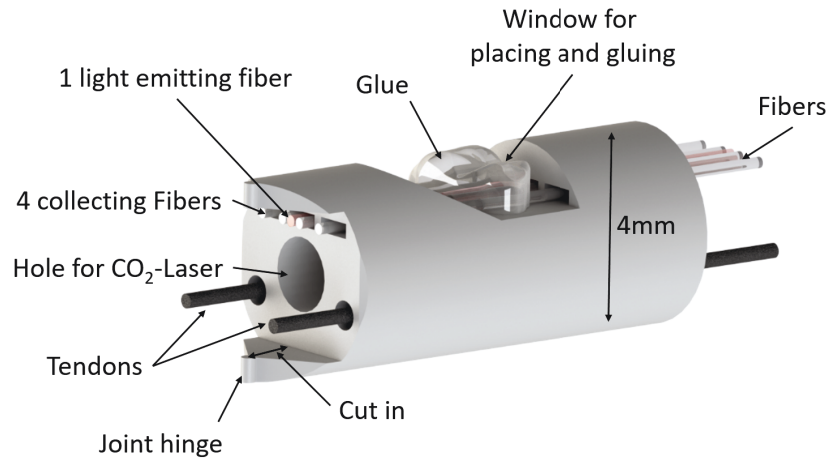


Figure 5.5: The final design of the lower link of the robot, in which the shape sensing optical fibers are fixed. The other important features of the link are also indicated. (Source: [30]) © 2017 IEEE

setup contains five optical fibers: one emitting fiber and four receiving fibers. A multi mode fiber with 200 μ m core diameter (Thorlabs Inc, USA) is used because of its wide emission/collection angle as well as its robustness. The emitting fiber together with two receiving fibers are located in the middle hole. These three fibers fit tightly into this hole with no overlap. Two further fibers (one on each side) are placed in the outer channels. These extend the range of the angle measurement significantly. All fibers are at the same height, protruding slightly from a flat surface. This alignment of the fibers is crucial, since it was found that if they were positioned within the joint, their range of collection angles was severely limited. The joint containing the fibers has a flat surface for the fibers as well as a flat opposite reflecting surface. The distance from the fibers to the reflective surface has a strong effect on the collection efficiency and was optimised to allow effective angle measurements. Several different cutaways had been tested to reach the optimal distance with the final cutaway, shown in Figure 5.5, being 1.42mm. In this arrangement, good signals could be observed on all four photo-transistors, indicating that the light collection efficiency is sufficient to allow for optical shape sensing. Using the final design *h*) allows collection of specific light distributions through the fibers across the whole angular range of -20 to $+20$ degree and shows promising results for joint angle measurement.

5.1.4 Multi-Layered Perceptron Based Angle Prediction

To calculate the angle using the values from the photo-transistor sensors a function $f(S_t) = a_t$ is needed, where S_t is the set of intensity values from the four photo-transistors at time t and a_t is the corresponding angle. In the current setup this function is five dimensional and thus not simple to determine. For that reason, a machine learning technique called multi-layered perceptron (MLP) is used to ascertain the function $f(S_t)$. MLPs are a subcategory of artificial neural networks and are specialised on function approximation. The MLP takes a dataset of input values with their corresponding output values also provided, and uses back-propagation of errors to iteratively adapt a weighted sum over all input values until an optimised mapping onto the output values is determined, i.e., until the error in $f(S_t) = a_t$ has been minimised. Once this training process is complete, the optimised function $f(S_t)$ can be used to calculate an unknown angle a_t for a given set of input intensities S_t . The optimised function output by the MLP training regime has four input nodes – one for each sensor – and one output node, which represents the angle. In addition, five hidden nodes are required to obtain a satisfactory angle prediction.

To apply the MLP to the system, training and test datasets were collected with the setup introduced in Section 5.2. The sensor values were read by the micro-controller and recorded on the PC, and a webcam was used to record the exact position of the joint. An incremental number was displayed in both, the data log and the webcam video, such that each frame could be associated with the corresponding sensor values. Training data points were extracted manually from the video frames and correlated to the related sensor values. The training set consisted of 52 data points recorded at two second intervals. This dataset is discussed in Section 5.3.

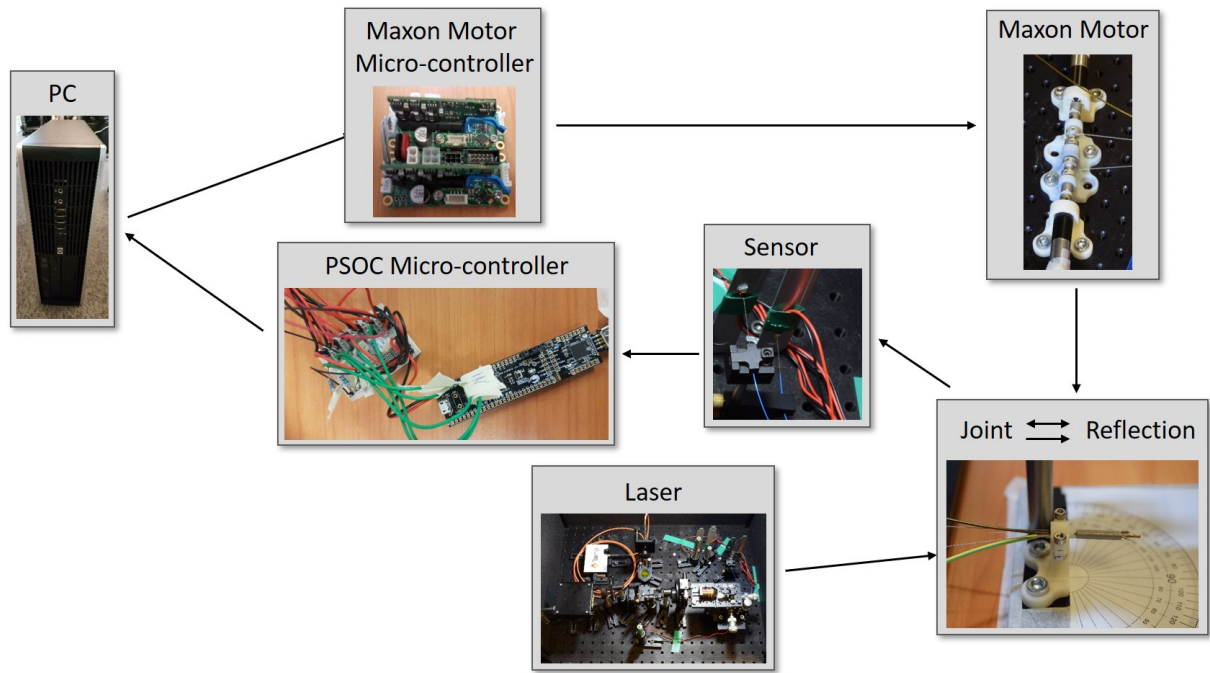


Figure 5.6: Principle of the shape sensing prototype. Diagram showing the components of the system. (Source: [30]) © 2017 IEEE

5.2 Shape Sensing Prototype

5.2.1 Overview

A single-joint prototype was used to assess the sensing capability of the proposed concept, as shown in Figure 5.6. A range of different theoretically valid joint designs were tested and the one with the best light response was selected. The iterative design process is discussed in Section 5.1.3. The upper link had a flat and highly reflective surface. The lower link was clamped in place (using a 3D printed mount) on an optical breadboard. Five optical fibers were secured in the lower link of the robot to measure the bending angle of the two-link joint, by collecting light reflected by the polished surface of the upper link. A super continuum laser source (Fianium WL-SC-400-4, NKT Photonics A/S, Birkerød, Denmark) was coupled to a central optical fiber (see Section 5.1.1). The light was reflected from the polished lower surface of the upper part of the joint and collected by the remaining 4 fibers. The collected light was then delivered to proximal photo-transistors (Kingbright, China/Taiwan) for detection, and the signals were converted by a PSOC micro-controller

and then received by a PC. The bend angle of the joint could then be calculated based on the modulated light intensity detected at each photo-transistor.

Custom control software was used to control the robot with two motor controllers (Maxon EPOS Module 36/2, Maxon Motor AG, Sachseln, Switzerland), which steered two brushless electrical commutated (EC) motors (Maxon EC13, Maxon Motor AG, Sachseln, Switzerland). The motors were used to drive the robot by altering the tension in the two tendons. To test the shape sensing a continuous motion was programmed, which drove the robot from right to left and back again over the entire range of the joint. This motion was observed using a HD webcam (C920, Logitech, Switzerland) mounted directly above the robot joint. The light intensity collected by each optical fiber was recorded by photo-transistors as the robot moved and these intensity values were correlated to the bending angle using a multi-layered perceptron (MLP) machine learning algorithm in order to demonstrate shape sensing.

5.2.2 Manufacturing Process

The two links of the robot were fabricated using additive manufacturing technologies. Two separate 3D printers were used. The base joint (Figure 5.5) that carries the CO₂-laser fiber and holds the sensing fibers was printed in acrylonitrile butadiene styrene (ABS) plastic using an Ultra 3SP HD printer (EnvisionTEC, MI, USA). This printer uses the 'scan, spin and selectively photocure' technology (3SP), which operates a laser to cure a liquid material in a similar manner to stereolithography. This printer has a voxel resolution of 50 μm and a large build plate. As such, it allowed printing of large parts with features small enough to precisely hold the five 225 μm diameter sensing fibers in a parallel alignment. Many different shapes and sizes of guiding holes were considered before a satisfying result was obtained (see Figure 5.4, Figure 5.5, and Section 5.1.3). ABS plastic was chosen rather than metal as it is softer and, hence, protected the fibers from being scratched during assembly. In addition, using ABS ensured high precision while printing the fiber channels. The upper link of the robot with a reflective base was printed in stainless steel

using an Mlab metal 3D printer (Conceptlaser, Germany). This printer uses the selective laser melting (SLM) technology that operates a laser to melt material layer by layer. This material was chosen, so that the base of the printed link could be polished manually to ensure a smooth and reflective surface to efficiently reflect the light from the delivery fiber back to the collection fibers. During the prototyping phase, the reflection profile of the laser light appeared to be extremely sensitive to the small surface asperities caused by the 3D printing process. To address this issue a polishing holder was manufactured to ensure that a smooth, flat surface could be reliably produced.

Prior to laser alignment and positioning the fibers in the robot joint, each of the optical fibers was cleaved at both ends using a manual cleaving tool (Swift CI-02 Cleaver, Opticus) to ensure that the fiber end faces were flat and provided optimal coupling and transmission. Then the optical fibers were manually positioned in the link using a 10x stereo microscope and were fixed in place. To do this an incorporated window was used to fix the fibers in a simple and effective manner using a glue gun.

5.3 Evaluation and Results

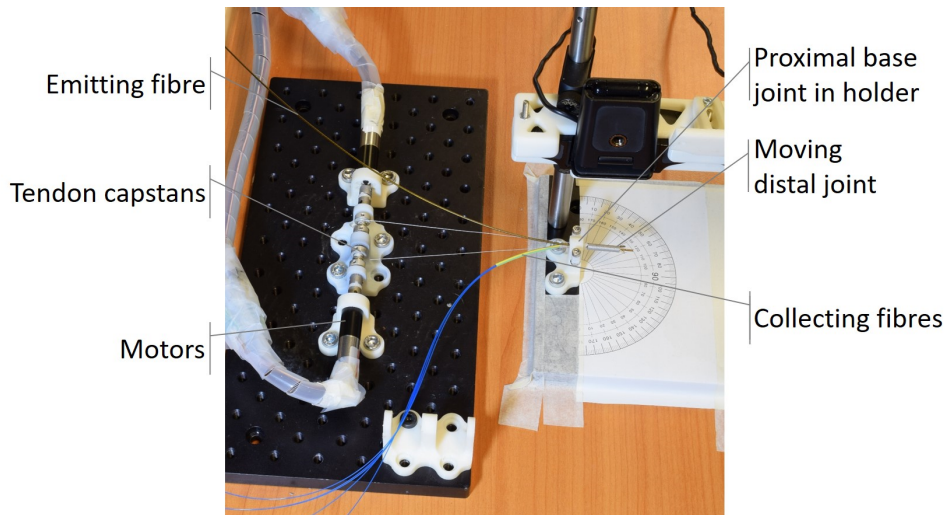


Figure 5.7: Photograph of the test setup showing the mounted robot, the driving motors, the angle measurement chart, and the webcam used for imaging. (Source: [30])
 © 2017 IEEE

In order to evaluate the shape sensing capability of the prototype robot, a test rig was built in which the base link of the joint containing the optical fibers was fixed directly below a webcam (Logitech HD Pro Webcam C920), as shown in Figure 5.7. The webcam was mounted above the joint and recorded the angular displacement as the joint was periodically rotated over the entire range of its motion. An angular measurement chart (i.e., a protractor) was positioned below the robot joint such that the angle of the joint could be measured manually for any given image frame after the collection of a dataset. The webcam video was recorded alongside the photo-transistor intensity values such that the angular displacement could be correlated to the corresponding photo-transistor intensities. Correlated intensity and angle data points of this sort were then used as separate training and test datasets for an MLP machine learning algorithm that was used to convert the optical signals into angle measurements. Figure 5.8 shows the captured video. The light from the laser can be seen as it is shining through the plastic and reflected from the metal surface.

