Design of an Environmentally Interactive Continuum Manipulator

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Master of Science Thesis

Delft University of Technology

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Preface

This thesis contains the research I have performed on continuum manipulators at the laboratory of Interactive Mechanisms Research Lab of the department of BioMechanical Engineering. The main research topics in this laboratory are spring balanced, compliant and underactuated mechanisms, which obtain functionality by a clever mechanical design instead of sophisticated control.

My research started at Tokyo Institute of Technology in Japan, where I did the IGM exchange program at the laboratory of Mechanical Systems Design for a period of 6 months. Their research about manipulators with a high degrees of freedom instantly caught my interest, which I therefore chose as a topic of my research. These manipulators can reach highly constraint areas with their high flexibility. During my literature research I encountered that current research done in this field mainly focus on control issues as accuracy and avoiding obstacles, rather than adapting to their environment. With my background at the interactive mechanisms laboratory, I found a new approach where the fields of underactuated mechanisms and continuum manipulators are combined into a manipulator design that can interact with the environment. When I returned to Delft I further worked out this principle into analytical models, leading to a final concept and a prototype, which are presented in this work.

I would like to show my gratitude to my supervisor Just Herder for all his advice, support and enthousiasm throughout my research. I would like to thank my supervisors in Japan, Yukio Takeda and Daisuke Matsuura for hosting me at their laboratory and all the advice they gave. I also would like to thank professor Tomiyama, for providing the chance to do the exchange to Japan within the IGM program. I also would like to thank my labmates in Japan for making me feel at home in Japan and my friends at the international students house in Tokyo. It was a memorable time. I would like to thank my labmates at the interactive mechanisms lab at TU Delft for providing a both intellectually stimulating as socially interactive environment. Finally, many thanks to my family and friends at home for the continuous support during my research.

Delft, Summer 2013

Daan Bakker

Table of Contents

Chapter 1

Paper: Design of en Environmentally Interactive Continuum Manipulator

Design of an Environmentally Interactive Continuum Manipulator

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Abstract—

Continuum manipulators are high degree of freedom structures that can use their increased degrees of freedom to navigate through an environment with obstacles. This type of manipulator is underactuated, which make them promising for adapting to their environments. However, current research is mainly focused on accurate positioning and obstacle avoidance, while the advantages of underactuated systems remain unused. Therefore this paper proposes a new design and approach of a continuum manipulator, which can navigate through an environment with obstacles by passively shaping the manipulator along the obstacles. The proposed design consists of a sequence of crosslink segments, where steering is done by an antagonistic pair of tendons and forward movement is done by a single pushing force at the base of the manipulator. Analytical models and a prototype show that this manipulator has a highly increased range of motion per segment compared with similar systems. The results also show that the manipulator is able to reach a target in a multi-obstacle environment using a simple binary control system with low input forces.

Index Terms: Continuum manipulators, Environmental interaction, Underactuated mechanisms

1 Introduction

Continuum manipulators are high degrees of freedom (dof) robotic arms, which can use their redundancy to reach for targets in an environment with many obstacles [1] [2]. These increased dof makes them promising for being applied as rescue robots, inspection devices and minimally invasive surgery devices. This type of manipulators is underactuated, which means that the number of actuators is less than the number of degrees of freedom. These manipulators are therefore promising for navigating through environments with obstacles by conforming their shape to their surroundings [1].

In the past decades an increasing number of continuum manipulators has been proposed using many different actuation principles. These include tendon-driven [3], [4], [5], pneumatically driven [6], [7] and a combination of both tendons and pneumatics [8], [9] manipulation.

Accurate kinematic modeling of continuum manipulators has always been one of the main challenges in the field of continuum manipulators. These kinematic models are used for modeling and controling the device. One often applied kinematic modeling approach is the constant curvature approach, where the shape of the continuum manipulator is estimated by a sequence of circular arcs [4]. Another oftenly used approach is the cosserat rod method [7] [10], which determines the shape of the manipulator using force-torque balance equations [11]. Using this approach a positioning error of upto 1.7% can be achieved [5]. However, these results are based on experiments where environmental contact is excluded. If environmental contact is involved, the accuracy of the system will be decreased, due to the uncertainty of obstacles' properties as size, position, shape, compliance and friction. Also, a sudden impact of the manipulator on an obstacle may lead to poor control due to control loop delays. In some previous researches it has already been pointed out that high dof manipulators are at a disadvantage for accurate positioning tasks, unless they are instrumented with numerous sensors and computationally intensive control strategies [12], [1].

