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DESIGN OF A MODULAR SOFT CONTINUUM ROBOTIC ARM

BY

THOMAS SCHWARZ

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

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ABSTRACT

In this thesis, a modular design of a soft continuum robotic arm is developed. This design enables the connection of an arbitrary number of identical modules in order to build a snake-like robot in a plug-and-play fashion. After introducing the purpose and motivation of this research, the necessary basics for this project are presented, followed by a review of existing soft continuum robots in the state of the art. The main part of this work starts with presenting the design of the required 3D manufactured parts as well as the fabrication of the soft deformable body of the robot. With the first successfully produced soft cylinder, a static experiment is presented. In order to find a fitting Finite Element Method (FEM) model for the silicone cylinder, different types of simulations are demonstrated and compared to the experimental results. After completion of the statics part, various programs are written to control the motors. By tracking the location of the robot's tip with the help of an electromagnetic tracking system, the repeatability of the robot is determined in different bending positions. Results of those experiments are presented and discussed. Finally, a conclusion and an outlook for further research in the future is given.

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1 Introduction

In order to mimic the locomotion and manipulation mechanism of soft biological organisms, soft robots have attracted increasingly more research interest in the last years. These robots “contain no (or few) rigid internal structural elements and are loosely modeled on animals with non-rigid body parts” [1]. Primarily they are made of deformable elastomeric material, which undergoes large continuous deformation when subject to internal actuator or external environmental forces. Thus, they are able to conform to the environment through adapting their shape to geometrically complex and variable environmental structures [2].

For articulation and locomotion of soft robots, various actuation strategies have been used including flexible fluidic actuators [3,4], tendon-driven [5], electro-active polymers [6] or shape memory alloys [7]. In the tendon-driven actuation, tendons inside the robotic arm are pulled by DC motors to generate curvature. This approach offers several advantages. Since the use of tendon-driven actuation has already been extensively proven in traditional hard continuum robotic arms, the mechanics can be used, modified and extended to soft tendon-driven robotic arms. Additionally, due to the softness and light-weight nature of soft robots, miniature motors and small batteries are sufficient for actuation.

In this work, a modular design for a tendon-driven soft robotic arm shall be developed, that enables connection to an arbitrary number of identical, independently working modules which combine with each other to build a snake-like soft robot. Potential future applications using such snake robots are presented in the following chapter.

2 Motivation

The advantages of soft robots compared to hard robots is for instance a safe interaction with humans, that makes them better suited for open-ended tasks in uncertain environments [8,9]. In the future, this can also be of interest in the field of medicine technology, demonstrated in figure 1.

Figure 1: Path planning for reaching a cancer in the small intestine from the oral cavity [10]

Other possible future applications of snake-like flexible robots are shown in figure 2.

(a) Fire fighting inside a road tunnel

(b) Search and rescue after an earthquake

(c) Inspection and maintenance inside a process plant

Figure 2: Future applications of snake-like robots [11]

Once a snake-like robot consisting of multiple identical modules is developed, there are no limitations for more complicated biological inspired robots, such as an octopus-like swimming robot or a walking robot (figure 3).

Octopus-like swimming robots

Walking robots

Figure 3: Applications with multiple snake-like robots

Within this research, to build a foundation for all these applications, a modular design for a snake-like robot shall be developed. Figure 4 shows a schematic demonstration of the use of a modular designed snake robot.

Multi-segment manipulator for reaching in cluttered environments

Figure 4: Snake-like manipulator for exploring cluttered environment

3 Basics

In this chapter, the necessary basics for the understanding of this work will be presented and briefly explained. These basics include the theoretical background for the technical components that are used within this thesis.

3.1 DC-Motors

Among the different types of DC-motors, the most common one is a brushed DC-motor.

Figure 5 demonstrates a schematic setup of a brushed permanent DC-motor.

Figure 5: Permanent magnet DC motor [12]

Once current is passing through the rotor windings, the magnetic field forces the rotor to rotate. The contact of the brush with the high speed rotor leads to an erosion of the brush over time. If the functionality is required over many years, continuous maintenance is inevitable. The efficiency of the motor is reduced by the fact that the

commutator has to be rotated along with the rotor. The advantages of those motors, however, are a cheap production, low complexity and a simple control [12].

3.2 Pulse Width Modulation (PWM)

While analog signals can have any voltage between low and high, digital signals can only be either low or high, in which the fixed high value depends on the electrical circuit. Digital signals cannot usually be varied freely. However, a technique called PWM is able to achieve a free variation of voltage. By repeatedly pulsing digital high and low signals, an average voltage between high and low can be produced, which is equivalent to an analog signal. This average voltage can be controlled by the frequency of high signal pulses [13]. The percentage of the time of a high signal compared to the overall time is defined as duty cycle. Figure 6 demonstrates the effect of different PWM frequencies causing different duty cycles.

Figure 6: PWM [13]

In a duty cycle of 25%, the signal would be high for 25% of the time and low for 75% of the time as shown in figure 7.

Figure 7: Duty Cycle of 25% [13]

The duty cycle can be determined with the following equation

$$Duty\ Cycle = \frac{T_{on}}{T_{on} + T_{off}} * 100\ \% \quad (3.1)$$

3.3 Hall Effect Sensor

In the 1870's Edwin Hall discovered that a magnetic field is able to generate a measurable voltage with the underlying principle of the Lorentz force. A Hall Effect Sensor makes use of this effect and basically consists of rectangular p-type semiconductor material passing a continuous current through itself. When a magnetic field is applied perpendicular to the flow of the current, a potential difference is generated and the output voltage is called Hall voltage.

Figure 8 demonstrates the principle of a Hall effect sensor [14].

Figure 8: Occurrence of the Hall effect [14]

The Hall voltage V_H can be determined through the following equation

$$V_H = R_H * (I/t * B) \quad (3.2)$$

Where:

- V_H is the Hall Voltage in volts,
- R_H is the Hall Effect co-efficient,
- I is the current flow through the sensor in amps,
- t is the thickness of the sensor in mm,
- B is the Magnetic Flux density in Teslas.

Hall Effect Sensors can be used in various applications where the presence or absence of a magnetic field needs to be detected. One important application is the sideways detection of rotational magnets to count the number of revolutions or the speed of rotation motors. This application requires the magnet to move sideways across the face of the Hall effect sensor (figure 9). When the magnetic field passes the sensor's zero field line, a linear output voltage can be measured.

Figure 9: Sideways detection of magnets [14]

The use of two Hall Effect Sensors in an angular displacement of 90 degrees allows directional movement detection, which is able to serve as a rotary encoder. Figure 10 describes the detection of the direction through two Hall Effect Sensors.

Figure 10: Two Hall Effect Sensors used as rotary encoder [14]

3.4 H-Bridge

To control the direction of a rotary motor, it is common to use an H-Bridge, which is shown in the figure 11.

Figure 11: H-Bridge for motor direction control [12]

Depending on which two of the four switches are closing the electric circuit, the motor is either turning clockwise or counter clockwise. The Bridge only allows for switching either both S_0 and S_3 or S_2 and S_1 at the same time [12].

3.5 Micro Controller Unit (MCU)

Three different types of pins are provided by the MCU:

- Digital IO pins,
- PWM output pins,
- Analog input pins.

Digital IO pins can be defined to be either input or output pins. When an input pin receives a voltage that exceeds a certain threshold, a HIGH signal is read by the MCU.

If the input voltage is lower than this critical value, the MCU reads a LOW value.

Digital output pins can be set either to HIGH (5V) or LOW (0V).

For the programming of the MCU, the Arduino Integrated Development Environment (IDE) can be used. This software uses a programming language similar to C++. A typical Arduino program contains a setup function and a loop function, in which the setup function is executed once after the start of the program. After that, the loop function is executed repeatedly [15].

3.6 3D Printing

“The technologies that build 3D objects by adding layer-upon-layer of material” is called Additive Manufacturing [16]. Other common designations are Rapid Prototyping or 3D printing. In general, for 3D printing a computer, 3D modeling software, machine equipment and layering material is used. With the use of Computer Aided Design (CAD), a three dimensional object can be designed [17]. In order to enable the 3D printer to print the object, the CAD file needs to be saved as an STereoLithography (STL) file. Through this format, the surfaces of the solid model are approximated with triangles. Figure 12 demonstrates how the surface of a simple object like a box can be approximated in different levels of complexity, where the first approximation is the easiest way to describe the model and the second one is an example for a high degree of complexity.