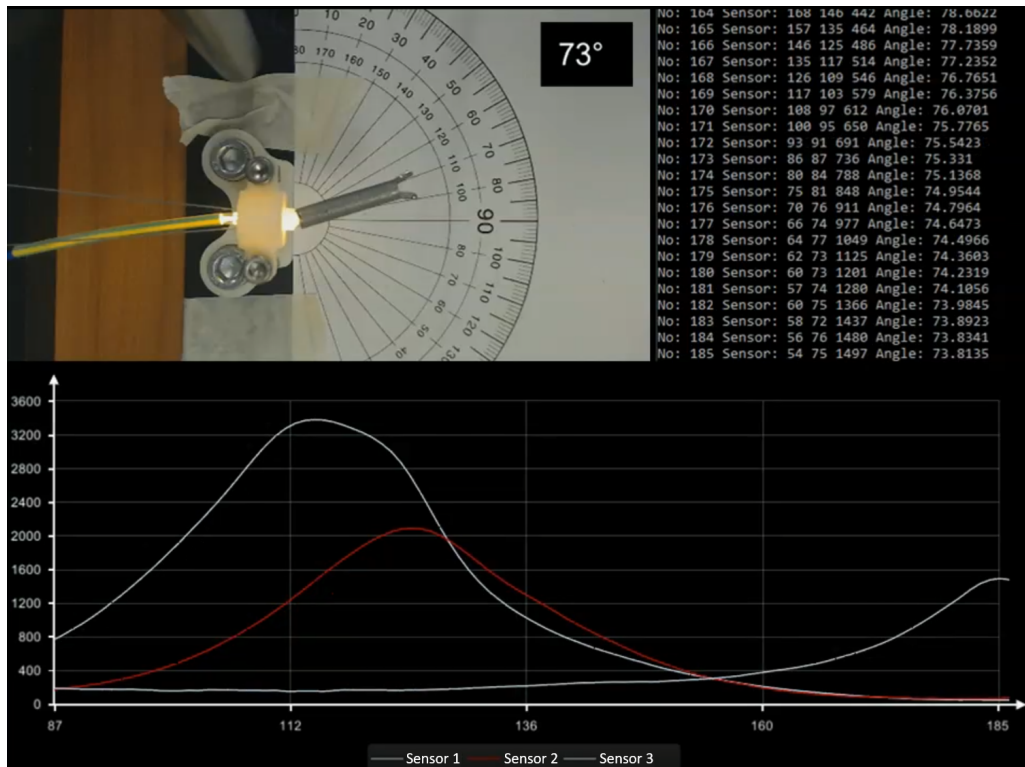


Figure 5.8: The interface for the angle sensing showing the prototype, the three sensor values, the ground truth angle, and the measured angle.

In the optimised joint design five optical fibers were used for the shape sensing measurements, one to deliver illumination and four to collect the reflected light and deliver it to the photo-transistors. The raw signals recorded by the four photo-transistors in this arrangement are shown in Figure 5.9. The data is plotted as a function of time as the robot joint was rotated through two cycles of 35° (i.e., 17.5° to either side of the central zero position).

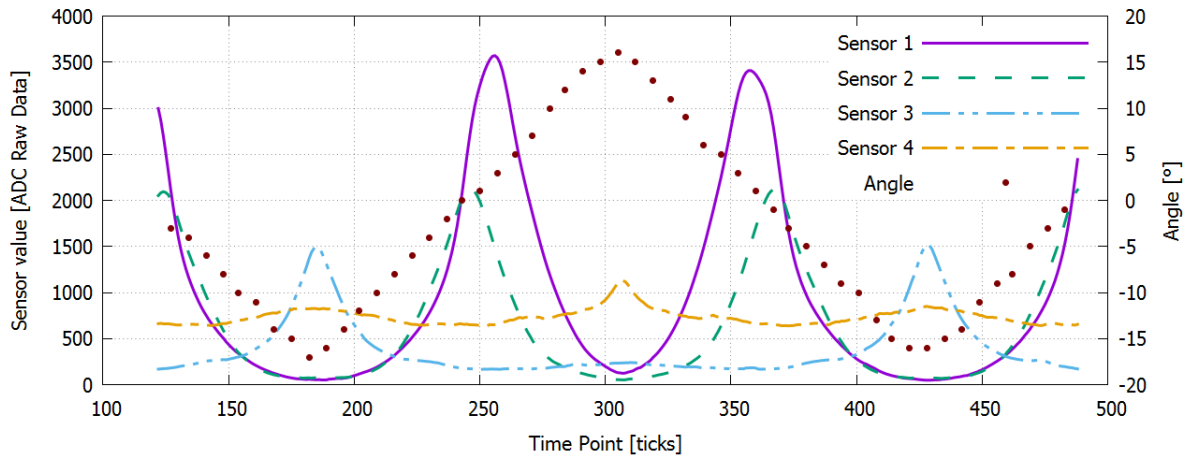


Figure 5.9: Photo-transistor intensity values and corresponding manually measured angles plotted as functions of time as the robot was rotated through its entire range of motion. Note that the intensities recorded by sensor 4 have been multiplied by a factor of five to account for the low signal levels recorded by this transistor. This explains the high background level observed with this sensor. (Source: [30]) © 2017 IEEE

In addition to the photo-transistor intensity values, the manually measured bend angle is also plotted in this graph, with the values displayed as red dots using the secondary y-axis on the right hand side. Thus, Figure 5.9 demonstrates how the photo-transistor intensity values vary as a function of angle. It is clear from the graph that the observed signals correspond to changes in angle in a repeatable and predictable manner, suggesting that they can be used to provide a readout of the angle. Sensors 1 and 2 correspond to the fibers directly adjacent to the central emitting fiber. These sensors detect peak signal levels for angles close to the central point (0°), which occur at time points 243 and 360, see Figure 5.9. The signals from both sensors 1 and 2 decrease to zero beyond angles of approximately -10° and $+13^\circ$ (which correspond to turning left and right respectively).

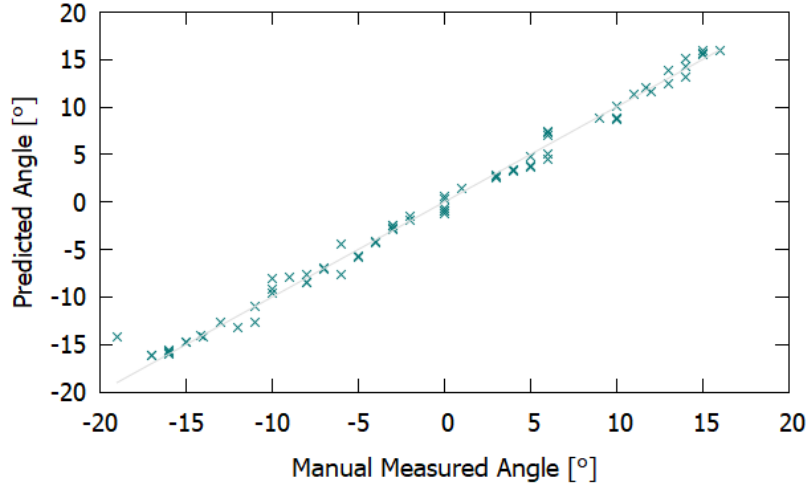


Figure 5.10: Plot of the angles measured using the optical sensors and the MLP algorithm as a function of the manually measured (ground truth) angle. The graph shows a linear $y = x$ relationship indicating good agreement between the values from the optical sensor and the ground truth. (Source: [30]) © 2017 IEEE

The 4th and 5th fibers (sensors 3 and 4) were placed further from the central emitting fiber (one on either side) and, hence, acted to increase the dynamic range of the angle measurements. Sensor 3 dominates the signal in the range of $-17^\circ < \theta < -7^\circ$, while sensor 4 dominates in the range from $+10^\circ < \theta < +17^\circ$. As such, these additional fibers increased the range of sensing from approximately $-10^\circ < \theta < +13^\circ$ to approximately $-17^\circ < \theta < +17^\circ$. The measurement range could be increased further simply by incorporating more fibers (at wider positions) into the robot joint or by using fiber arrangements with wider collection angles (e.g., higher NA fibers or fibers with distal lenses).

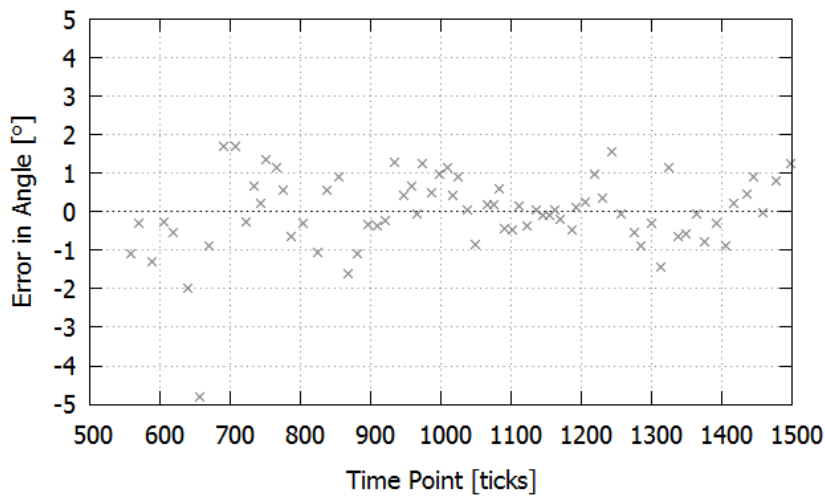


Figure 5.11: Error in the optically measured angle for all data points in angular degrees. (Source: [30]) © 2017 IEEE

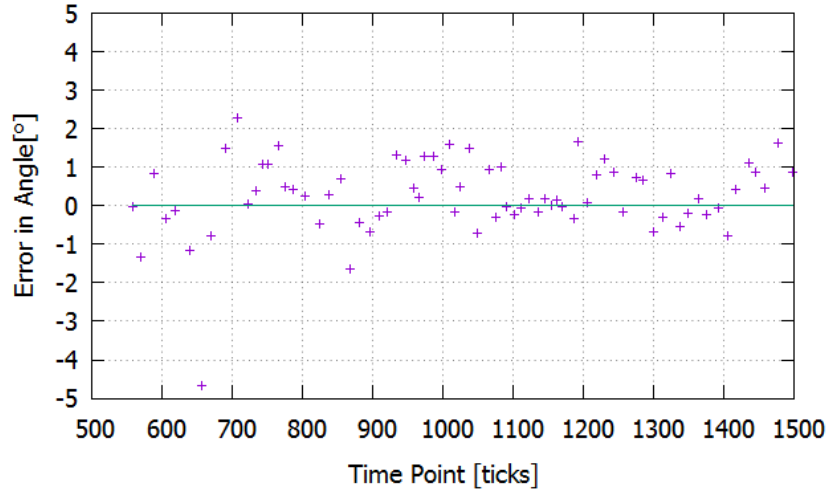


Figure 5.12: Error in the optically measured angle for the same data points shown on Figure 5.11 but using only three sensors. (Source: [30]) © 2017 IEEE

Similarly, the sensor setup used in the joint could be simplified if smaller angle sensing ranges were required. For example, as discussed above, sensors 1 and 2 alone could be used to provide sensing over the range of -10° to $+13^\circ$. A single detection fiber could also offer sensing over a similar range, however, this would not provide direct measurements of the direction of the turn, i.e., there would be uncertainty between, for example, -10° and $+10^\circ$. Nonetheless, this could be mitigated by using the motor control values to ascertain the direction of motion and then using the photo-transistor value to calculate the magnitude of the angle.

Overall, Figure 5.9 demonstrates that the fiber arrangement used in the prototype robot joint was suitable for shape sensing. The signals detected varied predictably over a range of approximately 35° .

After the collection of the training set and calculation of $f(S_t)$, the optimised MLP function was tested on a series of 74 test data points. The results of these tests are presented in Figures 5.10 and 5.11. In Figure 5.10, the predicted angles are compared to the manually measured angles. Since the graph shows a linear relationship, it can be concluded that there is a good agreement between the values measured with the optical sensors and using the MLP algorithm, and the ground truth. Figure 5.11 shows the error of the MLP for each time point. For most of the data points the error lies between -1° and 2° . The mean error is 0.7° . This is sufficient for reliable angle measurement.

As shown in Figure 5.9 the resulting values should also be identifiable with one sensor less. Therefore, it was tried to train the MLP neural network with the same dataset but using only the first three sensors and removing sensor 4. The results can be seen in Figure 5.12. A similar mean error as with four sensors of 0.71° was reached. This shows that the system can run with one fiber removed with only a marginal loss of precision.

Furthermore, once the training was complete, optical angle measurements could be performed in under 0.5s. The time taken to output an angle measurement was limited by the low frequency at which the micro-controller was operated in these proof-of-concept experiments and, hence, this could easily be improved in the future. Despite the slow operation of the micro-controller, the results nonetheless indicated that the system was capable of real-time shape sensing with an update rate of approximately 2Hz.

5.4 Conclusion

A prototype, single joint robot was designed to deliver a CO₂-laser fiber for soft tissue surgery. This device contains an integrated optical shape sensor – comprising five multi mode optical fibers – to provide measurements of the bend angle between the two links of the joint. Proof-of-principle results were demonstrated, illustrating that this approach can provide accurate, real-time shape sensing over a 35° bending range (i.e., over the entire bending range of the robot joint used in this study) with an average error of approximately 0.7° . Further, it was shown that a reduction of the number of fibers should be feasible, since there was a similar mean error of 0.71° training a neural network with only the first three fibers.

This method offers clear advantages compared to other shape sensing techniques, in particular to FBG, which is the most common shape sensing technique. The cost of this method is significantly lower. Instead of complex lasers and optical spectrum analyzers, light emitting diodes and photo transistors can be integrated into the sensor. These advantages come at a cost of additional fibers, which increases the size. While FBGs can incorporate several sensors into one fiber, when using optical sensing two or more fibers

are needed for each joint. Reducing the number of fibers to two fibers improves the usability of this angle sensor and is essential to create a full body shape sensing for a multi-joint robot.