Another research branch of continuum manipulators focuses on the development of path planning algorithms, which are used to navigate a continuum manipulator through an environment with obstacles. However, research is mainly done on avoiding these obstacles [13], [14], [15]. If there is environmental contact involved, this is done in a preknown environment and requires a computationally intensive algorithm [16]. Avoiding obstacles can be an advantage when either the environment or the manipulator may not be damaged. In most cases however, environmental contact is fully allowed, i.e. the continuum manipulator does not harm the obstacle and vice versa.

From previous research it can be seen that researchers are primarily focused on accuracy and avoiding contact with the environment. This is despite the fact that environmental contact is almost inevitable when one must reach in an environment with many obstacles and despite the fact that environmental interaction is mentioned to be promising for continuum manipulators. Evaluation criteria as range of motion of the system and reachability have lower priority in previous research. The advantages of underactuated mechanisms, i.e. adapting to an unstructured environment, remain unused in the control of current continuum manipulators.

Therefore a new approach is desirable, where environmental contact is included. Principles of underactuation can be used to passively shape and navigate the manipulator along obstacles. Underactuation has been succesfully applied in robotic graspers and underactuated fingers [17], [18], [19], but is still unexplored for continuum manipulators that interact with multiple objects. Underactuated fingers can shape around a wide range of obstacles using a single force, as in figure 1, regardless of the shape and size of the obstacle. Their self-adaptibility makes them suitable for grasping a wide variety of objects without the use of a sophisticated control algorithm. Current underactuated fingers would be unsuitable for manipulation tasks, since the motion of the finger is limited to a one-directional bend in the range of motion of $[0, \pi]$ rad.

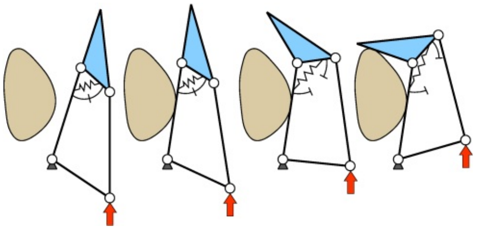

Figure 1. Closing sequence of an underactuated 2dof finger adapting to an object using a single actuator. Figure adopted from [19].

In order to illustrate the numerous potential advantages of environmental interaction a comparison is done between a rigid link structure and a continuum manipulator reaching a target in a confined area, see figure 2. The left manipulator uses actuators in each joint avoiding contact with the environment. When this manipulator is moved forward, it constantly has to adjust its shape to keep avoiding the environment, which requires a compuationally intensive control system. The right manipulator is a continuum style manipulator where environmental contact is allowed during manipulation. In this case the amount of actuators can be reduced drastically when the manipulator passively complies around the environment. Navigating through the environment can be done by using the shape of the environment, where control of the manipulator could be reduced to simple left/right tension control. Another advantage is that when the environment is used, the contact points from manipulator on the environment can form an extra support for the manipulor such that a less shaky movement is achieved. This adaptive approach reduces sensors, which therefore leads to a cost reduction.

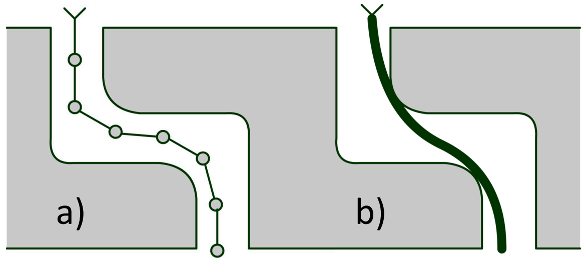

Figure 2. An environmental interaction case: (a) Discrete manipulator with obstacle avoidance (b) Continuum manipulator with environmental interaction

The main objective of this work is to develop a continuum manipulator that is able to move through and adapt to an unstructured 2D environment. The focus is on gaining a high reach using a small amount of actuators. Five different subgoals were defined:

1) Identify contact scenarios and define a benchmark environment.
2) Design of an environmentally interactive continuum manipulator.
3) Develop a mathematical framework to model the main characteristics of the manipulator.
4) Develop a simulation model to simulate the behavior of the model in different environments.
5) Develop a prototype to show the increased range of motion.