Figure 12: Surface approximation in STL files [18]

The object is then created in an additive process by “laying down successive layers of material” until the completion of the object, whereby each layer can be considered as a “thinly-sliced horizontal cross section of the eventual object” [18].

4 State of the Art

The upper category of soft robots is called continuum robots and belongs to the group of hyper redundant robots, as shown in figure 13.

Figure 13: Classification of continuum and soft robots [19]

These continuum robots have multiple degrees of freedom (DOF) and are called hyper redundant, since they are able to reach any point in their working field through a variety of different moving actions [19]. In the following, continuum robots are described in section 4.1 and an introduction to soft robots is provided in section 4.2.

4.1 Continuum Robots

The distinctive mark of continuum robots is their movement by deforming parts.

These types of robots can reach a high number of DOF. However, they do not necessarily have to be made of soft material. For instance, researchers have developed a trunk-like manipulator, which primarily employs rigid materials as shown in figure 14. The result is a flexibility that resembles biological structures [10].

Figure 14: Elephant trunk inspired continuum robot [10]

The upcoming section will focus on snake shape robots. A comparison of those robots is given using the following criteria [20, 21, 22, 23]:

- Discrete or continuous
- Number of sections
- DoF per section
- Actuators per section
- Actuation
- Actuator spacing
- Extensibility.

These criteria will be described in more detail in the following sections.

Discrete and Continuous Robots

While discrete robots move by having purely rotating or translating parts, continuous robots move by deforming parts. However, discrete robots do not necessarily have to be non-redundant. Many industrial robots possess a high number of small joints. Each joint adds additional degrees of freedom, which makes them highly redundant and they can approximately be considered as continuum robots as shown in figure 13 [20].

Number of Sections

More than one section adds redundancy to the robot, which increases its number of degrees of freedom. If these additional DOF are not linearly independent, redundancy would be added to the whole robot. For most robots, the number of sections is limited due to the fact that the sections in most of the cases are still actuated from the base of

the robot. That means, tendons and tubes for the actuation of later sections are passing through the first sections [20].

DOF per Section

The complexity of a robot's movement is represented by the degrees of freedom. To reach any point in a 3-dimensional working space from any direction, six degrees of freedom are sufficient. However, the robot would be restricted in the path it can take to reach the point. In order to avoid restrictions through the environment, a higher number of DOF is necessary, which could be reached by adding more sections [20].

Actuators per section

The number of DOF is strongly dependent on the number of actuators per section. For instance, only two actuators would give the robot only two linearly independent degrees of freedom. More than three actuators could achieve a bidirectional behavior of the robot. Bi-Directionality in many other robots is achieved by bi-directional actuators or by having springs pulling the robot in the other direction [20].

Actuation

The most common ways of actuation are the use of tendons and the use of hydraulic as well as pneumatic pumps. Table 1 shall show the main differences between tendons and pumps [20].

Table 1: Comparison of tendons and pumps acting as actuation

Tendons	Hydraulic/Pneumatic Pumps
Low power consumption	High power consumption
Lightweight motors sufficient	Heavy pumps required
Fast actuation	Slow actuation
Low forces	High forces
Simple closed form kinematics	Complicated kinematic model

This table indicates that a tendon-driven actuation is perfectly suitable for mobile applications, since the robots are possibly able to carry its own actuation through the lightweight motors.

Actuator spacing

The location of the actuators is described by the actuator spacing. The actuators of snake robots are usually located in symmetry around the center. The number of actuators influences the actuator spacing [20].

Extensibility

By the extensibility it is indicated if a robot purely bends or if lengthening and compression of the body is considered. The number of linearly independent degrees of freedom of a section for an inextensible robot is limited to two, while an extensible robot can have up to three linearly independent DOF [20].

4.2 Soft Robots

Instead of having rigid arms and joints like most industrial robots, soft robots consist of soft material such as silicone rubber. Pneumatic or hydraulic actuation is widely popular for soft robots since the pressure chambers can easily be embedded in the body of the robot [24-30]. Figure 15 shows various examples, of how the structure of soft robots was inspired by nature.

Figure 15: Examples of hydroskeletons and muscular hydrostats: (a) tube feet in starfish, (b) octopus arms, (c) colonial anemone, (d) mammalian tongue, (e) squid, (f) elephant trunk, (g) echinoid, (h) *Illex illecebrosus*, (i) inchworm, and (j) snail feet [10].

5 Design & Fabrication

In this chapter, all relevant steps of the manufacturing process of the robotic arm are explained. Before the fabrication of the first arm segment, a variety of tests are made with an existing prototype arm, which is the result of a previous master thesis.

5.1 Initial Situation

In a previous work, one arm segment has been produced, which can be actuated through three cables. To calculate the bending of the arm, three rubber stretch sensors have been used. Both the cables and the stretch sensors are shown in figure 16, which demonstrates the previous developed arm.

Figure 16: Schematic of the previous manufactured arm segment. (blue = silicone rubber; black = stretch sensors; yellow = cables; grey = plastic tubes)

These sensors were tested regarding their suitability to determine the curvature of the arm. As well as the cables, the sensors were arranged in a 120° angle over the cross section as shown in figure 17.

Figure 17: Cross section of the previous arm

However, the experimental results showed a significant deviation of their output over time. As a consequence, it was decided to remove these stretch sensors for future position control experiments. An additional decision was to use four instead of three cables to provide the arm a higher degree of actuation flexibility. The new cross section is shown in figure 18.

**Figure 18: Cross section of the
arm to be developed**

As shown in the figure, the new design shall include 4 cables (blue dots), that are distributed in an angle of 90° . The stretch sensors are removed but the tubes (blue circles) to guide the cables are preserved.

5.2 Choice of Motor

The choice of the motor should act as a basis for setting the geometrical parameters of the arm. Since the motors are the fundamental components that have to fulfill certain requirements, they cannot be varied in their size and thus set the dimensions for the other components that can be freely changed. Challenging for the motor choice is to find a motor that is smaller than the required diameter, simultaneously strong enough for all necessary bending movements and also precise to control.

Three types of motors are shortlisted for this project:

- a DC motor with hall effect sensor,
- a stepper motor
- and a servo motor.

As mentioned in the basics section, a DC motor is easy to use but the challenge consists in its accurate control. An added Hall Effect Sensor is able to precisely count the rotations of the motor shaft with a certain amount of programming. However, DC motors with added Hall Effect Sensors are only available in very small sizes, that are not able to provide the required tension of 10 N.

Servo motors can be controlled very accurately but only in a restricted rotation of $< 360^\circ$. There are also continuous servos, but control experiments with these servos showed a smaller accuracy. Another disadvantage is that most servos have a square or angular shape, which is not best fitted for the design of a round robotic arm.

A stepper motor is available in a round shape, precisely controllable and can effort the required tension. Thus, a stepper motor is chosen for this project and its dimension acts as a basis for the design of the motor holder.

With the force of the motor and the geometrical parameters of the arm to be developed, the curvature of the arm is predicted with the help of a MATLAB program. Figure 19 shows the predicted curvature of the arm for a motor force of 7 N.

Figure 19: Prediction of the curvature of the arm at 7 N

5.3 Mold

Various models for the mold of the silicone rubber arm segment are constructed with CAD, and then manufactured through 3D printing. The first model is shown in figure 20.

Figure 20: First mold version – vertical alignment (left: closed, right: open)

The first soft robotic arm fabricated with the help of this vertical mold shows some disadvantages of the corresponding mold design. Through the vertical alignment, the length of the arm varies by the amount of infill of the silicone rubber. If the arm is too long, a cut at the desired length is necessary. However, this procedure turns out to be highly challenging when aiming to cut it off straight. A horizontally aligned mold could avoid these weaknesses and challenges, since the length always remains the same. On top of that, if the infill amount is too high, cutting is a lot easier since the gap for the

excess silicone rubber can be designed much smaller. Two different designs of a horizontal mold are shown in the following figures 21 and 22.

Figure 21: First version of a horizontal aligned mold (top: open, bottom: closed)

The first version of the horizontal mold is a modification of the vertical mold. The liquid silicone rubber mixture can be poured into the mold through a funnel. This funnel has further important functions: After the mold is fully filled with silicone rubber, air bubbles in the liquid have to be removed in a vacuum chamber. During this process, the liquid level rises noticeably. Therefore, it is necessary to provide additional room for the liquid to rise in order not to lose volume in the arm.

To simplify the assembly and fabrication process, a second version of a horizontal aligned mold consisting of only two identical parts is designed (figure 22). This simplifies the printing of the mold and also speeds up the preparation process for the arm fabrication, since the mold contains fewer interfaces between the parts that need to be isolated.