Integrating shape sensing (using this approach or others) into snake-like robots can provide improved control during surgery and, hence, will offer clear advantages in the field of MIS. As such, future work on this topic needs to focus on extending the proof-of-concept device presented here to a multi-joint system with shape sensing incorporated into all joints. Such a device would allow for dexterous, close-loop control of an articulated CO₂-laser fiber, with feedback provided in three dimensions by the optical sensors. Importantly, feedback of this sort could be used to ensure that the bend angles of individual joints remain within safe zones in which the CO₂-laser fiber, the robot itself, and the surrounding tissue are all protected from damage caused by excessive bending.

Chapter 6

Control of Instruments

Minimally Invasive Surgery (MIS) is an established surgical technique aiming to improve patient recovery by reducing the amount and size of incisions. Endoscopic surgery is a sub-field of MIS which aims to use natural orifices instead of incisions to further improve patient recovery. Robotic endoscopy is typically performed using a flexible articulated endoscope inserted and remotely controlled by the endoscopist. Over the last few years, there has been an effort to develop such platforms [36, 1]. The general concept is to use a flexible master-positioning device and to deploy two articulated instruments which are then controlled remotely by the operator in a master-slave scenario. The control of such a robotic instrument is a complex task due to several limiting factors. The surgeon operates the robot instruments using handles, also called master device or controllers. To be able to move the robot with a remote master device the surgeon's control position (task space) needs to be transferred into joint angles (joint space). This task is called solving the inverse kinematics. Several different methods are published to solve inverse kinematics, e.g., Jacobian inverse or Damped least-squares. These methods have known disadvantages in practice, e.g., joint limits and performance. In this chapter a method using reinforcement learning is described. After the joint angles are calculated the instruments need to follow these joint angles which can be complex with problems such as cross-talk, backlash, and tendon slack. Therefore, algorithms must be developed to compensate for these issues.

The work developed here was published by Andreas Schmitz *et al.* in [27] and [32].

This chapter describes the implementation used to operate the 3mm instruments described in Section 3.4.2. First, Section 6.1 describes the method to solve the inverse kinematics problem with reinforcement learning. The learned network was then used to transform coordinates in task space to angles in joint space. Further, a mathematical model for cross-talk, tendon slack, and backlash compensation is described in Section 6.2. In Section 6.3, the integration of all components into an integrated system with the Robot Operating System (ROS) is described. The virtual simulator is described in Section 6.4. Finally, the components are evaluated in Section 6.5 and the conclusion is given in Section 6.6.

6.1 Inverse Kinematics

To convert the surgeons control positions to the joint angles of the instrument arm, a transfer function is needed, because the control positions are defined in the task space while the joint angles are defined in the joint space. A transfer function from joint space to task space is called forward kinematics and the function from task space to joint space is called inverse kinematics. Common methods for calculating inverse kinematics are Jacobian pseudo inverse [157] and Damped least-squares [158].

Jacobian approaches such as pseudo-inverse are known to cause high joint velocities in some configurations, e.g., singularities. These high velocities make a conversion difficult and often lead to jittering results. A well-known alternative is to use the Damped least-squares approach, but issues such as local minima and joint limits, although well addressed in the literature, are still open research questions. This is especially relevant in endoscopic applications, since here the joint range is usually much smaller than with traditional robotic arms. Finally, the Jacobian pseudo inverse is a linear approximation which is defined in a small range around the current state. Long distances are often not possible to calculate. The problem of reaching a target is known as the *Reacher Problem*. Usually, a 2D-Reacher is used to evaluate a new algorithm.

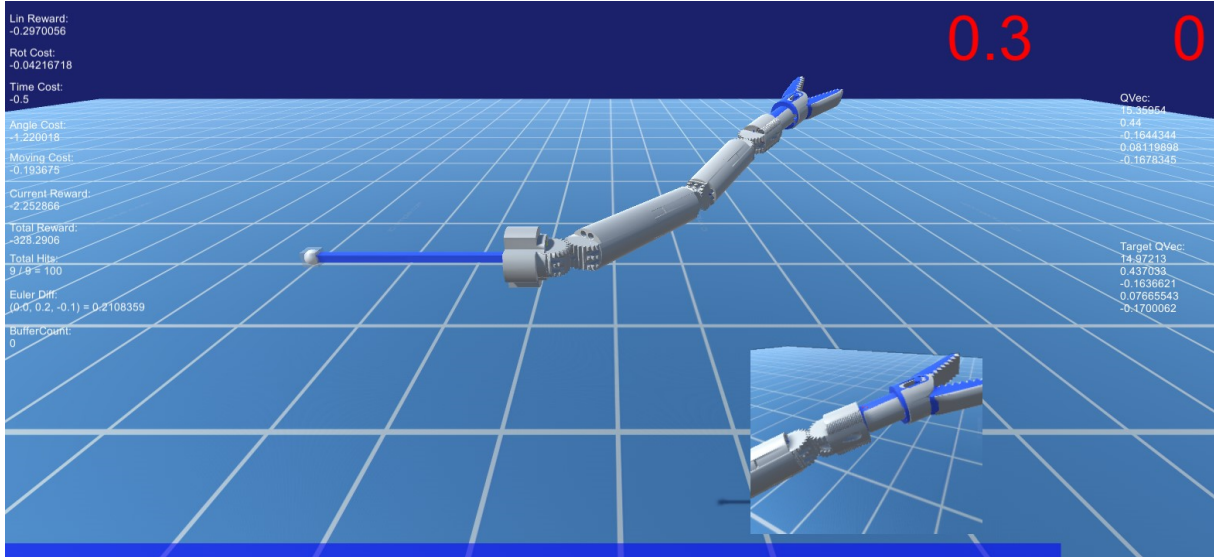


Figure 6.1: Interface for learning the inverse kinematics with PPO of one instrument arm.

6.1.1 Approach

To simulate the instruments used in this thesis, a forward kinematic model of them is required. It determines the resulting tip position out of a q-vector. The q-vector defines the angle of each joint of an instrument. A reinforcement learning algorithm tries to reach random positions starting from another random position by experimentally trying multiple possibilities. This way the method automatically finds a way how to reach a position from a certain other position. Other than training a network with a predefined dataset, RL will automatically solve the kinematic redundancy problem. The network will be trained until a good precision and success rate is reached. A drawback is that each added degree of precision will take exponentially longer. This training may take a long time, but the recall time is short. The input of the network is depending on the target position and the current robot configuration. After the training the model is exported and integrated into the robot control.

Then, during robot control, the network is repeatedly called until the target is reached or after a predefined number of iterations. If the number of iterations is exceeded the search for an inverse kinematics solution counts as failed. In this case the robot will not move. Safety mechanisms make sure that no unexpected behaviour appears, e.g., the joint speeds are limited.

6.1.2 Reinforcement Learning

Although reinforcement learning is not a new technology, it has become very popular in recent years. But in medical robotics rather few publications suggest the use of reinforcement learning or even deep learning in general.

The principle of any reinforcement learning is the optimization of a reward/cost function of an actor regarding an environment. The environment is the system in which the actor is working. An environment e is a description of the system as a tuple of $e = (s_1, s, o(s), a, r(s), d(s))$ with s being the inner state, defined by a set of inner state variables, a start state s_1 as a valid instance of the state space, and o a set of observations, which describes the variables that the actor can see. Further it has a set of actions a , which can be discrete or continuous and describe how the system reacts to the actors choices. It results in a reward $r(s)$ for the new state, the observation $o(s)$ of the new state, and a done state $d(s)$ which defines if the environment is in a final state. The basic learning principle is Q-Learning [186]. The central learning principle is:

$$Q^{new}(s_t, a_t) = Q^{old}(s_t, a_t) + \alpha \cdot \left(r_t + \gamma \cdot \max_a(Q(s_{t+1}, a)) - Q^{old}(s_t, a) \right) \quad (6.1)$$

with r_t being the reward of time step t , discount factor γ , learning rate α , and the expected future return $\max_a(Q)$. This Q-Learning function defines the expected reward for each state s_t choosing the action a_t . To train this function in each learning step, the change in the reward plus the expected future awards is added to the old expected reward. This way in each learning step the function converges more and more towards the real reward function.

An advanced version of this learning principle is Proximal Policy Optimization (PPO) which is state of the art [187]. In this thesis PPO is used. There are multiple implementations and libraries for reinforcement learning, like tf-agents and ml-agents. In this thesis ml-agents (Unity Technologies, San Francisco, CA, USA) is used which works closely together with the Unity3d graphics engine. It is based on Tensorflow (Google, USA) and

incorporates PPO. The environment is implemented as a derivative of an “Agent” class which has a function for all parts of the set e .

6.1.3 Development of the Learning Method

To get the model to learn is a challenging task. The default situation is that once the model is defined, embedded in the learning method, and everything is set up, the network is not learning well. There are several reasons why this might happen:

- **Faulty library.** Although using a library, the implementation of the learning algorithm might be faulty. There are many libraries available for machine learning, but there are flaws included in some of these libraries. Although this is true for all programming fields, deep learning is a relatively new field and these libraries are not stable yet.
- **The mass of adjustment parameters is not optimal.** Machine learning in general and reinforcement learning in particular have a high number of adjustable parameters. The more advanced an algorithm is, the more parameters it has. These parameters are crucial. Usually each parameter has a range where the algorithm is working, but if only one parameter is out of this range, the training may not work at all. Further, there are dependencies between these parameters, e.g., learning rate and number of learning steps.
- **Not enough training time.** The reinforcement learning needs time for the training. Often the learning time is increasing exponentially regarding many factors, e.g., model complexity or target precision. The reason that the model was not able to find a result can be because it needs a longer training time.
- **The target definition is too precise.** The target area in which the actor receives a reward is important. Often the target area is too small. With the defined target area becoming smaller the training time grows exponentially, which means that

quickly an unacceptable training time is reached. Bigger target areas are better for the beginning.

- **The task definition can be wrong.** Often the task definition is not possible to solve. The best way is to try to solve the task manually first.

Because of all these problems with machine learning, it is important to start with the most simple task possible. The target area should be relatively big in the beginning and the configuration parameters should be at their default values. Since there are often no default values in the publications it is good to find some in some working examples of the specific library.

In the development process of this thesis, first the model was defined as a single-joint robot, then as two-joint robot, both in 2D. The parameters were set to the values for a 2D-Reacher problem. Afterwards the training parameters and model parameters were modified one by one. Since training is fast with such a simple model, quick tests can be made. After the optimum was nearly found the model complexity was increased by adding joints one by one until the full arm was finished. If necessary, new model parameters were added while increasing the complexity, see Section 6.1.4.

6.1.4 Environment Definition

The implementation of the environment e , the definition of the reward function $r(s)$ and the learning hyper-parameters are crucial for successful learning.

State

The arm design is described in Section 3.4.2. It has a prismatic joint, 3 rolling gear joints, a distal-roll, and a total of $4 + 2$ DOF, see Figure 6.1. All gear joints have the same joint limit of 50° . The q -vector defines the angles of all joints, and thus the arm configurations. It is used to calculate the tip position and to determine the error in position and orientation.

Target

The target defines the position and orientation where the tip of the arm needs to go. The target is a 4×4 homogeneous transformation matrix of the tip. The transformation matrix consists of a 3×3 rotation matrix and a linear transformation:

$$\begin{pmatrix} R & \vec{b} \\ \vec{0} & 1 \end{pmatrix} \quad (6.2)$$

where R is a 3×3 rotation matrix, $\vec{b}$ is a transformation vector, and $\vec{0}$ is the vector $(0, 0, 0)$. For training purposes, it is calculated from a random q vector within joint limits. This assures that the target is always reachable. The target has an area around it, where it is counted as being reached. This area is defined by a maximal positional error and a maximal rotational error. Once the target is reached it needs to stay in the goal area for 20 steps. This is to prevent oscillations.

Reset

The environments reset function defines the new target and initializes the robot arm with a random starting position using a random q -vector within the limits. The random starting position together with the random target position ensures that all start-target-combinations are learned. This helps the algorithm to learn the robot's workspace.

Action

The action space in this environment is a continuous action vector A with the length of the number of joints N , $A = [-1, 1]^N$. Most reinforcement learning algorithms and especially PPO can only handle continuous action vectors from -1 to 1 . To transform an action vector a from A -space into a Δq in the q -vector space Q it is multiplied by a step size: $\Delta q_j = a_j \cdot s_j$ for each joint j with $a \in A$ and step size for each joint $s \in \mathbb{R}^N$. The new q of the environment state is calculated by modifying the current q vector: $q_{t+1} = q_t + \Delta q$. The

step factor can be seen as the maximal change in angle and the precision of a step. Thus, it is crucial for the learning quality and learning speed. If the step size is too big, the algorithm cannot find a solution, because the arm is not moving precisely enough. This is shown by a heavily jittering arm. Since the change in angle depends on the precision of the action vector, the jittering depends on the step size, the number of joints and the length of the arm. If the step size is too small, the algorithm cannot find a solution because the arm is too slow to get to the target or the algorithm would need too long to find the solution. It has been observed that the bigger the target area is, the bigger the step factor can be. Further, the environment needs different step size factors for different joint types, since the q -vector has different scales for prismatic and rotational joints. In this work two step sizes were used, one for the prismatic joint ($=2.0\text{mm}$), and one for all other revolute joints ($=0.1^\circ$).