This paper is structured as follows: In section 2 the method of this research is described. First, an environment and the evaluation criteria will be defined. Next, the design of the manipulator is done, after which the analytical model will be described. Section 3 shows the analytical and experimental results. Section 4 will interpret the results, compare the manipulatr with other continuum manipulators and underactuated systems, and give recommendations for future research. Finally, in section 5 the conclusions of this research will be presented.

2 METHOD

2.1 Define Environment

The main task for the to be designed continuum manipulator is to move from a point P_{start} to an end point P_{end} within an environment with obstacles. In literature there is a lack of benchmark tests that decribe a navigation task within an environment with obstacles. Therefore a benchmark navigation experiment will be proposed here.

Environments can have many different unknown properties that affect the movement of the manipulator. These unknown properties can be the properties which are visual on the outside, including the shape, dimensions and position of the obstacle and number of obstacles. There are also properties which are harder to determine from the outside, which include surface roughness, which influences the friction of the contact, and the stiffness of the obstacle.

Varying all these properties would lead to an endless amount of navigation tasks. However, we will consider only one general environment that has the main navigation challenge in it: Reaching a target at a highly constrained position in a 2D environment. The environment is based on a channel which has multiple bendings in it, as shown in figure 3a. Considering that navigating through this environment by the inner contact points takes the least effort, the movement can be reduced to a zigzag-motion around two circular obstacles, as depicted in figure 3b. Circular objects are applied because they have a continuous surface; their size is defined by one variable; and expirements are easily reproducable experimentally. The minimum range of motion that is required to move through the environment is given by α and β. These measures are dependent on the total width t of the manipulator. The zigzag navigation experiment around round obstacles can be considered as a benchmark test for evaluating continuum manipulators that interact with the environment.

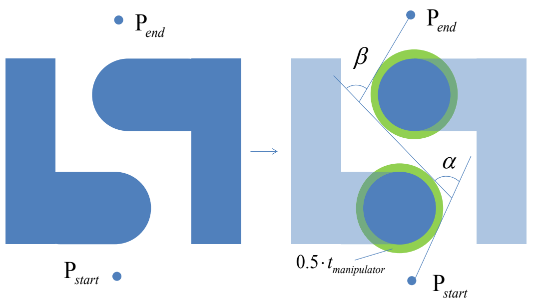

Figure 3. (a) An environment in which the manipulator navigates from a starting point P_{start} to a target point P_{end}. (b) The environment can be reduced to a two-obstacle field with a minimum required range of motion of the manipulator of α and β dependent on the width of the manipulator, $t_{manipulator}$

2.2 Performance indicators

In order to evaluate the performance of the manipulator three evaluation criteria were defined:

1) Reachability: The ability to reach the target within an obstacle environment. A continuum manipulator is able to reach the target kinematically if the required rotations to navigate through the environment is within the range of motion of each segment of the manipulator. The range of motion of one segment is defined as: The minimum and maximum rotational displacement of one segment of the manipulator measured from its equilibrium position. The RoM of a system RoM_{system} with n segments is defined by equation 1.

$$RoM_{system} = n \cdot RoM_{segment} \tag{1}$$

2) Control effort: This evaluation criterion describes the effort it takes to navigate through the environment. This is dependent on the amount of actuators that are needed to control the manipulator, and the complexity of the control system.
3) Actuation forces: This criterion considers the forces that are required to manipulate the obstacles through the environment with obstacles. Two forces are distinguished:
Firstly, the force required to steer the manipulator into the right direction. Secondly, the force required to move the manipulator forwards. This force is dependent on the friction and the reaction forces of the manipulator on the environment.

2.3 Conceptual Design

The approach for the conceptual design of the manipulator is based on the Pahl and Beitz method [20], which is a systematic approach for designing mechanical systems.

2.3.1 Function Analysis

The main function for the manipulator is to move the tip through an environment with obstacles from a position P_{start} to a target point P_{end}. The environment in which the manipulator is navigated through is defined in section 2.1. The main function is subdivided into three different subfunctions:

1) Advancement: This is the function where the tip of the manipulator should be able to move forward through an environment with obstacles.
2) Choosing directions: The manipulator should be able to choose a direction in order to reach its goal.
3) Passively adapt: This mean that the manipulator should be able to follow a path by passively adapting to the environment.