Figure 22: Second version of a horizontal aligned mold (left: open, right: closed)

For the fabrication of the soft arm, the two horizontal aligned molds turn out to be more convenient than the vertical mold in order to obtain soft cylinders with the same length and flat front sides. Thus, they are used for this work. Fabrication results of all the molds presented are shown in the subchapter 5.6.

5.4 Motor Holder

In order to create a snake-like design, the motor holder should fulfill all the following requirements:

- It should have the same diameter as the silicone cylinder to be produced.
- It has to take up an adequate motor that is not able to move after installation and provide enough space for it to rotate freely inside.
- The connector between the soft cylinder and the motor holder can be fixed and removed without using glue to guarantee a plug-and-play design.
- The tendon ends can get through the outer wall of the holder to fix and release them simply from outside without opening the holder.
- In order to connect two modules with each other, the design should include a male and a female version of the motor holder.

The resulting motor holder, that aims to fulfill all those requirements, is shown in figure 23.

Figure 23: Motor holder

5.5 Connector

The main aspects about the design of the connector are listed below.

- A permanent fastening of the silicone cylinder is required. For this purpose, the use of glue is reasonable.
- Holes for the tendons at the exact location of the tubes have to be provided.
- Fixing and Removing from the motor holder should match the plug-and-play fashion, which excludes the use of glue.

The result of the connector design is shown in figure 24. One connector is fixed to each one side of the silicone cylinder.

Figure 24: Connector

5.6 Fabrication

The silicone rubber type used for this work is Ecoflex 00-30. After mixing the two components, the mixture is poured into the previously shown molds and then placed in a vacuum chamber to extract enclosed air in it. After that, a curing process of at least four hours is necessary. Better results are obtained if the curing takes place outside the vacuum chamber. The plastic tubes, that are needed to guide the tendons through the silicone arm and to protect the silicone from getting cut by the tendons, are placed, stretched and fixed in the mold before the mixture is poured in. The stretching aims to guarantee a straight alignment of the tubes. In order to obtain a solid soft robotic arm, which is free of air bubbles, the following criteria have to be considered:

- The overall time in the vacuum chamber should not exceed a certain limit, since air bubbles that are trying to get out of the liquid get stuck during the curing process. A result of not fulfilling this criteria is shown in figure 25.

Figure 25: Result after a whole night in the vacuum chamber

- The silicone rubber has to be filled in the funnel from a certain height. The higher it is poured from, the thinner is the falling mixture, which leads to less bubbles in the mixture reaching the funnel.
- The mold has to be repeatedly put in a vacuum chamber for a few minutes.
- Each time the mold is taken out of the chamber, it has to be shaken to ensure a homogenous distribution of the liquid in the mold. Permanent slight vibration on a vibration table would deliver best results.

If the mold is only put once in the vacuum chamber for a certain time and without shaking it in between, a demonstration of the result is shown in figure 26.

Figure 26: Unsuccessful result of fabrication through air pockets in the arm

By observing all the previously mentioned steps, a successful fabrication can be achieved. Following this procedure, three silicone cylinders are produced. Figure 27 shows the result of a successful fabricated silicone arm.

Figure 27: Successful Fabrication of a robotic arm

5.7 Assembled Modules

After designing and manufacturing all the necessary components, three modules are assembled. Figure 28 shows two connected modules.

Figure 28: Two connected modules

Figure 29 demonstrates a bending motion of two connected modules.

Figure 29: Bending motion of two connected modules

6 Statics Simulations

In order to determine the bending behavior of the fabricated silicone cylinder, a static experiment is made, in which different forces are applied to one tendon and the displacement of the tip of the cylinder is measured by an electromagnetic tracking system (EMS). The experimental results are then compared to different simulation models. At the end of this chapter, a conclusion about the models is established.

6.1 Static Experiment

The experimental setup for the static experiment is shown in figure 30.

Figure 30: Setup for measurement of the force related displacement

The displacements in Y- and Z-direction are shown in the following plot.

Figure 31: Y- and Z-displacement of the tip of the arm over force

As seen in the plot, for small forces from 3 to 10 N, the displacement in the Y-direction is greater than in the Z-direction. At a force of around 14 N, the displacement is identical for both directions and for higher forces the plot allows for the assumption of higher displacement values for the Z-direction.

These experimental results define the displacements that have to be approximated by simulation models in the following.

6.2 Simulation Models

To create a realistic model for further displacement- and stress studies, three Finite Element Method (FEM) models with the following material properties are developed.

Table 2: Material properties for FEM models

	Silicone Rubber	Medical Tubing	ABS
Young's Modulus (MPa)	0.04	6.89	2600
Poisson's Ratio	0.48	0.4	0.33

Since the force changes its effective direction through deformation and displacement of the silicone cylinder, different load types are used and compared with the experimental values to determine the most accurate modeling type. Thus, the three following load types are used, which are shown and discussed in the upcoming subchapters.

Table 3: Different load types

6.3 Concentrated Load

In model 1, a concentrated force is applied in the center of the tube where the tendon is pulled. The resulting displacements in the Y- and Z-direction are demonstrated below.

Figure 32: Deformed mesh and resulting displacements

In the Y-direction, the highest displacement is around 27 mm at the tip, whereas in the Z-direction the same region where the EM tracking sensor is located only shows a displacement of around 18 mm.

The following plots compare the simulation values with the experimental results both in the Y- and Z-direction.

Figure 33: Plot of simulation and experimental results in Y-direction

For the smallest applied force of 3N, the simulation shows smaller displacements than measured in the experiment. For a force of around 4N, the displacement in the simulation matches the real results. For higher forces, the simulation results are drifting apart from the measured values. In the Z-direction, the slope of the simulation curve behaves differently, as shown in the following figure. In this dimension, all simulation values are smaller than the experimental results but follow the experimental trend.

Figure 34: Plot of simulation and experimental results in Z-direction

6.4 Moment

Instead of a concentrated load, a moment around a reference point in the center of the cylinder tip is applied. The contour plots are displayed in figure 35.

Figure 35: Deformed mesh and resulting displacements

The contour plots look similar to the previous ones for the concentrated force. For the Z-direction, however, the middle zone of the cylinder is green instead of yellow, which indicates a higher compression of the whole arm. The maximum Y-displacement is around 38 mm while in Z a maximum of 87 mm is reached. This value shows up at the compressed side (blue) as well as at the strained side (red) of the arm.

The plots for both dimensions in comparison with the experimental results are demonstrated in figure 36.

Figure 36: Plot of simulation (moment) and experimental results in Y-direction

Compared to model 1, the highest Y-displacement is around 10 mm smaller. The trend line of the simulation remains qualitatively the same.

A clear difference is recognizable in Z (figure 37). Instead of following the trend line of the experiment, the simulation results in much smaller displacement values (< 10 mm).

Figure 37: Plot of simulation (moment) and experimental results in Z-direction

6.5 Moment + Concentrated Load

The last load type is a combination of the first two models in form of a moment and an additional concentrated force applied on the previously shown reference point in the center of the upper side of the cylinder. This method should compensate the weakened compression of model 2. The simulation results in the following contour plots.

Figure 38: Deformed mesh and resulting displacements

In the Y-direction, the tip is displaced 27 mm whereas the maximum Z-displacement is almost 17 mm. The course of the displacement in the Y-direction (figure 39) and in the Z-direction (figure 40) is displayed in the following plots.

Figure 39: Simulation (moment + concentrated force) and experimental results in Y-direction

The simulation results in the Y- as well as in the Z-direction look very similar to the results of model 1. In the Y-direction, the values are drifting apart from the experimental results and in the Z-direction they follow the same trend line. This leads to the assumption that the concentrated force has a significantly higher influence on the simulation results than the moment.

Figure 40: Simulation (moment + concentrated force) and experimental results in Y-direction

6.6 Variance of Material Properties

Since the simulation results of model 1 and 3 in the Z-direction follow the same trend line as the experimental results, it is assumed that the load type is appropriate and only the material properties of the silicone cylinder have to be adjusted in order to match the simulation results with the real values. Increasing the Young's Modulus from 40 to 105 kilopascal (kPa) results in the following plot (figure 41).

Figure 41: Matching plot in Z-direction after varied material properties

In the range of 5N to 12N, the simulation matches the experimental results very accurately. Deviations only occur for the smallest applied force of 3N and the highest force of 15N. This leads to the conclusion that the model is applicable for forces from 5N to 12N, which is the range that the motors are working in for the actuation of the

arm. For very small forces and those greater than 12N, this model is not accurate anymore.