Reward

The reward function is the step reward the agent gains by each step regarding an action. It is possible to have all the reward only in the last step while all other step rewards are zero. Since this is a very flat reward function it is hard for the algorithm to find a solution and learn the optimal policy. Because of that, the reward function used here is mostly the cost of the distance between the tip and the target. It is defined by multiple factors, which consist of:

- The positional cost, defined as the norm of the distance of the target and the tip position.
- The rotational cost is defined as the difference between the orientations of the tip and the goal. Precisely, the difference of the quaternions of the tip and the goal is converted to an euler vector. The cost is the euclidean norm of the euler vector.
- Time cost which is a constant ($= 0.5$).
- Angle cost, which penalizes too much bending as a quadratic function of all angles. It helps to force the arm into a smooth curvature instead of, e.g., keeping all angles

straight and just bending the last one to full extent. This factor was important for nice bending arms. This cost is of lower magnitude compared to the rotational and positional cost to make sure that it is always beneficial to reach the target.

To calculate the difference between two angles, Algorithm 4 is used.

Algorithm 4 Angle Difference

```

1: function ANGLE DIFFERENCE(Quaternion Tip, Quaternion Target)
2: return Quaternion d
3:   Quaternion d = Tip · Target-1
4:   ToEulerAngle(d)
5:   Unify(d) ▷ Keep d ∈ [−π, π]

```

Observations

The observations are the set of variables the agent can see. More precisely, they are the input parameter of the neural network (NN), while the actions are the output. In this case, the observations are a vector of 21 float values consisting of:

- Q-vector (5),
- Tracking error (3),
- Tracking error norm(1),
- Euler difference of orientation and target orientation quaternions (3), and
- Information if the tip has reached the target area (1) to stay in it.

Curriculum

In machine learning, especially in reinforcement learning, it often happens that either a problem is too hard to learn at all or that it is too easy to learn and the algorithm finds an optimal solution quickly but then the target was so loose that it could have found more precise solutions. Inspired by teaching classes in school, curricula change the problem after a predefined amount of steps by changing model parameters. It showed that

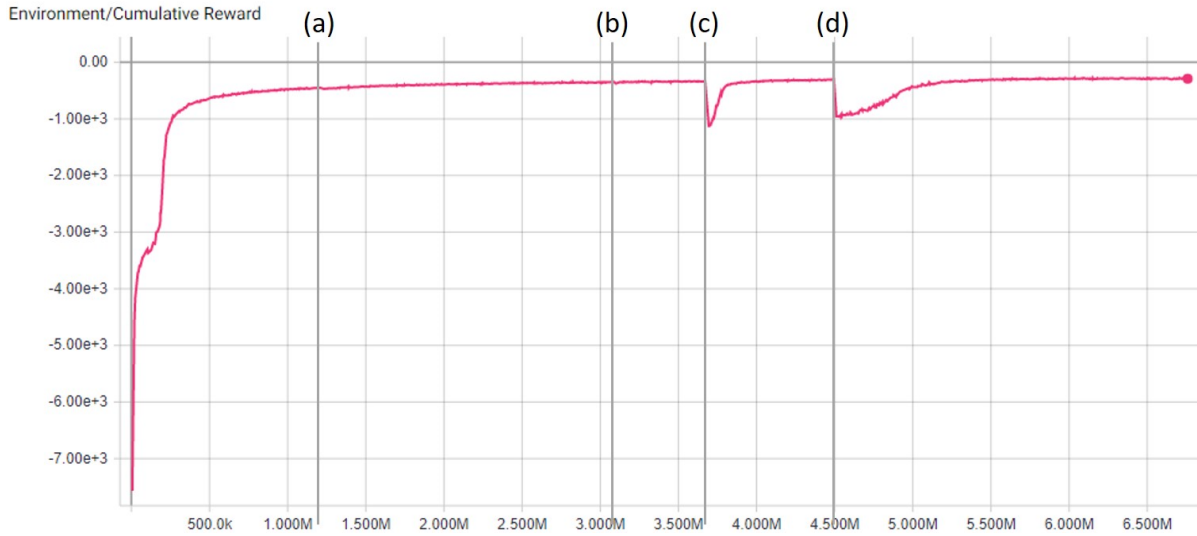


Figure 6.2: The learning curve of the network. At time points (a)-(d) the curriculum switched to a new set of parameters. The learning process took approximately 20 hours. (Source: [32])

learning the orientation is comparably easy in one step, but hard to learn with curricula, while learning the positioning is hard to be learned in one step, but comparably easy to learn with curricula.

Multiple parameters were tested. The parameters finally used for the curriculum were the maximal position and rotational error, as discussed in the next section. These were reduced in each curriculum step to become more precise every time. Figure 6.2 shows when the new curriculum steps were activated during the learning process and how they affected the gained rewards.

Model parameters

To test how the learning behaves, the model was highly parametrised. All parameters were tested and the best set was experimentally chosen. Some of the parameters were used in the curricula. The following parameters are included in the parameter list:

- **goal_size:** This parameter is part of the curriculum and determines the size of the goal area in Cartesian space in millimetres. During learning a range between 10 and 0.1 was used.

- **goal_rot:** This parameter determines the size of the goal area in rotational degrees. During learning with curriculum a range between 10.0 and 0.1 was used.
- **step_size:** This parameter specifies how fast revolute joints can move. This is discussed in the *Action* paragraph. The value was set to 0.1.
- **trans_step_size:** Similar to the step size of revolute joints, the prismatic joint needs to have a separate step size because the range of motion is different. This value was set to 2.0.
- **max_steps_agent:** The maximal number of steps which are performed during learning for one trial. This determines how much time the arm has to reach the goal. The value was set to 500.
- **moving_cost_factor:** Moving cost specifies the cost per millimeter. This reduces the amount of unnecessary movement, e.g., overshooting. This value is set to 10.
- **time_cost:** Time cost is a constant cost for each time step. This makes sure the agent is not waiting. The time cost was set to 0.5.
- **on_goal_num:** This parameter specifies the number of steps the agent needs to stay on the goal before it counts as being reached. This is to prevent the agent from moving the arm randomly and hitting the target while passing. It was set to 20.
- **angle_cost:** Angle cost determines the cost for the bending angle at each hinge joint. This is used to get smooth arms. This cost is quadratic regarding to the joint value of a joint up to the maximum of this parameter value. It was set to 1.
- **rot_cost_factor:** Rotation cost factor scales the angle difference to the cost scale. It means for each degree the instrument tip rotation is not matching the target rotation the cost increases by this value. This parameter was set to 0.2.

Integration

The learned Tensorflow model was integrated into the control system to calculate the inverse kinematics for a real robot. The time consuming part is the training of the network. The whole training is offline. To get the IK for a target, it only needs to gather predictions from the trained model. After training, the model is exported to a Tensorflow frozen network and the Tensorflow library loads the exported model. The component receives the target position from the master device and scales it to the right reference frame, calculates the joint values and sends it to the robot control component. It further includes safety features to avoid unintentional movements. Although the network usually remains inside the joint limits, it is verified that no joint limits are exceeded and that the target is approximately reached. The latter check ensures that no untrained region is hit or that the robot does extreme movements. If the target position is in an area around the current tip position, only the last q-vector (joint angles) is used, otherwise an intermediate step of the path is transmitted.

6.2 Instrument Control and Compensation

In order to obtain a stable bending motion and improve control accuracy, the actuation compensation mitigates joints coupling, backlash, and tendon slack. In this section, the actuation compensation for the tendons is presented.

6.2.1 Joint Coupling

Because the tendons for the joints are passing through other joints, moving an earlier joint along the kinematic chain affects the tendons of all other joints. Because of this, while moving one joint, the joints coming afterwards are moving, too. A compensation model is needed to reduce this effect. The instrument is composed of a serial chain of

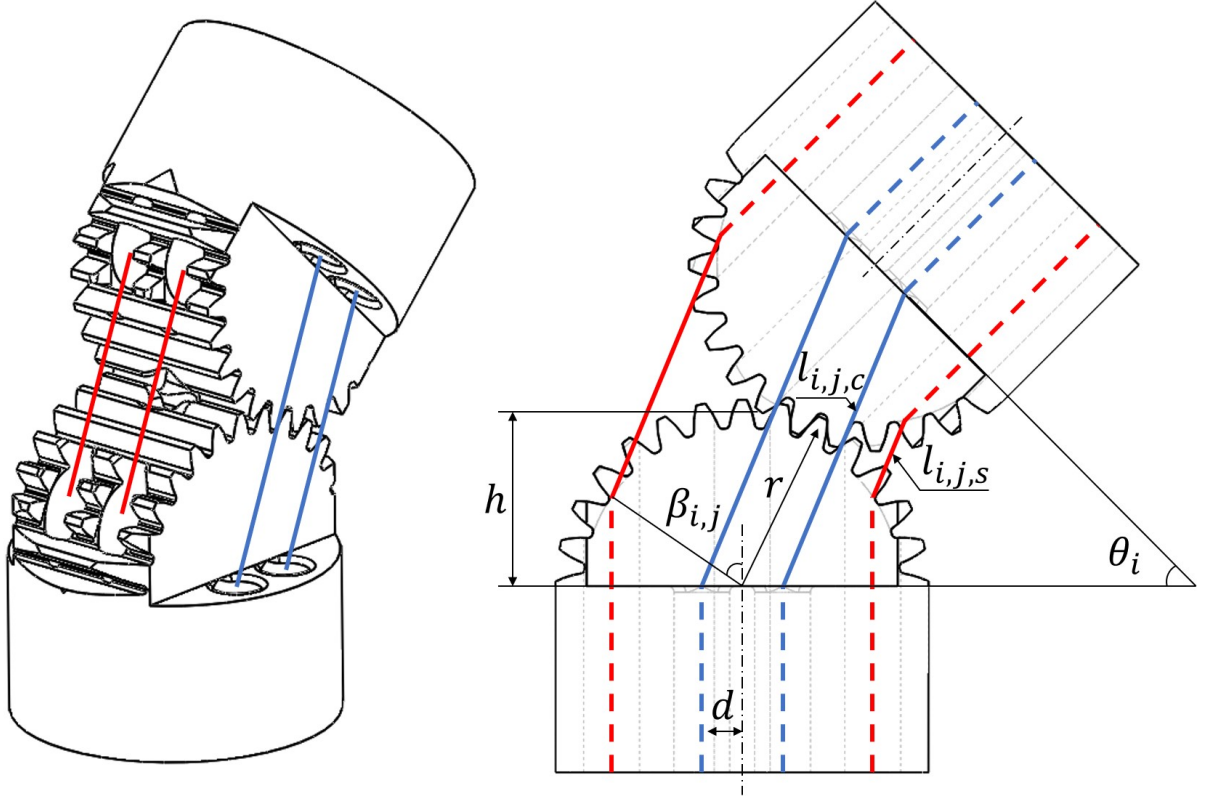


Figure 6.3: Schematic view of tendons' length change. Tendons come out from two different surfaces. (Source: [27]) © 2020 IEEE

rolling gear joints with 4 DOF along with a translational DOF and a gripper. The vector q is composed of the joint values of the instrument:

$$q = [d_1, \theta_1, \theta_2, \theta_3, \theta_4, d_2]^T \quad (6.3)$$

with d_1 being the displacement of the translation, θ_i the bending angle in degree of the i th ($i \in [1..3]$) joint, θ_4 is the rolling angle of the distal-roll and d_2 the displacement in mm of the gripper for opening and closing.

Figure 6.3 shows the joint setup and the tendons passing through the joint (blue and red lines). The length of each tendon between the upper and lower surface is $l_{i,j,s}$ and $l_{i,j,c}$ with j being the tendon index. There are two different types of tendons, shown in the figure as blue and red lines. One type comes out of the side cut outs (blue $l_{i,j,c}$) and the other is routed through the gears (red $l_{i,j,s}$).

Tendon Length

The tendon length for the two types is described by different models, which are obtained by the following geometric calculations.

For tendons going from the upper to the lower gear surface (red line), the tendon length $l_{i,j,s}(\theta_i)$ is calculated by:

$$l_{i,j,s}(\theta_i) = 2r(1 - \cos(\beta_{i,j} - \frac{\theta_i}{2})) \quad (6.4)$$

where r is the radius of the rolling surface and $\beta_{i,j}$ is a constant angle depending on the design describing the point where the tendon leaves the gear. $\beta_{i,j}$ is half of the maximum bending angle of the i th joint.

The length $l_{i,j,c}(\theta_i)$ of the tendons which are routed through the side cutouts (blue lines), can be expressed as:

$$l_{i,j,c}(\theta_i) = 2r - 2d\sin\frac{\theta_i}{2} - 2(r - h)\cos\frac{\theta_i}{2} \quad (6.5)$$

where h is the height of the cutout and d denotes the distance between the tendon holes for tendon j and the central axis of the link.

From Equations 6.4 and 6.5, r and h primarily affect the cross-coupling behavior of the gear joint. Therefore, these two parameters can be used to determine the design of the gear joint.