Based on these subfunctions the system's requirements were extracted. First, the manipulator is subdivided into a system consisting of n segments each having 1 dof, as shown in figure 4. This system is used as a general model for analysis purposes. An equilibrium position at the neutral position at 0 rad is desired. In order to reach a high reachability the range of motion per segment should be as high as possible.

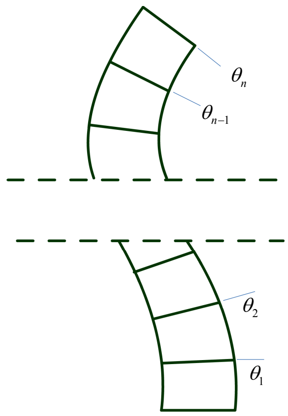

Figure 4. A general model consisting of n segments, where each relative angle is denoted by θ_i

2.3.2 Conceptual Design

For each of the derived functions multiple subsolutions which were evaluated on the previous requirements which led to a final concept. For an elaboration on the conceptual design we refer to appendix [A].

Choice of Advancement Principle:
As for the advancement of the manipulator whole body translation is chosen, which means that the manipulator is moved forward as a whole by a single pushing force at the base, applied by an actuator or manually by an operator. Other translation principles that were considered consisted of extensible mechanisms. However, these mechanisms generate extra friction by the additional moving parts and is sensitive for failure due to many moving parts.

Choice of Steering Mechanism:
Choosing manipulators directions can be done in several ways as applying torques in every segment or adjusting the length of the sides of the manipulator, e.g. by pulling cables, push rigid links or extend pneumatic muscles. Since a small amount of actuators is desired, tendons or pushing cables were considered. Eventually, tendon driven actuation was chosen because it is the best option for transmitting forces over large distances without the effects of buckling.

Choice of Segment Design:
In order to passively adapt to the environment and to create a large reachability, a high range of motion is desired at an equilibrium position at 0 rad. The designed mechanism that satisfies these criteria is a mechanism that consists of two crossed links, see figure 5. The cross sectional joints consist of two consecutive bases AB and CD of length b connected by two crossing links AD and BC of length l. Due to a variable instantaneous center of rotation the range of motion is increased. Two springs with spring constants k_1 and k_2 are attached to points AC and BD respectively in order to create an equilibrium position at $\theta = 0$ rad. Other segment designs that were considered, including single revolute joints and fourbar mechanisms, have a smaller RoM and couldn't match the desired motion profile. Therefore these options were not selected.

2.3.3 Work out Final Concept

After considering multiple concepts with multiple subsolutions the final concept consists of the combination of previously taken choices. A schematic representation of this final concept with a small sequence of three subsegment and their operating forces are shown in figure 6. Steering is done by pulling two tendons, threaded through each end of the segments, with a force F_1 and F_2. By pulling these tendons the whole structure adjusts to an equally generated arc. If an obstacles obstructs the manipulator, the manipulator will form around it. The model is translated by using whole body translation. This can be done by applying a single force, e.g. done by an operator or by an external actuator. A variable stiffness can be achieved by pulling both tendons. This final concept will be further analyzed in the next sections.

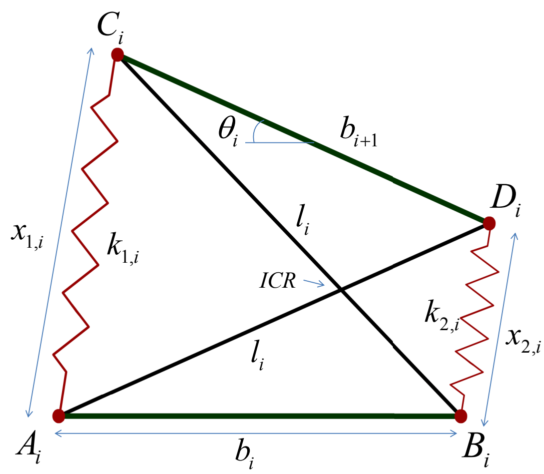

Figure 5. Schematic representation of the ith cross four-bar segment shown at a random θ. Bar CD rotates at an angle θ by the 4 revolute joints A, B, C and D. The Instantaneous Center of Rotation (ICR) is located at the intersection of the two cross links.

2.4 Modeling

To validate the working principles of the continuum manipulator three different models will be developed, tested and compared with each other.