6.7 Errors and Conclusion of Simulations

One main reason for the mismatch of the simulation and the experiment is that in the real model the tubes can freely slide inside the cylinder, whereas in the simulation they are fixed. This leads to further bending in the Y-direction and smaller compression in the Z-direction. When trying to adjust the model by varying the material properties, it is possible to match the experimental results in the Z-direction since the same trend line is followed. In the Y-direction, however, the curve is hard to fit to the experiments due to its divergent slope. Another possible error is that the simulations have to be run with a linear elastic material behavior since every try to run it as a non-linear material gets aborted after some hours, independently of the adjusted increment size. However, in reality the material shows non-linear and hyper elastic characteristics. Thus, a non-linear simulation is suspected to deliver more appropriate results in both dimensions. For the considered force range, however, the adjusted model with varied material properties is capable of imitating the real bending behavior very accurately in the Z-direction and can be used for future simulations in this dimension. For more precise results in the Y-direction, further tries in running non-linear simulations can be done as part of a future work.

7 Kinematics

This chapter explains the mathematical procedure to determine the theoretical position of the tip of the arm. These calculations can later be used to compare the theoretical positions with the robot's actual measured position and to evaluate the accuracy of the robot. After that, dynamic measurements of the end effector coordinates are presented.

7.1 Operation Spaces & Coordinate Transformations

Following the concept of [19], a mathematical model for a soft continuum manipulator can be described by dividing it into four subspaces: actuator space, joint space, configuration space and task space. For one module of the soft robotic arm, these subspaces and the associated parameters are shown in figure 42.

Figure 42: Operation spaces of the soft robotic arm

The actuator space contains the variables motor torque and shaft angular displacement/velocity. The joint space variables include the length and the tension of the tendons. Assuming constant curvature, the configuration space is parameterized by the denoting robot length, the curvature and the angle of the manipulator plane. In the

task space, the position and orientation of the end effector is described. For various soft continuum manipulators, the actuator space and joint space are robot-specific, whereas the configuration space and task space are robot-independent.

Widely used for kinematic modeling of traditional hard continuum robots is the piecewise constant curvature approximation [20]. For this approximation, the following conditions have to be fulfilled:

- 1) No external forces other than the cable force applied on the robotic arm exist
- 2) The cables are parallel to the center line of the arm
- 3) The mechanical properties of the arm are uniform.

The kinematic of the robot is then described by the configuration space using the homogenous transformation matrix. Adopting the constant curvature approximation, this matrix can be defined by the curvature $\kappa = \frac{1}{r}$, the mean arm length $l = r * \theta$ and the bending angle ϕ . The rotation around the z-axis with the angle ϕ can be described with equation (7.1).

$$T_{\phi} = \begin{bmatrix} \cos \phi & \sin \phi & 0 & 0 \\ -\sin \phi & \cos \phi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7.1)$$

The transformation for the bending in the XY-plane is described by equation (7.2), where the input parameter are curvature κ , length of the tendons l and radius of the arc r .

$$T_{r,\theta} = \begin{bmatrix} \cos \kappa l & 0 & -\sin \kappa l & r(1 - \cos \kappa l) \\ 0 & 1 & 0 & 0 \\ \sin \kappa l & 0 & \cos \kappa l & r \sin \kappa l \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7.2)$$

The product of these transformations finally describes the transformation from the base coordinate system to the tip coordinates of the robotic arm (eq. 7.3), as demonstrated in figure 43.

$$T_{r,\theta} = \begin{bmatrix} \cos \phi \cos \kappa l & \sin \phi & -\cos \phi \sin \kappa l & \frac{\cos \phi (1 - \cos \kappa l)}{\kappa} \\ -\sin \phi \cos \kappa l & \cos \phi & \sin \phi \sin \kappa l & \frac{\sin \phi (\cos \kappa l - 1)}{\kappa} \\ \sin \kappa l & 0 & \cos \kappa l & \frac{\sin \kappa l}{\kappa} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7.3)$$

Figure 43: Coordinate transformation from base to tip

The end effector movement is described in the task space and defined by the three special coordinates x , y and z . For the mapping from the configuration space to the task space, only the last column of the transformation matrix has to be considered (eq. (7.4) to (7.6)).

$$x = \frac{\cos \phi (1 - \cos \kappa l)}{\kappa} \quad (7.4)$$

$$y = \frac{\sin \phi (\cos \kappa l - 1)}{\kappa} \quad (7.5)$$

$$z = \frac{\sin \kappa l}{\kappa} \quad (7.6)$$

Solving for the configuration variables by inverting the above equations, the mapping from the task space to the configuration space can be derived as shown in equations (7.7) to (7.9).

$$\kappa = \frac{2 \sqrt{x^2 + y^2}}{x^2 + y^2 + z^2} \quad (7.7)$$

$$\phi = \text{atan2}(y, x) \quad (7.8)$$

$$l = \frac{1}{\kappa} \arcsin(z \kappa) \quad (7.9)$$

7.2 Comparison of Theoretical to Measured Curvature

When actuating one motor, the cables have an offset of 180 degrees to each other where cable 1 is located at $\varphi_1=0^\circ$ and $\varphi_2=180^\circ$. With the following equation, the length of the two actuated cables can be determined.

$$l_i = l (1 - \kappa \delta \cos(\varphi_i - \phi)) \quad (7.10)$$

Inserting for l_1 and l_2 with $\phi = 0$, because the bending is assumed to take place only in the XY-plane, the equation can be solved for the curvature κ , where $l_2 - l_1$ is equal to the rolled up cable length.

$$\kappa = \frac{\Delta l}{2\delta l} \quad (7.11)$$

Δl is defined in the actuator space by the revolutions of the motor shaft. Rotating the motor with one half revolution, Δl is equal to one half of the spindle circumference. For a spindle diameter of 8 mm, $\delta = 13,5\text{mm}$ which describes the distance from the cables to the neutral axis of the arm, and a module length of 105 mm, the curvature becomes

$$\kappa = \frac{\Delta l}{2\delta l} = \frac{\pi r}{2\delta l} = \frac{\pi * 4 \text{ mm}}{2 * 13,5 \text{ mm} * 105 \text{ mm}} = 0,0044326 \frac{1}{\text{mm}}$$

To compare this result for the theoretical curvature with the real value, one module is actuated by one half revolution of the motor shaft so that it bends in the XZ-plane. The radius of the curvature is then measured as shown in figure 44.

Figure 44: Measuring procedure to determine the real curvature

A wire acts as a reference for the starting height of the soft material. Attaching a ruler at the upper end of the soft material in the same bending angle as the arm, the radius can be measured. The curvature can then be calculated with the equation

$$\kappa = \frac{1}{r} \quad (7.12)$$

The radius is measured to be 235 mm, which results in a curvature of $0,004255 \frac{1}{mm}$.

This is close to the theoretical value. Little changes could come from inaccurate spindle windings.

When trying to compare the measured coordinates of the robots tip in figure 44 with the theoretical coordinates, it turns out that the tracked coordinates change in an unrealistic way as soon as the sensor gets too close to the metal of the motors. This makes a comparison between theoretical and measured coordinates impossible.

7.3 Dynamic Experiments

After a program is written to control the motors, first dynamic experiments to visualize bending motions can be done. For this purpose, the electromagnetic tracking system is used. By tracking the position of a sensor, that is placed central on the top of one module, the X-, Y- and Z-coordinates are tracked during the arm is bending.

7.3.1 Bending Test in XZ-Plane

The following plot shows a test plot of a repeated bending motion in the XZ plane.

Figure 45: Tracking of X-, Y- and Z-Coordinates during bending in XZ plane

Since the robot moves only in the XZ-plane, the expected displacement in Y for a perfect straight bending would be a flat line. However, the red line shows peaks, which is most-likely an effect of vibration when the tip reaches its desired end position. This vibration effect is stronger on one side (minima of blue curve) as the movement on this side is less smooth, which is visible on the noise in the X-curve right before the minima. Also the time for the change of bending direction is shorter on the minima. The Z-curve shows its maximum at the minima of X and its minimum at the maxima of X.

7.3.2 Bending in Y-Direction in YZ-Plane

Within 15 repetitions, the dynamic bending behavior of the arm is tested. For this experiment, one module is bended from the upright home position to a bended position in the positive Y-direction (position 1) as shown in figure 46.

Figure 46: Bending from home position to position 1

The results of this dynamic experiment is shown in the following plot (figure 47).

Figure 47: Experimental results of 15 repetitions in YZ-plane

The plot shows a contrary course of Y and Z, while X follows the trend of Z.