The distal roll motion at the gripper is actuated by two tendons, as shown in Figure 6.4. The pulling angle α is the angle between the tendon and the surface of the link. The length of the tendon is related to the rolling angle θ_4 and is calculated as follows:

$$l_r(\theta_4) = \sqrt{[(\varphi_0 - \theta_4)R_r]^2 + h_r^2} \quad (6.6)$$

where φ_0 is the initial angle of rolling, R_r is the radius of the cylinder plus the radius of the rolling tendon, and h_r is the height of the cylinder. φ_0 determines the maximum

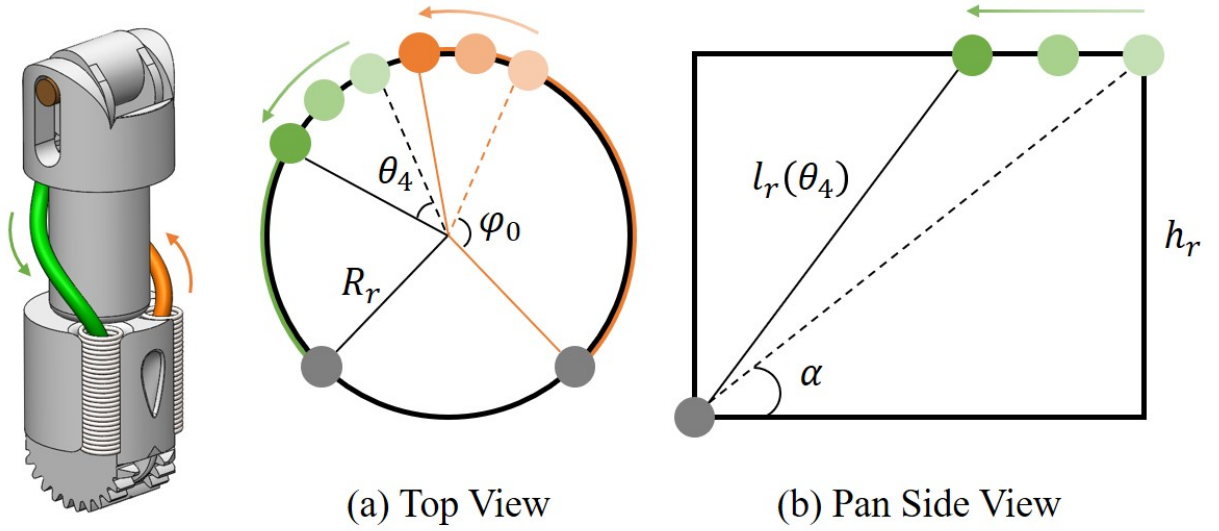


Figure 6.4: The geometry and motion of the roll joint at the gripper. (a) Two tendons for distal roll move around the cylinder. (b) The change in tendon length with a rolling angle. (Source: [27]) © 2020 IEEE

rotation angle. Therefore, one way to achieve a large rolling angle is to make the initial angle of rolling as big as possible during the design.

Tendon Length Difference for Control

When the robot starts, the motors are in zero position, so the total length cannot be used to control the joints. Assuming the robot starts in a straight position, the difference between the targeted position and the straight position is used. The straight position is called zero position of the arm and the q -vector is all zero.

For both types of tendons (blue $l_{i,j,c}$ and red $l_{i,j,v}$) the differences between the state θ_i and the initial state 0 is:

$$\Delta l_{i,j,s}(\theta_i) = l_{i,j,s}(\theta_i) - l_{i,j,s}(0) \quad (6.7)$$

$$= 2r(\cos\beta_{i,j} - \cos(\beta_{i,j} - \frac{\theta_i}{2})) \quad (6.8)$$

$$\Delta l_{i,j,c}(\theta_i) = l_{i,j,c}(\theta_i) - l_{i,j,c}(0) \quad (6.9)$$

$$= 2(r - h)(1 - \cos\frac{\theta_i}{2}) - 2d\sin(\frac{\theta_i}{2}) \quad (6.10)$$

The length for the rolling tendons changes in a different way than the gear joints. The difference of length changes for the rolling tendons is as follows:

$$\Delta l_r(\theta_4) = l_r(\theta_4) - l_r(0) \quad (6.11)$$

$$= \sqrt{|\varphi - \theta_4|^2 \cdot |R_r|^2 + h_r^2} - \sqrt{|\varphi|^2 \cdot |R_r|^2 + h_r^2} \quad (6.12)$$

To determine the change in tendon length for any joint j , the following function incorporating $\Delta l_{i,j,s}$, and $\Delta l_{i,j,c}$, and Δl_r can be used:

$$\Delta l_{i,j} = \begin{cases} \Delta l_{i,j,s}(\theta_i), & \text{Tendon } j \text{ in joint } i \text{ is in a cutout} \\ \Delta l_{i,j,c}(\theta_i), & \text{Tendon } j \text{ in joint } i \text{ is on the gear} \\ \Delta l_r(\theta_i), & \text{Tendon } j \text{ is the central gripper tendon} \end{cases} \quad (6.13)$$

As a result, the change in length of each tendon $\Delta L_{i,j}$ can be presented as follows:

$$\Delta L_{i,j} = \sum_{k=1}^i (\Delta l_{i,j}(\theta_i)) \quad (6.14)$$

This function is used to move the robot joints into the specified angle. The tendon length $l_{i,j}$ is converted to motor values mv .

6.2.2 Tendon Slack

In the described tendon-driven system, a single actuator cannot control the tensions of two tendons individually. Due to that, a reduction of the tension while moving the joint, called slacking, is a problem. If tendons are slack it may cause the tendons to derail from the capstans, resulting in failure of the actuation unit. To reduce the slacking problem, the tendons should be pre-tensioned. For the distal-roll, it is important to maintain the tension to keep the posture. Slack could cause instabilities as well as a decrease in the stiffness.

Tendon slack can be determined by calculating the total change in length of two tendons for a single joint. Therefore, the tendon slack $\Delta l(\theta_i) + \Delta l(-\theta_i)$ can be calculated as follows:

$$\Delta l_{i,j,s}(\theta_i) + \Delta l_{i,j,s}(-\theta_i) = 4r \cos \beta_{i,j} (1 - \cos \frac{\theta_i}{2}) \geq 0 \quad (6.15)$$

$$\Delta l_{i,j,c}(\theta_i) + \Delta l_{i,j,c}(-\theta_i) = 4(r - h)(1 - \cos \frac{\theta_i}{2}) \quad (6.16)$$

The first type of tendon slack $l_{i,j,s}$ in equation 6.15 is not constant and always greater than zero, which means moving the joint loosens the tendon when both tendons of that joint are driven by a single capstan. In this case, the central tendon for the gripper should be pulled to provide the tension required to prevent slack.

As for the second type of tendon slack $l_{i,j,c}$ in equation 6.16, when r and h have the same values, the sum of the two tendon actuation lengths is always zero. This indicates that a pair of tendons can be driven simply without considering the tendon slack. This is the reason why during the design in Section 3.6 the distance r and the distance h was chosen to be equal.

6.2.3 Backlash

The control of the joints includes a significant amount of backlash. This means, turning the motor when changing the direction does not result in a motion in the joints. Differently said, moving a joint from the start position to a certain position and then returning to the initial motor position does not result in the joint returning to the start position. The backlash is a combination of backlash in the gears, tendon elongation, gap between capstans and motors, and general backlash in the assembly. This can be reduced by quality manufacturing. In this case, the backlash is assumed to be constant and experimentally measured.

The backlash compensation for the i th joint is given by:

$$mv_i = mv_i + \begin{cases} \text{sgn}(\dot{\theta}_i) \cdot e_{b,i}, & \text{direction changed} \\ 0 & \text{direction not changed} \end{cases} \quad (6.17)$$

where mv are the motor values of the i th joint in qc. $\text{sgn}(\dot{\theta}_i)$ accounts for the change of motion direction and $e_{b,i}$ is a constant that represents the actuation compensation to overcome the backlash of the i th joint during the motion transmission. The backlash compensation modifies the motor values mv so that the compensated values are sent to the motors. This reduces the backlash effect.

6.3 System Integration with ROS

The integration of the whole project was done using the Robot Operating System (ROS). This is a framework for network communication between system parts called nodes. The advantage of ROS is that multiple people can work on separate parts, called nodes, of a system with minimal overlap. Each of the separate nodes runs as an own executable, in contrast to libraries or plugins, and connects over network using predefined protocols. This means that every component can be developed, operated, and tested without the other components. Another advantage of ROS is that it has several tools to debug the algorithms. For example, the data from the master device to the inverse kinematics can be saved in a file, which is called a bag, and then replayed afterwards for analysis purposes. This way problems in the inverse kinematics implementation were easily found.

Although not supported, the ROS framework can be integrated into Visual Studio C++ and Unity. It natively supports Ubuntu as an operating system. However, there is a relatively new version supporting basic functions on Windows including all libraries necessary to build Windows programs for ROS. The supporting programs, mainly for debugging, are only fully functional on Ubuntu. For this purpose the Windows Subsystem Linux (WSL) with Ubuntu was used.

ROS consists of a core node and multiple client nodes which it can run on both Windows and Ubuntu. ROS defines several connection types. Topics and services are two of them. Topics are continuous data streams. For each topic a message type file describes the data format. Services are commands, which return an answer directly after the request is received.

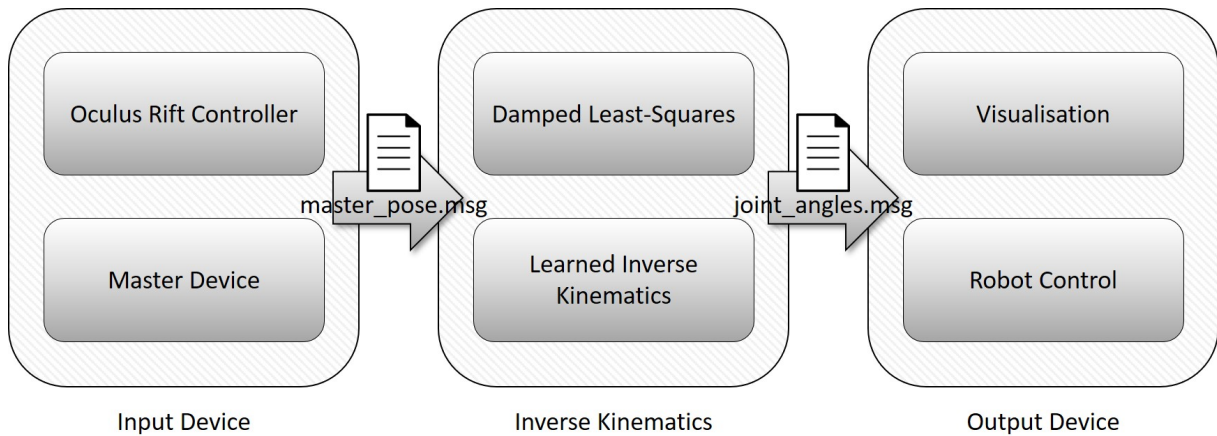


Figure 6.5: The architecture of the robot control system using ROS with three main components: An input device, inverse kinematics, and an output device. Each of them have two implementations.

An architecture was developed to integrate all parts to a fully functional system. It is shown in Figure 6.5. The system consists of three main components:

- **The input component** implements the master device used to control the robot. Two different nodes are implemented for this component. One node implements the Oculus Rift (Facebook, USA) handles, see Section 6.3.1, and the other one implements a master device developed in the Hamlyn centre by another PhD student. In the scope of this thesis the Oculus Rift node was implemented. This component retrieves and publishes the 6D positions of the two handles.
- **The inverse kinematics component** calculates the joint angles from the two 6D positions of the control handles. It has two implementations, one uses the Damped Least Squares Jacobian Pseudo Inverse and the other uses the learned inverse kinematics described in Section 6.1. The learned inverse kinematics belongs

to the scope of this thesis. This component publishes the joint angles for all joints of both instrument arms.

- **The output component** processes the joint angles. Two implementations were made, a visualization component using Unity, see Section 6.3.3, and the robot control for the real robot, see Section 6.3.4. In the scope of this thesis both nodes were implemented.

6.3.1 Oculus Rift Input Device



Figure 6.6: The VR Oculus Rift system consists of a head-mounted display, two controllers, and two tracking cameras.

The Oculus Rift input device node is a component to read the 6D position of the two Oculus Rift controllers and sends it to the inverse kinematics. The Oculus Rift system, shown in Figure 6.6, consists of a head-mounted display, two hand-held controllers, and two tracking cameras. The head-mounted display enables the virtual reality (VR) view and is used for the VR-simulator. The two controllers are used as one type of input device to steer the robot. They do not need a hardware connection to the system, which gives them more freedom for handling. The controllers are tracked with gyroscopes for fast response times and additionally with the tracking cameras to compensate for drift. The controllers need to be calibrated once per setup. 6D position and orientation data for

each controller are transmitted to the program. Additionally they have three buttons and two triggers on each handle, which can be used to close the gripper.

This node was derived from the virtual simulator described in Section 6.4. It is implemented in Unity and uses the Oculus library to synchronise the position. All the data fusion is already done by the driver. As Unity does not naturally have any libraries for ROS, this node uses ROS Unity [188] to connect over a Websocket.

Once the node reads the data from the Oculus controllers, it packs them into a ROS message using the *master_pose* message type given in Listing 1. This message type is composed of a header to synchronise the messages, two 3D position vectors for the left and right handle and quaternions for both handles to transfer the rotations. These messages are then transmitted to an inverse kinematics node.

Listing 1 6D position from Master Device to Inverse Kinematics.

```
learned_ik/master_pose.msg:
  std_msgs/Header header
    uint32 seq
    time stamp
    string frame_id
  float64[3] delta_pos_left
  float64[3] delta_pos_right
  float64[4] qua_left
  float64[4] qua_right
```

6.3.2 Inverse Kinematics

The inverse kinematics node receives two control positions in 6D and outputs the joint angles of each joint of both instrument arms. This node is written in C++ and includes Tensorflow as a library. The output message consists of a header, two vectors with joint angles for both arms in radian and the input message. It is shown in Listing 2. The input message is transferred to be able to visualise the targets together with the arms.

The inverse kinematics used in this system is described in Section 6.1. It uses a trained and exported Tensorflow network, called frozen network, to convert the target positions

to joint angles. Further, this node implements safety mechanisms to avoid an unexpected behaviour as described in Section 6.1.4. This does not give the trained inverse kinematics explainability, where it is possible to understand the outcome of the network and it can be debugged, but it makes sure that the robot is within expected parameters.