The data seem to behave stable and accurate over the 15 repetitions. Analyzing the data for each dimension carefully, however, it turns out that the curves have a trend in a certain direction over time. For the X and Z-direction, the amplitude decreases while the amplitude of Y increases. This means the accuracy of reaching position 1 decreases from repetition to repetition. In the X-direction, the deviation after 10 repetitions is 0,69 mm, in the Y-direction 3,9 mm and in the Z-direction 5,38 mm. This leads to an error in X of 1,6 %, in Y of 4,63 % and in Z of 7 % of the corresponding start displacements. In order to determine the repeated accuracy of the robotic arm in more detail, experiments for the repeatability are done in the next chapter.

8 Repeatability

In order to determine the accuracy of the soft robotic arm, the repeatability of reaching one and the same point in the working field of one arm segment shall be determined. For this purpose, the same experimental setup as for the dynamic experiments is used. Before the experiments will be described, the procedure to calculate the repeatability is demonstrated.

8.1 Computational Procedure

With the tracked coordinates of each experiment, the center coordinates of X, Y and Z need to be determined by calculating the mean of the values of each dimension.

$$x_s = \frac{1}{n} \sum_{j=1}^n x_j \quad ; \quad y_s = \frac{1}{n} \sum_{j=1}^n y_j \quad ; \quad z_s = \frac{1}{n} \sum_{j=1}^n z_j \quad (8.1)$$

The next step is to determine the distance from each point to the center coordinates by using the following equation.

$$l_j = \sqrt{(x_j - x_s)^2 + (y_j - y_s)^2 + (z_j - z_s)^2} \quad (8.2)$$

With these distances, the mean distance to the center coordinates can be calculated.

$$\bar{l} = \frac{1}{n} \sum_{j=1}^n l_j \quad (8.3)$$

The distances l_j as well as the mean distance $\bar{l}$ are plugged into the following equation to determine the mean variance S_l .

$$S_l = \sqrt{\frac{\sum_{j=1}^n (l_j - \bar{l})^2}{n - 1}} \quad (8.4)$$

Using the mean variance and the mean distance to the center coordinates, the repeatability RP_l can be calculated.

$$RP_l = \bar{l} + 3S_l \quad (8.5)$$

In the upcoming subchapters, the repeatability is determined for reaching various points in different bending motions. It is differentiated between bending out of a standing position of the arm and bending out of a hanging position. The next subchapter starts with the bending out of a standing position. All tracked coordinates refer to the coordinate system of the electromagnetic field generator and are measured in inches to this reference coordinate system.

8.2 Bending out of Standing Position

The experimental setup for the standing position is shown in figure 48. A subsequent view from the top (figure 49) clarifies the coordinates of the tracking system.

Figure 48: Experimental setup for bending out of standing position

Figure 49: View from the top (left: EM field generator as reference)

8.2.1 Bending in Positive Y-Direction in YZ-Plane

The bending motion is identical to the dynamic experiments with the exception that the arm stops after reaching the desired position to wait for vibrations to fade away. For this experiment, only the lower motor is actuated. Figure 50 shows the bending motion from the home position to position 1, where the tip coordinates are tracked.

Figure 50: Bending from home position to position 1

Within 30 repetitions, the coordinates at position 1 are tracked. Each bending is started from the home position. Due to the fact that the motors get really hot when they are connected too long to the power source, the power source is thus turned off for a little while after each 10 repetitions to give the motor a short break to cool down. The experimental results of the tracked coordinates are plotted in the following three-dimensional figures from the XZ- (figure 51) as well as from the YZ perspective (figure 52). The units of the axis are inches to the reference.

Figure 51: Scatter plot of position 1 from the XZ perspective

Analyzing the plot from the XZ perspective, it turns out that the points approximately follow a linear trend in the negative X- and the positive Z-direction. The first repetition is represented by a point in the lower right corner of the diagram and the coordinates of the last repetition are located in the upper left corner. Furthermore, the points can be separated in three groups of each ten points. In the Z direction, the deviation of the lowest to the highest point is around 18 mm. In the X-direction, the points show a much smaller deviation of only around 5 mm. To investigate the trend of the Y component of these points, the YZ perspective is shown in the following plot (figure 52).

Figure 52: Scatter plot of position 1 from the YZ perspective

From YZ perspective, the trend of the points looks similar to the XZ scatter plot. The course of the points can be approximated through a straight line that starts from the lower right corner and ends in the upper left corner of the coordinate system. This means, the points follow the diagonal of the XYZ cubic room. The deviation of the Y-coordinates is around 7,5 mm. To demonstrate the course of the X-, Y- and Z-direction over the 30 repetitions, the trend of each dimension is plotted in figure 53.

Figure 53: Trend of X, Y and Z within 30 repetitions

This plot demonstrates the course of X, Y and Z over all repetitions and indicates whether it follows a negative or a positive trend. It shows a negative slope for X and Y and a positive trend for the Z-direction. The fact that the slope of Z is significantly higher also confirms that the deviation in Z-direction is clearly higher than in the X- and Y-direction. The exact coordinates of the tracked points are listed in the appendices.

Analyzing the coordinates of each dimension carefully, a significant jump in X is visible after each run of 10 repetitions. This effect shall be demonstrated in the following plot of X (figure 54).

Figure 54: Trend of X

This plot visualizes a significant drop of the X-curve after the 10th and 20th repetition. As described in the beginning of the experiment, after 10 and after 20 repetitions a short break was made to give the motors time to cool down. During this break, the robotic arm stayed in the bent position at position 1. So it is assumed that a correlation exists between the time the robot stays in a bent position and the X coordinates of the tip. The course of the Y- and Z-curve in the following figures shows no significant drop after the 10th and 20th repetition. Y is also decreasing over all repetitions. However, it follows a linear trend as demonstrated in the following plot (figure 55). The overall decrease is around 7 mm, where the slope is approximately linear over the experiment.

Figure 55: Trend of Y

Since the slope of the curve is approximately linear, the center Y-coordinate is located within the middle repetition run between 11 and 20. As a result, the distances from these coordinates to the center coordinate is very small. In contrast to the course of X and Y, the Z-coordinates are increasing over the whole experiment as shown in the following plot (figure 56). The overall increase is around 18 mm and approximately linear.

Figure 56: Trend of Z

Calculation of Repeatability

Since the X-coordinates show a significant drop after the breaks at 10 and 20 repetitions, it makes sense to calculate the repeatability not only for all 30 repetitions but also separately for each 10-repetition-runs in order not to get a falsified perception of the repeatability of the arm. Therefore, the computational results for different sections of repetitions are presented in the upcoming table, using the equations introduced in the beginning of the chapter.

Table 4: Computational results for repeatability

repetition		1-10	11-20	21-30	1-20	1-30
mean distance to center coordinates [mm]	$\bar{l}$	1.575	1.606	1.565	3.462	5.355
mean variation [mm]	S_l	0.657	0.810	1.083	1.711	3.057
Repeatability [mm]	RP_l	3.552	4.046	4.822	8.596	14.522

The units in the table are inches of deviation. Within 30 repetitions, for instance, position 1 is reached with a deviation of 14,5 mm. As the plot already indicated, the lowest repeatability is obtained when all 30 repetitions are considered since there are two significant drops of X contained. For a consideration of only the first 20 repetitions, only one drop of X influences the repeatability, whereby the deviation decreases from 14,5 mm to 8.59 mm. The highest repeated accuracy is obtained if only 10 repetitions are considered. In these cases, the repeatability is not influenced by a recognizable drop of X. Comparing the three 10-repetition-runs amongst each other, the repeatability decreases from run to run.

8.2.2 Bending in Negative Y-Direction in YZ-Plane

In order to investigate how symmetrically the arm behaves., the arm is bent from the home position in the negative Y-direction to position 2, which represents the previous position 1 mirrored at the XZ plane. Figure 57 demonstrates the positions of the bending motion.

Figure 57: Bending from home position to position 2

The experimental setup and the measuring procedure stay the same as in the previous experiment. To identify the influence of the break in the bent position after 10 repetitions, however, this break is shortened in this experiment and the arm is moved to the home position before the break.

The trend of the X-, Y- and Z-coordinates are plotted in figure 58.

Figure 58: Trend of XYZ coordinates within 30 repetitions

Analyzing this plot, it turns out that the trend of X, Y and Z is just the opposite of the previous experiment. That means, the slope of the X- and Y coordinates is positive and Z follows a negative trend. Another difference is that no significant drop of X is visible anymore. This leads to the assumption that it has a positive influence on the repeatability to leave the robotic arm in an unbent position during breaks.

In order to allow a more detailed investigation, each dimension is presented separately in the following plots. Figure 59 shows the trend of the X-Coordinates.

Figure 59: Trend of X at position 2

The course of X rises gradually. Every increase is followed by a plateau, which means the X-coordinate remains constant for at least one repetition and it exists no decrease over the whole experiment. The overall increase is around 5,5 mm, from which the longest continuous rise happens between the 8th and 13th repetition. These findings shall be compared with the course of Y, which is shown in figure 60.

Figure 60: Trend of Y at position 2

In contrast to the previous plot of X, the course of the Y-coordinates shows no steps and rises more continuously instead. Thus, a direct correlation between the X- and Y-course is not justifiable. The overall increase of Y is around 22,5 mm. Only one decrease of Y is visible, which is from the 10th to the 11th repetition. Figure 61 shows the course of the Z-coordinates. With an overall decrease of roughly 7,65 mm, the course of the Z-direction behaves in an opposite fashion compared to the X- and Y-direction. It also shows an opposite slope of the previous experiment with bending in the positive Y-direction. As well as the course of the X-direction, the plot contains steps which make it less continuous than in the Y-direction. Only one increase is recognizable from the 13th to the 14th repetition.

Figure 61: Trend of Z at position 2

Table 5 contains the computational results for the repeatability of this experiment.

Table 5: Computational results for repeatability

repetition		1-10	11-20	21-30	1-20	1-30
mean distance to center coordinates [mm]	$\bar{l}$	2.154	2.129	2.060	4.023	6.023
mean variation [mm]	S_l	1.331	1.285	1.065	2.425	3.460
Repeatability [mm]	RP_l	6.148	5.984	5.263	11.293	16.404

As expected, the lowest repeatability is obtained when taking all 30 repetitions into account. Since the course of each dimension follows a linear trend, the error compared to the center coordinates gets higher from repetition to repetition. This means, the more repetitions are considered for calculating RP_t , the lower the repeated accuracy. Thus, the repeatability increases since the deviation decreases from 16,4 mm to 11,3 mm deviation when considering only 20 repetitions and roughly doubles up again when only calculating the repeatability for 10 repetitions. In a comparison between the three 10-repetition-runs, it turns out that the repeatability increases from run to run.

Comparing this experiment with the previous one, the repeatability of this experiment is worse although the breaks in the bent position are omitted.

8.2.3 Bending Using 2 Motors

After testing the accuracy of one motor, the repeatability of the interaction of both motors shall be tested. For this purpose, the arm gets repeatedly bent from the home position to position 3, which follows the direction of the negative Y-axis rotated by 45 degrees. Figure 62 indicates the bending direction.

Figure 62: Bending direction obtained by simultaneously working motors

This bending position can only be reached through a collaboration of both motors, in which both rotate with the same speed. Figure 63 demonstrates the home position and the bent position (position 3), where the repeated measurements are made.

Home position

Position 3

Figure 63: Bending from home position to position 3

The experimental results of X, Y and Z are shown in the next plot (figure 64).

Figure 64: Trend of XYZ coordinates within 30 repetitions

The trend of the coordinates over 30 repetitions looks very similar to the previous experiment, where the arm got bent by only one motor. The X- and Y-coordinates are increasing over all repetitions, while the Z-coordinates are decreasing.

In the next step, each dimension is analyzed separately. Figure 65 shows the course of the X-coordinates.

Figure 65: Trend of X at position 3

As already seen in the previous figure, X is increasing over the whole experiment. Within the first four repetitions, the rise of X is low. From the fourth to the sixth repetition it increases steeply. Between the sixth and the 30th repetition, the increase of X almost follows a linear trend with two exceptions between the 19th and 20th as well as

between the 23rd and 24th repetition, where X slightly decreases or stays constant. Similarly looks the plot of the Y-coordinates in figure 66.

Figure 66: Trend of Y at position 3

However, there are some recognizable differences. The Y-coordinates are not always increasing at the same repetitions as X increases. Additionally, they increase at repetitions where X stays constant or decreases, which is the case between the 19th and 20th repetition.

The Z-coordinates in figure 67 change in an opposite fashion. They almost constantly decrease over the experiment with one exception from the 17th to the 18th repetition, where they obviously increase.

Figure 67: Trend of Z at position 3

Table 6 contains the results for the repeatability of this experiment.

Table 6: Computational results for repeatability

repetition		1-10	11-20	21-30	1-20	1-30
mean distance to center coordinates [mm]	$\bar{l}$	1.889	1.377	1.346	3.151	4.373
mean variation [mm]	S_l	0.757	0.833	0.724	1.841	2.623
Repeatability [mm]	RP_l	4.159	3.878	3.519	8.672	12.242

As expected, the repeatability decreases with the number of considered repetitions. The lowest repeatability is obtained when considering all 30 repetition runs (12,24 mm deviation). If only 10 repetitions are considered, the repeatability is clearly higher. Comparing the 10-repetition-runs amongst each other, the smallest deviation is achieved in the section from the 21st to the 30th repetition. This means, the deviation is getting smaller and thus, the repeatability gets higher over the repetitions, which was not the case for the previous experiments with a single motor. Also the overall repeatability in 30 repetitions is higher than in the previous experiments, which means that a bending with two motors can be more accurately repeated than with using only one motor.

8.3 Bending out of Hanging Position

For various future applications of soft robots, such as an octopus-like robot, a hanging position for the soft robotic arms is required. Thus, another experimental series is made in a hanging position of the arm. The results can then be compared to the repeatability of the experiments in the standing position.

Figure 68 demonstrates the hanging bending positions. For this experiment, the arm is repeatedly bent from position 4 to position 5.

Figure 68: Positions for bending out of the hanging position

The view from the top, which shows the coordinate system of the EM tracking system, is presented in figure 69.

Figure 69: View from the top

The course of the coordinates of X, Y and Z during the experiment is shown below.

Figure 70: XYZ coordinates for bending from position 4 to position 5

Analyzing the plot of figure 70, it turns out that especially the X- and Z-curves proceed asymmetrical in the beginning of the coordinate tracking, whereas it looks symmetrical towards the end. Between these phases, there exists a transition period in which the asymmetrical peaks fit their height to each other. With these findings, the overall tracking time gets divided into three time periods, which separate the asymmetrical (1), the transition (2) and the symmetrical time period (3). With the help of this classification, further results of the experiment can be related to one of these periods, which might be helpful for justifications of later findings. Figure 71 demonstrates the division into the three periods, showing the course of X.

Figure 71: Zoom of tracked X-Coordinates and division into three time periods

The same phenomenon is visible in the course of Z (figure 72), where the division into the three periods is also demonstrated in the following plot.

Figure 72: Zoom of tracked Z-Coordinates and division into three time periods

Since the bending is taking place in the XZ plane, Y stays almost constant and is not influenced by the transition from asymmetrical to symmetrical bending. Therefore, it is not considered in the further analysis. In the following, the repeatability is first determined for the left bending position (position 4) and afterwards for the right bending position (position 5).

8.3.1 Bending in Negative X-Direction

The trend of the coordinates X, Y and Z is plotted in figure 73.

Figure 73: Trend of the coordinates X, Y and Z over 20 repetitions

It is recognizable that all three dimensions do not have a clear rising or falling trend anymore, as it is the case in all standing positions. While the course of Y is almost perfectly flat, there is a drop visible in the X- as well as in the Z-curve. This drop occurs in both dimensions exactly after the 7th repetition, which is represented by the transition point between period 1 and period 2. During period 2, both dimensions are slightly increasing from repetition 8 to repetition 17. In the symmetrical period 3 from repetition 17 till the end, there is no noticeable increase or decrease to see.

In the next step, the dimensions X and Z are analyzed in separate plots. Figure 74 shows the course of the X-coordinates.

Figure 74: Trend of X at position 4

The plot of X clearly visualizes the drop after the 7th repetition (end of period 1), where X descends by around 0,11 inches. After the 9th repetition it further decreases by roughly 1,25 mm. From the 10th repetition it increases till the 18th repetition (in period 3) from where on it stays constant till the end of the experiment.

The plot of Z in figure 75 looks almost identical. The drop at the 7th repetition is slightly higher with around 4 mm.