Listing 2 Joint angles and original targets transmitted from inverse kinematics nodes.

```
learned_ik/joint_angles.msg:
  std_msgs/Header header
    uint32 seq
    time stamp
    string frame_id
  float64[] left_arm
  float64[] right_arm
  learned_ik/master_pose targets
```

6.3.3 Visualization

The visualization node displays the robot configuration of the two arms and the two target positions. This way it is possible to analyse if the reference frames fit and the inverse kinematics works properly. It receives the joint angles of both arms together with the target position. The exact message is defined in Listing 2. The visualization node is based on Unity3D and uses the CAD designs exported from SolidWorks.

6.3.4 Robot Control

The robot control node can be used in addition to the visualisation node. The node controls the physical robot by receiving joint angles with the message shown in Listing 2. It implements the backlash and joint coupling compensation, derived in Section 6.2, to convert the joint angles to motor values. The motor values are then sent to the motors with aid of the Maxon motors C++ command library. All motors are controlled in position mode. The library and motor controllers ensure that the motors stay within acceleration and speed limits.

6.4 Virtual Simulator

During the thesis a virtual simulator was developed with the Unity Engine, shown in Figure 6.7. It uses the Oculus Rift, shown in Figure 6.6, as the controller and display. An ENT surgery scene is presented in Virtual Reality (VR) using the *i²Snake* equipped with two instruments in a head phantom. The meshes from this head phantom used in the VR simulator were downloaded from the BodyParts3D online library [189].

The view of the surgical scene is from the perspective of the *i²Snake* head. By moving the *i²Snake* head around, the operator can have a look at the scene. Since it is displayed in VR the operator can also move his head to look around. Of course, the current technical limitations make it impossible to use VR in real surgery, because the endoscopic cameras are too limited. The cameras have currently a too low resolution for VR and would need a wide angle lens for at least 180 degrees pictures. But the simulator showed prototypically how much value a VR view would bring to surgical scenarios. This simulator was shown during several occasions and received good response from the audiences.

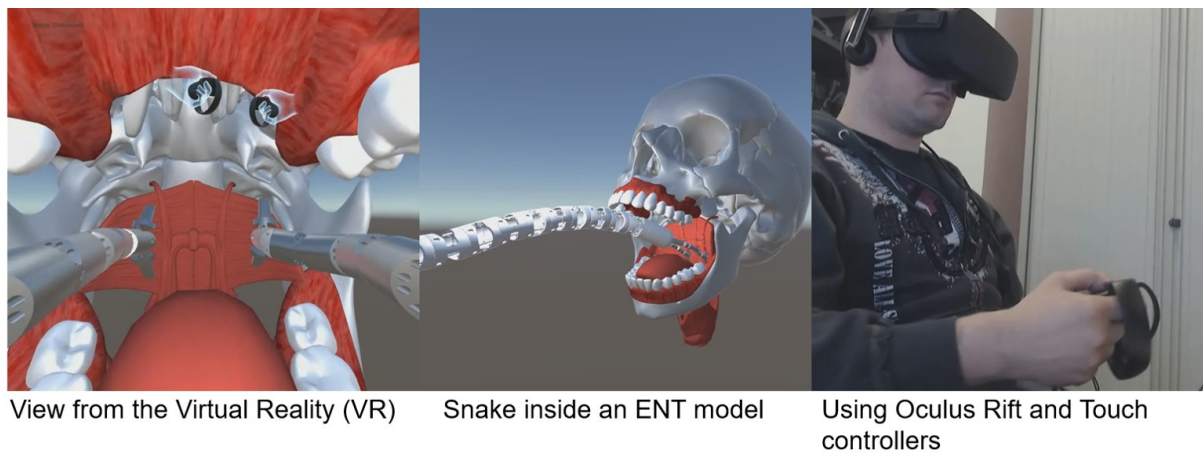


Figure 6.7: The VR-simulator using the Oculus Rift.

To perform the virtual tasks the operator can move the tip of the instruments or the *i²Snake* head by moving his hands using the Oculus hand controllers. If the B-button is held down the *i²Snake* head follows the movement of the hand controllers, or if X and A-buttons are pressed the left and right instruments follow the two hand controllers. Releasing these buttons acts as a clutch allowing the operator to adjust the position of

his hands. This way it is possible to move or rotate the *i²Snake* and the robotic arms further after the handles reached the end of their tracking area. This way the hands are mapped to the tip position of the instruments, which gives a feeling of the instruments being the hands of the user and a very natural feeling of control. The operator can close the gripper by pressing the grasping button on the Oculus handles.

Because the simulator was implemented in an early stage of the project, it uses three independent Damped Least Squares inverse kinematics to control the *i²Snake* and the two instruments. All other Unity visualisations like the inverse kinematics training or the ROS visualisation are based on the simulator.

6.5 Evaluation

In this section the capabilities of inverse kinematics and the control of the surgical instruments are evaluated. First, in Section 6.5.1 the performance of the learned inverse kinematics is compared to the one of the DLS implementation used in this thesis. Then, tests are performed to measure the benefits of backlash compensation in Section 6.5.2. Following to that, the positioning accuracy for the whole arm when following trajectories in task space is evaluated in Section 6.5.3. In Section 6.5.4 the repeatability of the distal-roll is shown.

6.5.1 Learned Inverse Kinematics

To validate the learned inverse kinematics implementation, a dataset of 10,000 random target points was generated. The targets consist of homogeneous matrices which are either reachable or non-reachable (the target-space was increased by 20% compared to the workspace of the instrument). During the evaluation, 3 metrics were saved: position error, orientation error, and computation time. The results of the reinforcement learning inverse kinematics (RL IK) algorithm were compared to the Damped Least-Squares Jacobian pseudo-inverse (DLS) algorithm implemented with EndoRob [5], which aims to minimize

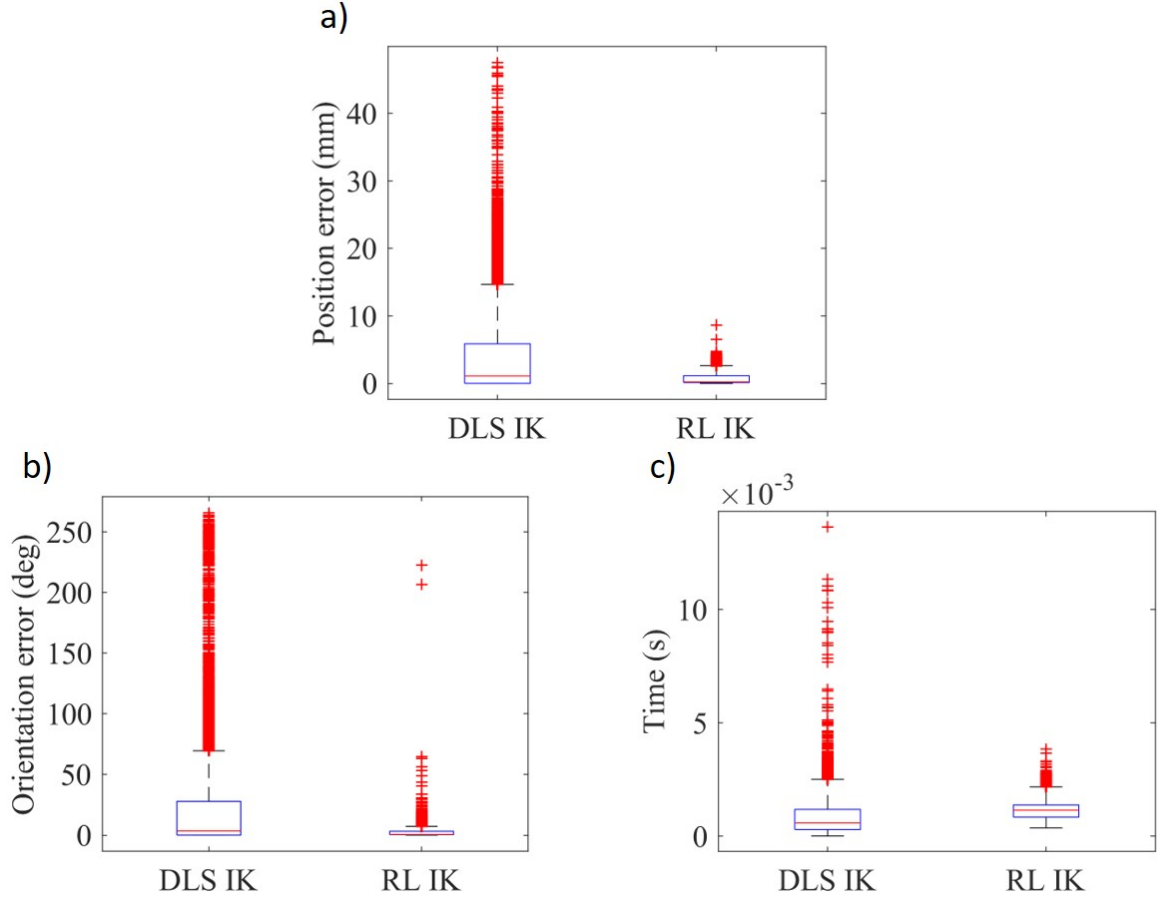


Figure 6.8: Statistical comparison between Damped Least-Squares Jacobian pseudo-inverse (DLS) and reinforcement learning inverse kinematics (RL IK) of the position error (a), orientation error (b), and time (c) as metrics using box plots. The red line of each dataset shows the average. (Source: [32])

the error vector $\vec{e}$ consisting of the position error and the orientation error. The solution to the damped least squares is equal to:

$$\dot{q} = J^T(JJ^T + \lambda^2\mathbb{I})^{-1}\vec{e} \quad (6.18)$$

with J the Jacobian matrix of the robot and λ a non-zero damping constant [158].

The results are shown in Figure 6.8. The main advantage of the developed RL IK approach compared to DLS is its ability to enforce joint limits which resulted in reduced position error by 3.63mm and orientation error by 21.70°. Regarding the computation time, RL IK is more consistent than DLS which needs more time to converge in complex cases or outside the workspace. The detailed results are shown in Table 6.1.

	Position Error [mm]	Orientation Error [°]	Time [s]
DLS	4.34	23.88	0.00086
RL IK	0.71	2.18	0.00114

Table 6.1: Comparison between DLS vs RL IK

6.5.2 Backlash Compensation

To evaluate the backlash compensation described in Section 6.2.3 two different measurements using the same input requests for the robot were made, one without compensation, the other using the backlash compensation. To obtain the measurements one joint of the arm was moved in a sinusoidal repeating motion. All other joints were relaxed so that they had no influence on the measurement. The moving joint had an orientation so that the arm was moving left and right.

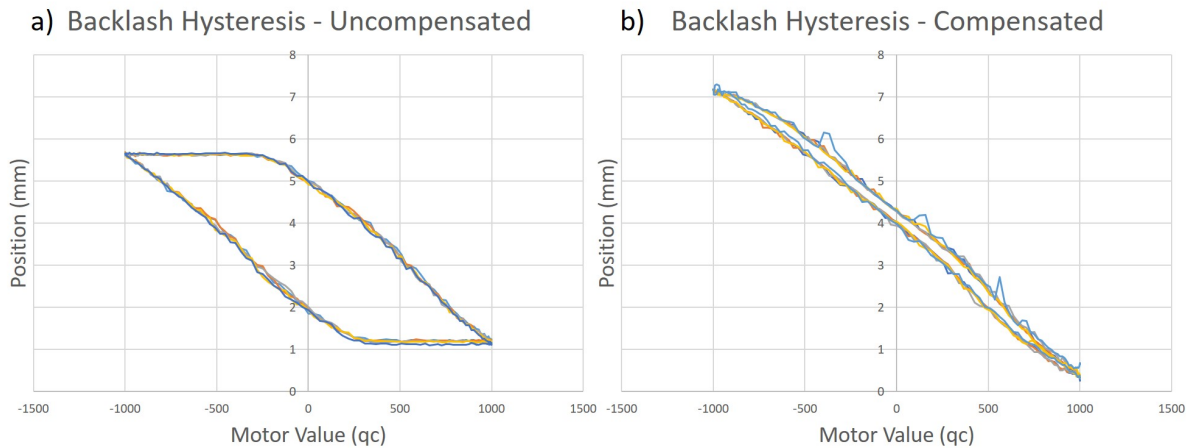


Figure 6.9: The result of the backlash compensation displayed as a backlash hysteresis: (a) the motion of the joint without backlash compensation, (b) with backlash compensation enabled (backlash compensation value 700qc).

In order to collect motion data of the instrument, the data collection was performed using an Aurora system control unit (Northern Digital Inc., Waterloo, Canada) and an electromagnetic (EM) sensor (Aurora Micro 6 DOF Sensor Tool) which allowed millimeter-scale accuracy of tracking resolution, an RMS error of 0.48mm and 100Hz recording frequency. The flexible instrument was equipped with one miniature EM sensor at the tip, another sensor was fixed at the testbed. The distance of the sensors was recorded in millimeters.

In Figure 6.9 (a) the uncompensated backlash is shown. The measurement was done over the motor values range of $-1000qc$ to $1000qc$. The unit quad counts (qc) is the internal unit used for positioning by the Maxon motor command library. The differently coloured lines correspond to different cycles in the backlash measurement motion. After this experiment, the backlash was measured and determined to be $700qc$.

The same measurement was done again, but this time using the backlash compensation to update the motor values. The resulting hysteresis is plotted in Figure 6.9 (b). The measurement is still running over the motor values range of $-1000qc$ to $1000qc$, with the compensation applied afterwards. It is obvious how much the backlash hysteresis is reduced. A small over-compensation can be seen in the corners. Although the same mechanical limits apply to the joints, in the same range of inputs the joint now bends to higher angles.