Figure 75: Trend of Z at position 4

It is expected that the X- and Z-coordinates at the end of the experiment remain roughly the same. The justification of this assumption is the following: In period 1, the cable length that is rolled up on the motor spindle varies from one side to the opposite side of the arm. It can happen that one cable gets stuck somewhere in the motor holder, which shortens it. As long as one cable is longer than its counterpart, the bending from one side to the other side is asymmetrical. As soon as the stuck cable gets released after a while through the repeated motion, the lengths of both cables equalize again. This is visualized by the drop at repetition 7. Until the bending is completely symmetrical (in period 3), it takes some time for the cables to get rolled up equally on the spindle. This

process happens in the transition period from the 8th to the 18th repetition. After that, the bending is symmetrical in period 3.

The computational results for the repeatability are listed in table 7.

Table 7: Computational results for repeatability

repetition		1-10	11-20	1-20
mean distance to center coordinates [mm]	$\bar{l}$	2.185	1.040	2.361
mean variation [mm]	S_l	1.216	0.367	1.180
Repeatability [mm]	RP_l	5.834	2.139	5.900

The repeatability of the first ten repetitions is only slightly higher than the repeatability of all repetitions. This is justified by the fact, that the drop after the 7th repetition causes the main decrease of the repeatability. Since this drop happened within the first ten repetitions and afterwards the coordinates are only slightly increasing, the achieved repeatability in the second half of the experiment is significantly higher. A deviation of only 2,13 mm over 10 repetitions offers a promising basis for a future investigation of tendon-driven soft robots.

8.3.2 Bending in Positive X-Direction

The trend of the X, Y and Z coordinates measured at position 5 is plotted in figure 76.

Figure 76: Trend of the coordinates X, Y and Z over 20 repetitions

The plot shows a decrease of X and an increase of Z to a comparable extent after repetition 6. The drop occurs one repetition earlier than the drop on position 4. This means that the drop happened on the way from position 4 to position 5, since the first measurement was made at position 4.

Separate plots of X and Z are visualized in the following.

Figure 77: Trend of X at position 5

As already noticed in the previous trend of the X-, Y- and Z-coordinates, the drop of X happens at the 6th repetition and is around 4 mm, which is clearly higher than the drop at position 4 (2,8 mm). The subsequent increase looks similar to position 4. However, it is slightly higher with an increase of around 2 mm instead of 1,2 mm. Analyzing the plot of Z in the upcoming figure, it looks like the curve is mirrored. Every increase of X turns into a decrease of Z and vice versa. The increase of Z after repetition 6 is around 5,5 mm. That means the influence of the scenario causing the drop of the coordinates is higher in the Z-direction than in the X-direction.

Figure 78: Trend of Z at position 5

Table 8 shows the results for the repeatability at position 5.

Table 8: Computational results for repeatability

repetition		1-10	11-20	1-20
mean distance to center coordinates [mm]	$\bar{l}$	3.376	1.142	2.657
mean variation [mm]	S_l	0.940	0.379	1.486
Repeatability [mm]	RP_l	6.199	2.279	7.119

The repeatability of all considered repetition sections is lower than at position 4. In addition, the difference between the repeatability of 10 repetitions and the repeatability of all repetitions is higher than at position 4.

8.4 Comparison of Results

Comparing the repeatability of the standing and the hanging position within 20 repetitions, the accuracy of the hanging position (mean repeatability of 6,375 mm deviation in 20 repetitions) is clearly higher than the accuracy of the standing position (mean repeatability of 9,435 mm deviation in 20 repetitions). In all measurements out of the standing positions, a linear trend of the coordinates over the repetitions (drifting) is recognized. The measurements of the hanging position show no drifting. However, during the bending in the hanging position a clear drop of the X- and Z-coordinates occurs within the first 10 repetitions. Calculating the error caused by the drifting in the standing position and the error caused by the drop in the hanging position, it turns out that the error of the drop (mean error of 48,5 %) is significantly higher than the errors caused by the drifting in the standing position (mean error of 9,35 %). The errors are determined as described in subchapter 11.2 of the appendices. Despite a bigger error, the repeatability in the hanging position is higher, which leads to the conclusion that drifting is worse for the repeatability than a single significant drop. In a comparison between the accuracy of using only one motor and using both motors, the repeatability of using two motors (12,24 mm deviation in 30 repetitions) is higher than using only one motor (mean deviation of 15,3 mm in 30 repetitions). Comparing only the standing positions using one motor, it turns out that the first experiment with breaks after each 10 repetitions has a higher repeatability than the second experiment without breaks. That means, leaving the arm in a bent position does not necessarily lead to a lower repeatability than taking breaks in the home position.

9 Summary & Conclusion

The result of this work is a modular design for a soft continuum robotic arm. Within this research, three identical modules were developed, whereby each module is independently actuated and controllable. This design allows a connection of an arbitrary number of modules to a snake-like soft robot.

After giving an introduction and the motivational backgrounds behind the research about soft robots, the theoretical basics for this work are explained. The basics part is followed by the state of the art of continuum and soft robots.

The practical part of this work started with the design and manufacturing of the necessary components, which include a mold for the fabrication of the soft part of the robotic arm as well as the hard components of the robot. After a successful fabrication of the soft part and several optimization processes in the design of the hard components, three modules were manufactured and assembled.

In order to allow realistic future simulations of the produced silicone arm, different static simulation models were explored. These models were compared to the real force related behavior of the arm, which was obtained by a static experiment in which different forces were applied to the arm and the displacement of the tip was measured by an electromagnetic tracking system (EMTS). One dimension of the experimental results

could be matched by the simulations. For matching both dimensions, however, a non-linear simulation has to be done, which was not possible within this research.

After a program was written to control the motors, first kinematic experiments could be done using the electromagnetic tracking system to record the tip position. Furthermore, a mathematical model to determine the theoretical position of the tip of one module is introduced. However, the measured coordinates of the EMTS could not be compared with the theory, since the sensor was interfered by the metal of the motors which led to unrealistic measured tip coordinates.

Since all measured position values were influenced by the metal in the same way, a comparison among the measured positions of the robotic arm was still possible. This enabled various series of measuring the repeatability for one module in reaching different bending positions. It was differentiated between bending out of a standing position and bending out of a hanging position. It turned out that all measurements in the standing position had a certain trend over the repetitions. The coordinates in the hanging position showed a drop between two repetitions, which decreased the repeatability. Overall, however, the repeatability in the hanging position was higher than in the standing position. In addition to a comparison between the standing and hanging position, the use of only one motor was compared to using both motors. The result was a higher repeatability for using two motors. The highest repeatability was 2,13 mm deviation within 10 repetitions, which offers a promising basis for future research in the field of soft robots.

10 Limitations & Outlook

For future investigation in the field of tendon-driven soft robots, some improvements are suggested to obtain more precise results for the experiments.

Since the electromagnetic tracking sensor is influenced by metals in the tracking environment, the measured coordinates were changed in an unrealistic way, so that they could not be compared to the theoretical calculated tip coordinates. When it came to a dynamic tracking during a bending motion, it turned out that the signal could only be tracked in a useful fashion, if only the motor at the bottom was controlled. Once the motor close to the robot's tip, where the electromagnetic tracking sensor was located, was controlled, the tracked signal showed a significant interference in the form of huge and high-frequency vibrations. In order to obtain precise results during dynamic tracking and also to measure more realistic coordinates that can be compared to the theoretical tip position, the electromagnetic tracking system is not the right measuring tool since the developed robotic arm contains too much (current-carrying) metal. A potential solution could be an image-based tracking system that follows the colored robotic arm in front of the white wall. Another option could be offered by a laser-tracker. Both suggested tracking system are insensitive to electromagnetic interference through the robot.

For future simulations of the soft part, more accurate results are achieved by running a non-linear simulation, which is very challenging since the job aborts easily.

Regarding the actuation of the robot, the following weaknesses are recognized.

When the module had to carry not only its own weight but also another module that was connected to it in the hanging position, the strings broke after several bending motions. For future control experiments with more than one module, it is suggested to either increase the number of strings that are going through one tube or switch to stronger materials for the cables. This decision has to be a tradeoff between strength and still maintaining flexibility to roll up on the spindle.

The cable contraction is not always symmetrical, which was especially visible in the hanging position before the drop of the coordinates occurred. This could have several reasons such as a stuck cable in the motor holder or simply an uneven rollup on the spindle. To improve this effect, a change of the spindle design might be helpful, which guides the cables in a more distinct fashion so that the cable is not able to randomly roll up along the whole spindle width.

The programs within this research control both motors with the same speed, which allows the arm to bend in 8 directions including north, northeast, east, southeast, south, southwest, west and northwest. To control the arm in a complete circle so that it can reach any point in its working environment, the programs need to be modified so that they allow the user to define different motor speeds for both motors. This could be done nicely in a graphical user interface.

11 APPENDICES

11.1 Tables with Tracked Coordinates

Table 9: Measured Coordinates for 8.2.1

	left			home		
	x	y	z	x	y	z
1	3.12	12.04	9.49	1.36	8.6	12.15
2	3.11	12.04	9.49	1.51	8.64	12.23
3	3.13	12.02	9.52	1.51	8.64	12.2
4	3.12	12.02	9.52	1.52	8.6	12.22
5	3.11	12.01	9.54	1.52	8.6	12.18
6	3.12	11.99	9.54	1.52	8.58	12.19
7	3.1	11.99	9.61	1.54	8.57	12.17
8	3.11	11.98	9.62	1.52	8.54	12.15
9	3.11	11.98	9.64	1.52	8.51	12.15
10	3.1	11.97	9.67	1.55	8.53	12.12
11	3.06	11.96	9.71	1.43	8.49	12.05
12	3.07	11.94	9.74	1.49	8.48	12.08
13	3.06	11.94	9.75	1.49	8.47	12.06
14	3.05	11.93	9.77	1.52	8.45	12.06
15	3.05	11.93	9.8	1.49	8.44	12.02
16	3.05	11.91	9.82	1.43	8.42	11.94
17	3.05	11.9	9.86	1.49	8.42	11.96
18	3.04	11.9	9.87	1.47	8.41	11.9
19	3.04	11.89	9.89	1.45	8.38	11.89
20	3.03	11.88	9.91	1.46	8.39	11.83
21	2.99	11.87	9.95	1.46	8.38	11.85
22	2.99	11.85	10.01	1.47	8.39	11.82
23	2.99	11.84	10.03	1.48	8.42	11.77
24	2.98	11.83	10.06	1.35	8.48	11.5
25	2.98	11.82	10.08	1.39	8.47	11.52
26	2.98	11.81	10.09	1.42	8.45	11.51
27	2.98	11.81	10.11	1.48	8.43	11.59
28	2.98	11.79	10.15	1.45	8.45	11.5
29	2.97	11.79	10.16	1.48	8.45	11.49
30	2.97	11.77	10.18	1.49	8.46	11.44

Table 10: Measured Coordinates for 8.2.2

	home			right		
	x	y	z	x	y	z
1	1.34	8.92	12.33	4.38	18.23	5.46
2	1.37	8.78	12.24	4.4	18.3	5.43
3	1.39	8.69	12.22	4.4	18.34	5.43
4	1.39	8.7	12.19	4.4	18.36	5.42
5	1.39	8.67	12.19	4.42	18.4	5.42
6	1.4	8.63	12.16	4.43	18.42	5.4
7	1.38	8.66	12.17	4.43	18.45	5.4
8	1.36	8.64	12.17	4.43	18.48	5.37
9	1.35	8.62	12.14	4.44	18.51	5.37
10	1.36	8.6	12.12	4.45	18.54	5.36
11	1.35	8.59	12.1	4.46	18.53	5.36
12	1.32	8.6	12.11	4.47	18.6	5.34
13	1.31	8.59	12.07	4.48	18.62	5.34
14	1.32	8.57	12.02	4.48	18.65	5.35
15	1.32	8.54	12	4.49	18.68	5.33
16	1.32	8.54	11.98	4.49	18.7	5.31
17	1.32	8.51	11.96	4.49	18.73	5.29
18	1.32	8.51	11.92	4.51	18.77	5.28
19	1.32	8.53	11.89	4.52	18.81	5.28
20	1.31	8.49	11.9	4.52	18.83	5.28
21	1.31	8.5	11.85	4.54	18.84	5.26
22	1.24	8.57	11.87	4.55	18.87	5.24
23	1.25	8.48	11.83	4.55	18.92	5.23
24	1.24	8.49	11.81	4.56	18.92	5.23
25	1.25	8.49	11.75	4.57	18.96	5.22
26	1.26	8.46	11.73	4.57	19	5.19
27	1.27	8.53	11.63	4.57	19.02	5.19
28	1.26	8.48	11.63	4.58	19.05	5.19
29	1.27	8.54	11.57	4.58	19.09	5.18
30	1.27	8.53	11.54	4.59	19.1	5.17

Table 11: Measured Coordinates for 8.2.3

	x	y	z
1	5.66	18.65	5.08
2	5.66	18.66	5.08
3	5.67	18.66	5.08
4	5.68	18.66	5.07
5	5.72	18.69	5.06
6	5.76	18.72	5.04
7	5.77	18.74	5.04
8	5.78	18.76	5.03
9	5.8	18.77	5.01
10	5.81	18.78	5.01
11	5.83	18.8	4.99
12	5.85	18.81	4.98
13	5.87	18.82	4.97
14	5.88	18.83	4.97
15	5.9	18.85	4.94
16	5.91	18.86	4.94
17	5.92	18.87	4.93
18	5.94	18.88	4.94
19	5.96	18.9	4.91
20	5.96	18.91	4.9
21	5.98	18.92	4.89
22	6	18.94	4.87
23	6.02	18.94	4.87
24	6.02	18.95	4.87
25	6.04	18.96	4.86
26	6.05	18.98	4.84
27	6.07	18.99	4.83
28	6.08	19	4.82
29	6.1	19.01	4.81
30	6.11	19.02	4.8

Table 12: Tracked Coordinates for 8.3.1 (left) and 8.3.2 (right)

	x	y	z		x	y	z
1	-0.33	1.73	11.25		0.51	1.65	10.97
2	-0.33	1.73	11.25		0.51	1.65	10.96
3	-0.32	1.73	11.26		0.49	1.66	11.02
4	-0.33	1.73	11.25		0.52	1.65	10.97
5	-0.33	1.73	11.25		0.52	1.65	10.97
6	-0.33	1.73	11.25		0.52	1.65	10.96
7	-0.33	1.73	11.25		0.36	1.68	11.18
8	-0.44	1.72	11.09		0.37	1.68	11.18
9	-0.42	1.72	11.13		0.34	1.69	11.22
10	-0.47	1.71	11.03		0.34	1.69	11.21
11	-0.47	1.71	11.03		0.34	1.68	11.21
12	-0.46	1.71	11.04		0.35	1.68	11.21
13	-0.46	1.71	11.05		0.36	1.68	11.2
14	-0.46	1.71	11.06		0.36	1.68	11.19
15	-0.46	1.71	11.07		0.37	1.68	11.18
16	-0.44	1.72	11.1		0.4	1.68	11.15
17	-0.43	1.72	11.12		0.42	1.68	11.14
18	-0.42	1.72	11.13		0.42	1.67	11.13
19	-0.42	1.72	11.13		0.43	1.68	11.13
20	-0.42	1.72	11.13		0.43	1.68	11.13

11.2 Calculation of Errors

$$error = \frac{\text{overall deviation}}{\text{displacement of 1.run to home}}$$

11.2.1 Standing Position – Positive Y-Direction

$$error\ x = \frac{0,14}{1,51 - 3,11} = 0,0875 = 8,75\ \%$$

$$error\ y = \frac{0,27}{12,04 - 8,6} = 0,07849 = 7,849\ \%$$

$$error\ z = \frac{0,69}{12,15 - 9,49} = 0,2594 = 25,94\ \%$$

11.2.2 Standing Position – Negative Y-Direction

$$error\ x = \frac{0,21}{3,04} = 0,069 = 6,9\ \%$$

$$error\ y = \frac{0,87}{9,31} = 0,0934 = 9,34\ \%$$

$$error\ z = \frac{0,29}{6,87} = 0,0422 = 4,22\ \%$$

11.2.3 Standing Position – 2 Motors

$$error\ x = \frac{0,45}{3,9} = 0,1153 = 11,53\ \%$$

$$error\ y = \frac{0,37}{9,15} = 0,0404 = 4,04\ \%$$

$$error\ z = \frac{0,28}{4,95} = 0,056 = 5,6\ \%$$

11.2.4 Hanging Position – Negative Y-Direction

$$\text{error drop in } x = \frac{0,11}{0,33} = 0,33 = 33 \%$$

$$\text{error drop in } y = \frac{0,01}{0,01} = 1 = 100 \%$$

$$\text{error drop in } z = \frac{0,16}{0,18} = 0,8 = 80 \%$$

11.2.5 Hanging Position – Positive Y-Direction

$$\text{error } x = \frac{0,16}{0,47} = 0,3404 = 34,04 \%$$

$$\text{error } y = \frac{0,03}{0,09} = 0,33 = 33 \%$$

$$\text{error } z = \frac{0,22}{0,46} = 0,47 = 47 \%$$

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