6.5.3 Positioning Accuracy

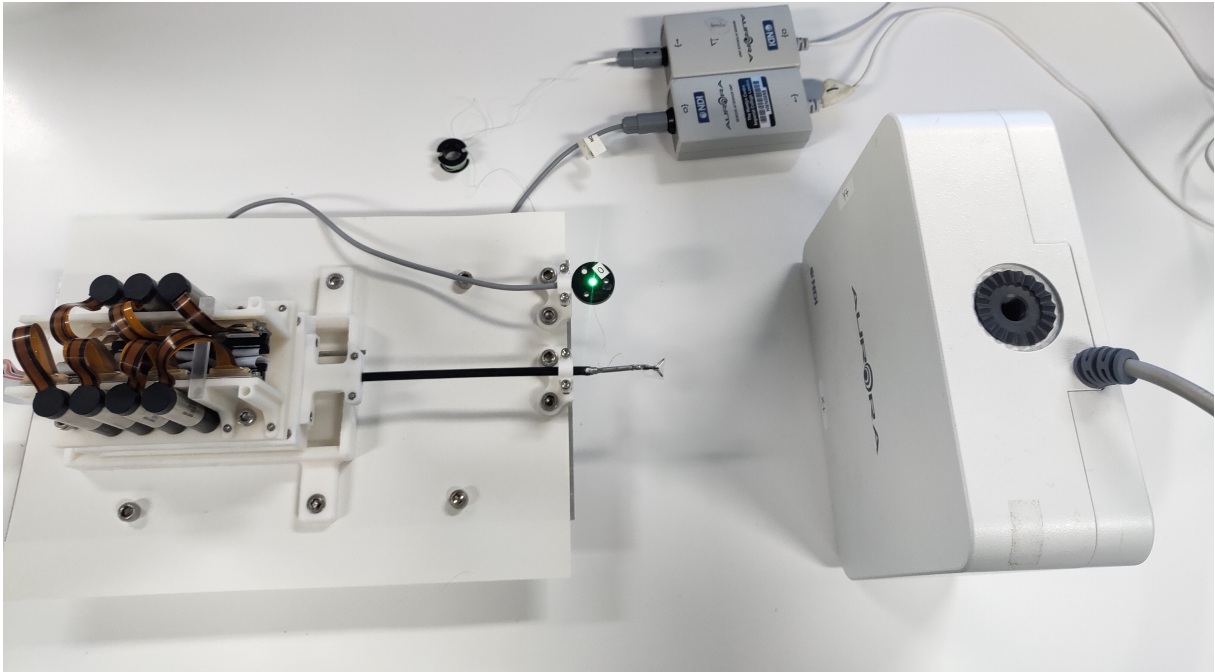


Figure 6.10: The positioning accuracy was measured using a high precision EM-Tracker.

To validate the accuracy of the compensation control method, the instrument is required to track a given end-effector trajectory. This was evaluated using the setup shown in

Figure 6.10. The recorded and predicted trajectories of the gripper under various compensations are shown in Figure 6.11. The joint variables q of the trajectory are obtained by using *ikine*-function of the Robotics Toolbox for MATLAB as the inverse kinematics solver. The red curves are the given trajectory of the gripper, while the blue dots are the recorded trajectories. In case 1, the instrument uses all the compensations, including decoupling, backlash, and central tendon tension. In cases 2, 3, and 4, the instrument uses all compensations except backlash, central tendon, and decoupling respectively. In case 5, only the compensation of decoupling is included. In these five cases, the trajectories of the gripper are measured using the EM sensor. They are following the same circular input trajectory, shown as the circle in the image, with the various compensations. The results are shown in Figures 6.11 and 6.12.

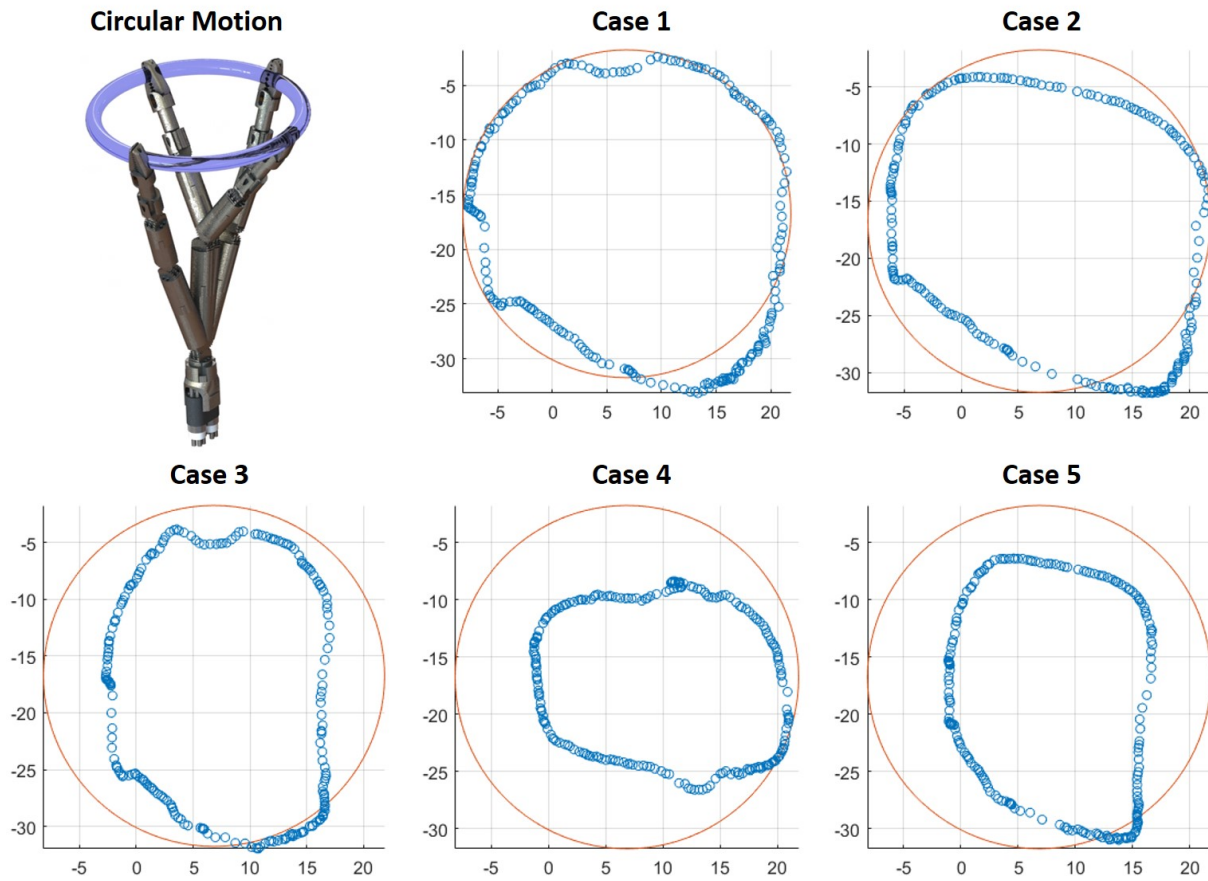


Figure 6.11: The resulting trajectories when doing a circular motion using different compensations. Case 1: All compensations; Case 2: Decoupling, central tendon; Case 3: Decoupling, backlash; Case 4: Backlash, central tendon; Case 5: Decoupling. (Source: [27])
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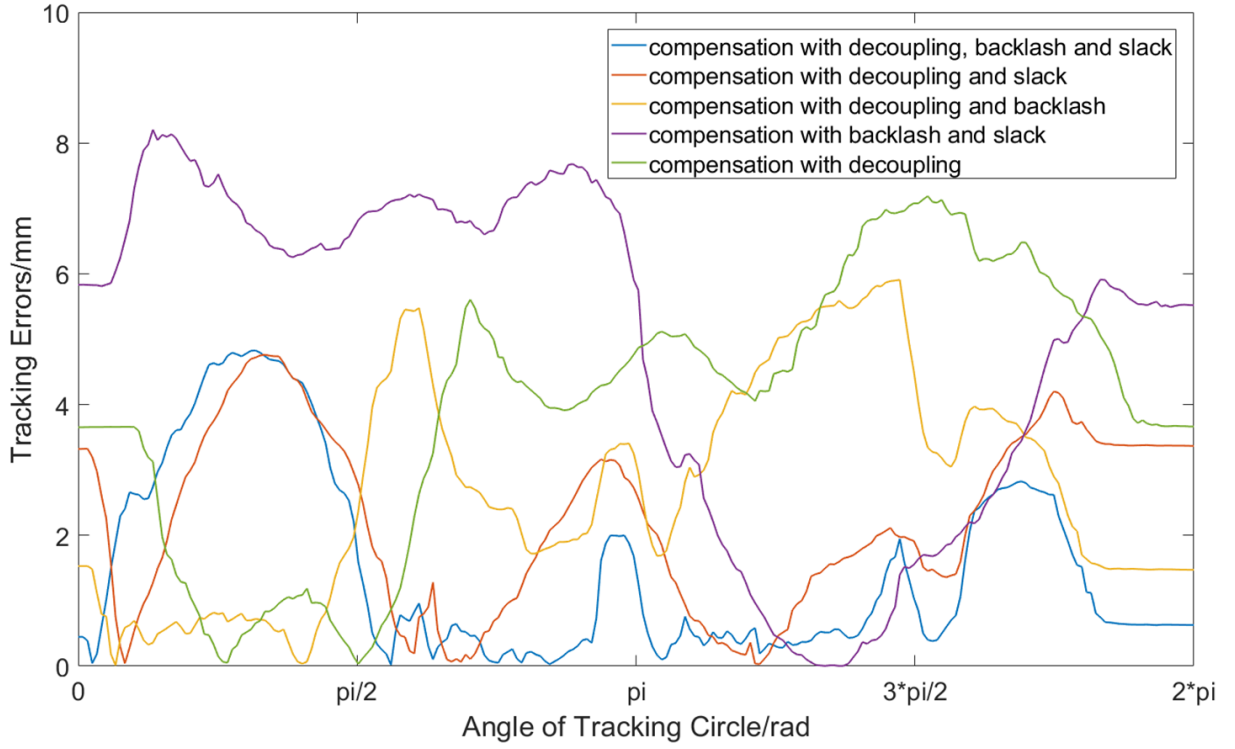


Figure 6.12: Positioning errors of the circular motion using five different combinations of compensations. (Source: [27]) © 2020 IEEE

The curves in Figure 6.12 show the positioning errors between the target trajectories and the recorded trajectories using different compensations. The curves of cases 1 to 5 are in blue for case 1, orange for case 2, yellow for case 3, purple for case 4, and green for case 5. In the figure it is obviously shown that the motion with all the compensations has the overall best result, and the average positioning error of case 1 is 1.49mm. The average positioning errors for the other cases are 2.23mm, 2.70mm, 4.88mm, and 3.00mm respectively. The maximum positioning errors for these five cases are 4.83mm, 4.76mm, 5.91mm, 8.20mm, and 7.19mm respectively. Thus, the positioning error is relatively small after applying all available compensations.

For case 1, it can be seen that the recorded trajectory matches reasonably well to the desired trajectory compared to the other cases. However, there is an important deviation when the instrument moved to the lower right position of the circle. It also appears in other cases as well, so it cannot be solved by any of these compensations. A reasonable explanation of this motion is that a gear had a small irregularity or a tendon was kinked.

Case 2 is the second best case. It has the decoupling compensation and the central tendon is pre-tensioned. This means that additional stiffness is given to the arm. It also shows the exceptional error in the lower right of the target circle. The missing backlash compensation only helps if one joint changes its moving direction. As the trajectory is given and all joint values are pre-calculated, the advantage of backlash compensation only appears in certain areas of the trajectory.

Case 3 has the backlash and decoupling compensation activated. As explained before the backlash compensation is important in certain areas and it can be seen that it has advantages compared to case 2 in areas where case 2 is weak. This means both compensations are additionally helpful.

Case 4 uses backlash compensation and tensions the central tendon and shows the system without joint decoupling. While comparing case 4 with case 5, which only uses decoupling, it is recognisable that decoupling is the most important compensation.

6.5.4 Repeatability

The repeatability of the circle motion was recorded with the EM sensor. The instrument tracked the same circular trajectory for five times. The result can be seen in Figure 6.13. The error is calculated as the average of the differences between the positions of each trial with the previous one:

$$error_{rep}(\alpha) = \frac{1}{n+1} \left(\sum_{i=1}^n |pos_i(\alpha) - pos_{i+1}(\alpha)| + |pos_n(\alpha) - pos_1(\alpha)| \right) \quad (6.19)$$

with α being the angle on the circle, $n = 5$ the number of trials, pos_i the position of the i th trial on data point α . The red area shows the maximal deviation.

The average repeatability error is 0.48mm. The maximum error occurs at the angle of $\pi/2$ and $3/2\pi$. This is where the moving direction of the second joint changes, which indicates a moving irregularity in the second joint. It shows that the circular motion is relatively stable.

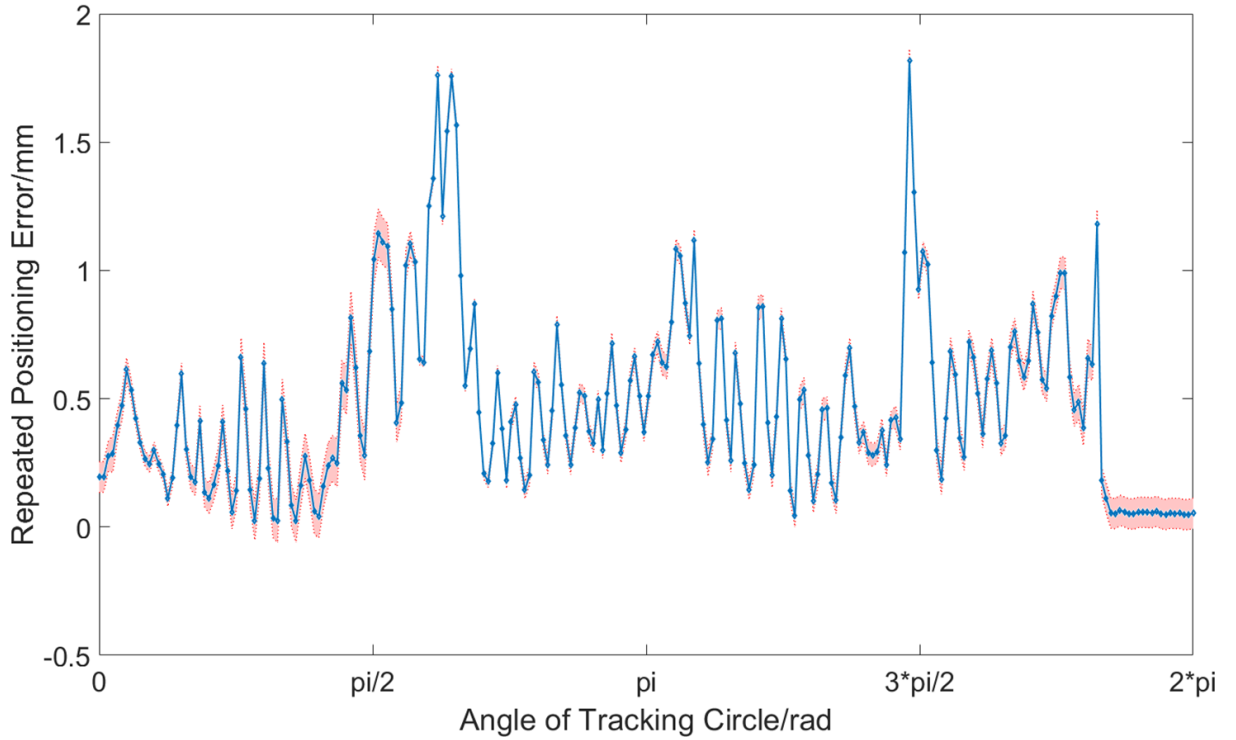


Figure 6.13: Repeatability error of the gripper with five trials. The graph represents the average difference between the positions of these trials, the red area shows the maximum deviation. (Source: [27]) © 2020 IEEE

6.6 Conclusion

This chapter showed the control system for moving the robotic instruments described in previous chapters. It consists of a learned inverse kinematics and a compensation for backlash, cross-talk and slacking. Everything was integrated in ROS and a visualisation was developed. The reinforcement learning of the inverse kinematics has proven to be overall more consistent than the commonly used damped least squares inverse kinematics solver and can handle joint limits intrinsically. In fact, joint limits reduce the search space which makes the training of the neural network more efficient. It is expected that further development and longer training will further increase the overall performance for real-time teleoperation during endoscopy. In future work the learning of inverse kinematics can include two arms simultaneously and therefore detect the collision of the two arms, so that the inverse kinematics itself avoids a collision between the arms. Further, an additional abstraction layer for giving only the resulting pose instead of the whole path could increase the speed enormously but adds a small additional error on top.

A static model of actuation compensation was developed with consideration for the coupling, tendon slack, and backlash effects. An experimental setup was created to verify the proposed model. The positioning accuracy was obtained by the tracking tasks using different compensations. During the tracking task the instrument needed to follow a predefined motion to measure the repeatability. The movements of the instrument showed to have a good repeatability. However, even though the compensation model helped to greatly increase the accuracy, there is still room for improvements to allow for more accurate movements.

Chapter 7

Conclusion

This thesis contributed significantly towards a snake-like robot with robotic instrument arms for gastrointestinal endoscopic surgery. Two types of instruments were successfully built. In the next section the contribution is described, followed by the next tasks and an outlook into the future further away.

7.1 Contribution of Thesis

The mechanical engineering contribution includes a distal-roll gripper. This gripper incorporates a rolling motion at the tip with a gripper and enables a stable in-place rolling motion. Beside this great advantage, the distal-roll was made necessary by the flexible shaft. The flexible shaft is introduced here because the instruments are deployed through the flexible body of the *i²Snake*. The flexible shaft consists of a flexible coil cable and is able to transmit the actuation force for the arm.

This thesis proposes two main joint types, a hinge joint and a gear joint. Both joint types are suitable for small scale surgical instrument arms with a diameter of $\varnothing 3\text{-}4\text{mm}$ with their own advantages and disadvantages. The main advantage of the hinge joint is the minimal length of a link which is by principle smaller than the minimal length of the gear joint. Slippage and strong non-linearities come as a price for the small minimal length.

To improve on these disadvantages, a new rolling gear joint was developed. Because of the gear, this joint increases the stability by preventing slip. It also reduces the non-linearities which are problematic with the hinge joint, because one of the properties of the rolling joint is that it maintains constant length while moving. This increases the controllability of the joint significantly. Further, the gear joint has a bigger bending range of now 82° . This makes the gear joint preferable if the necessary length is available.

In addition, the contribution includes two instruments decreasing the diameter of a rigid-link arm to 4mm and further to 3mm by using the new joints. The 4mm-instrument had 7 DOF and was built to be arm-like.

Because the complexity of the 3mm instrument needed to be reduced, the arm design was optimised using a genetic algorithm. The optimisation used a pre-recorded suturing and knot tying task and created instrument variants under strict mechanical constraints. Multiple optimal designs with different focuses were discussed and the importance of the prismatic joint and the distal-roll were discovered. During optimisation the algorithm demonstrated the importance of some key features: the wrist, the rolling motion and the prismatic joint. Although it is possible to compensate for missing features the resulting instrument arms get complex and become mechanically unfeasible. These features simplify the instrument design which everyone would natively expect, but if just one of them is missing the required degree of complexity is surprising.

A shape sensing possibility other than Fiber Bragg Grating using light intensity modulation was proposed. It measures the angle of a joint with an accuracy which is sufficient for shape sensing of a rigid-link robot. The shape sensing concept consists of one of these angle sensors in each joint. The results were promising although the complexity of the approach is a limitation. The number of fibers necessary for one joint needs to be reduced to two fibers per joint. This can be done by analysing the light pathways and optimising the fiber, e.g., by placing the emitting fiber on the right side of the joint and the collecting fiber on the left side.

In terms of control, this thesis contributes a novel learned inverse kinematics using Proximal Policy Optimisation reinforcement learning. It does not need pre-calculated or recorded datasets but it learns the association itself from a model. The learned association defines a way from any possible position to any target, reachable or unreachable. It demonstrated to be stable, able to work with redundancy, and to find solutions even for the most complex cases. The joint limits were always natively respected. Nevertheless, a safety layer is required to filter out possible dangerous cases.

Further, the thesis contributes a mathematical model for controlling instruments using the rolling gear joint. This mathematical model is used to compensate for backlash and joint coupling. It is shown that it reduces the joint coupling problem and the backlash hysteresis significantly and improves the control. Further, this model derives criteria for modelling the gear joint to reduce the non-linearities.

These contributions made articulated 4mm instruments for the *i²Snake* robot with a diameter of $\varnothing 16\text{mm}$ possible. This is the maximal diameter for a transoral endoscopic surgery robot. The 3mm instruments can be used in two different ways. First, they can be used to reduce the diameter of the *i²Snake* further, which leads to better breathing and thus less stress for the patient, or, second, they can be used to introduce better sheath for the instruments themselves.

7.2 Future Research

This thesis developed robotic, fully-actuated, rigid-links, tendon-driven instrument arms and integrates them into a system. As future work a full system evaluation would be helpful including the use of a master-positioning system such as the *i²Snake*. Improvement of the fabrication techniques and assembly as well as error testing including a user study followed by clinical trials would be necessary to turn this research into commercial products. An improvement of the rolling gear joint could reduce the non-linearities further, if it is possible to create a stable cut-out for the tendons which are passing out of the gear.

Regarding future research, there are several open areas with significant impact on robotic surgery. A closed-loop control for the instrument arms' positioning would greatly increase the surgical precision reachable with the arms and control. For closed-loop control shape sensing is inevitable. Currently not many possibilities are available for shape sensing in this size. Fiber Bragg Grating is an incredible technique and absolutely dominating the field. But it is also a complex technique which needs complex and expensive machines for production as well as for operation. Using microelectromechanical systems for shape sensing is a promising field. Although still expensive in production, the operational costs are neglectable. Cameras are another possibility for shape sensing.

Having closed-loop control and always knowing the state of the system, the research can develop in directions of autonomous helping tasks. This field is a huge research area and is currently already engaged. Learning from demonstration is a field with highly promising outcomes. Snakes with four or more instruments are easily imaginable, of which two arms are directly controlled by the operator, two arms are holding tissue, one is holding the camera and auto adjusting the view, and another one can automatically suck liquids or blot dry tissue. Also, multi-user operations are imaginable, in which two arms are controlled by each operator. One operator is the surgeon and the other one is an assistant.

Minimisation is always an important and also challenging task. This thesis offered instruments with decreased diameters of $\varnothing 4\text{mm}$ and $\varnothing 3\text{mm}$. An instrument of $\varnothing 2\text{mm}$ was already in the planning phase. But even smaller instruments with different techniques like actuated fibers are on the horizon, enabling bronchoscopy or endovascular surgery.

Although tendons are broadly represented in research and have huge advantages over other actuation technologies, other minimised actuators are important to research. The main drawback of tendons is the increasing complexity with the number of joints and the different backlash effects. Other actuators, such as shape memory alloys, magnetic actuators, or artificial muscles need more investigations.

Finally, the last research field derived from this thesis is virtual reality (VR). During the thesis a VR demo was developed, in which the whole operation area could be seen from the *i²Snake* head's point of view. It was recognisable that many people from different areas including surgeons had a high interest in that view. Although, technological limitations make such a device in a real scenario currently impossible, the advantages of such an immersive view is outstanding.

7.3 Conclusion

This thesis made a great contribution towards snake-like robotic endoscopic surgery. Two different flexible instrument prototypes for endoscopic surgery with a diameter of $\varnothing 4\text{mm}$ and $\varnothing 3\text{mm}$ have been presented. An improvement in the joint design as well as a stable in place roll was demonstrated. To combine the new approaches into a working solution, a system control was developed using reinforcement learning inverse kinematics and compensation for backlash and joint coupling.

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Appendix A

Best Design Award



Figure A.1: The *i²Snake* team won the Hamlyn Robotics Challenge 2017 best design award.

The *i²Snake* Robotic Platform for Endoscopic Surgery won in the Hamlyn Robotics Challenge 2017 the best design award. It finally led to the journal paper in the annals of Biomedical Engineering. The work was done in collaboration with G. Gras, K. Leibrandt, P. Wisanuvej, A. Schmitz, C. A. Seneci and G.-Z. Yang.

Appendix B

Best Demonstration Award

Schmitz A. and Berthet-Rayne P. won the best demonstration award for "The *i²Snake* VR simulator" in the Hamlyn Christmas Showcase 2017.



Figure B.1: Best demonstration award for the *i²Snake* VR simulator.

Appendix C

Authorisations

C.1 Authorisation to re-use Figure 1.1

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C.5 Authorisation to re-use Figure 2.5

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Towards a follow-the-leader control for a binary actuated hyper-redundant manipulator

Conference Proceedings:

2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)

Author: Svenja Tappe

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Date: Sept. 2015

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Highly articulated robotic probe for minimally invasive surgery



Conference Proceedings:

Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.

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Robotic Forceps Manipulator With a Novel Bending Mechanism

Author: Chiharu Ishii

Publication: Mechatronics, IEEE/ASME Transactions on

Publisher: IEEE

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A Single-Port Robotic System for Transanal Microsurgery—Design and Validation

Author: Jianzhong Shang

Publication: IEEE Robotics and Automation Letters

Publisher: IEEE

Date: July 2017

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Triaxial Catheter-Tip Force Sensor for MRI-Guided Cardiac Procedures

Author: Panagiotis Polygerinos

Publication: Mechatronics, IEEE/ASME Transactions on

Publisher: IEEE

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FBG-based shape sensing tubes for continuum robots

Conference Proceedings:

2014 IEEE International Conference on Robotics and Automation (ICRA)

Author: Seok Chang Ryu; Pierre E. Dupont

Publisher: IEEE

Date: 31 May-7 June 2014

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Electromagnetic Positioning for Tip Tracking and Shape Sensing of Flexible Robots

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Publication: IEEE Sensors Journal

Publisher: IEEE

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A novel mechatronic tool for computer-assisted arthroscopy

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Publication: Information Technology in Biomedicine, IEEE Transactions on

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Snake robot shape sensing using micro-inertial sensors

Conference Proceedings:

2013 IEEE/RSJ International Conference on Intelligent Robots and Systems

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Development of artificial hand gripper by using flex force sensor

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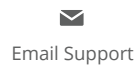
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Effective Manipulation in Confined Spaces of Highly Articulated Robotic Instruments for Single Access Surgery

Author: Konrad Leibbrandt

Publication: IEEE Robotics and Automation Letters

Publisher: IEEE

Date: July 2017

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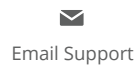
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Efficient Exploratory Learning of Inverse Kinematics on a Bionic Elephant Trunk

Author: Matthias Rolf

Publication: Neural Networks and Learning Systems, IEEE Transactions on

Publisher: IEEE

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