An analytical model will model forces that are required to actuate the manipulator and derive the contact forces of the manipulator on the environment. This is done by applying the energy approach, a form finding technique that is well suited for cable tensioned systems [21], [22]. The model will be used to calculate the actuation forces and the forces on the environment. The mathematical model will give us

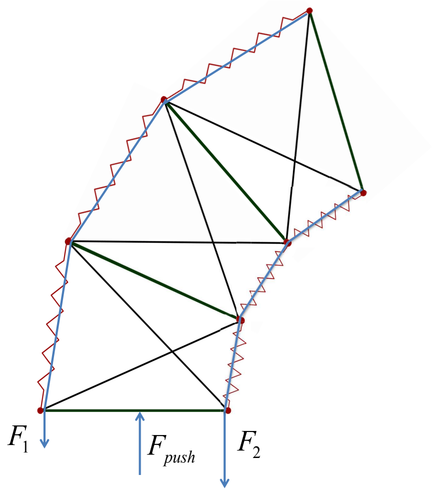

Figure 6. Schematic representation of a small sequence of cross segments. The force inputs F_1 and F_2 are used to bend the manipulator. F_{push} is used to move the manipulator forward.

insight in the working principle and can be used to optimize the internal mechanism.

In the Working Model 2D software environment, the manipulator is tested for different environments and compared with the results of the mathematical model. In a dynamic environment it is tested whether the manipulator is able to reach the target by pushing it through an environment with obstacles. This simulation model will gain insight in physical principles and determines the reachability of the manipulator.

A prototype is made and evaluated in an experimental setup. Experiments are done to verify the basic working principles and measure the performance indicators. Results will be compared and evaluated.

2.4.1 Analytical Model

As mentioned, the main principle that is used for calculating the shape of the manipulator and forces on the environment is the energy approach. This is a process to find the equilibrium configuration for cable tensioned structure [22], by minimizing the energy function. The main strength of the energy approach is that it is well suited for structures where the lengths of the cables are not yet specified [21]. Other advantage is that modification of parameters, as number of segments can be easily done, which makes this principle suitable for optimization purposes. Also this method makes it possible to add energies to the energy equation, such as friction or gravitational influences, to further specify the model.

In the energy approach the system is divided into generalized coordinates as shown in figure 4, and the energy of the total system is calculating by adding the potential energies U as a function of the generalized coordinates $[\theta_1, \theta_2, ..., \theta_n]$. The equilibrium position $[\theta_1, \theta_2, ..., \theta_n]_{eq}$ is then found by minimizing U. The coordinates of the seperate joints at a segment i, see figure 5, are calculated by equation 2 and 4, by applying rotational matrices R_i and the relative coordinates towards point A, $A_{relative}$. We assume frictionless interaction between the tendons and the hole through which they travel. Frictional forces are expected to increase as the curvature of the manipulator increases due to larger normal forces.

$$C_i = Base_{i-1} + R(\theta_i) \cdot A_{relative} \quad (2)$$

Similarly,

$$D_i = Base_{i-1} + R(\theta_i) \cdot A_{relative} \quad (3)$$

Where rotational matrix $R(\theta_i)$ is defined by:

$$R(\theta_i) = \begin{pmatrix} cos(\theta_i) & -sin(\theta_i) \\ sin(\theta_i) & cos(\theta_i) \end{pmatrix}$$

Spring energy The potential energy $U_{springs}$ done by the zerolength springs with spring constant $k_{1,i}$ and k_2,i in each segment i is defined by equation 5. In this equation $x_{1,i}$ and $x_{2,i}$ are the length of the springs.

$$U_{spring} = \frac{1}{2}\sum_{i=1}^{n} k_{1,i} \cdot (x_{1,i})^2 + k_{2,i} \cdot (x_{2,i})^2 \quad (5)$$

Implementing θ_i as a function of $x_{1,i}$ and $x_{2,i}$, derived by the law of cosines, the spring energy equation becomes as shown in equation 6. In this equation it is assumed that $b_1 = b_2 = b$, $l_1 = l_2 = l$ and $k_1 = k_2 = k$, for providing a symmetric behavior.

$$U_{spring} = \sum_{i=1}^{n} k_i \cdot (l_i^2 - b_i^2 \cdot cos(\theta_i)) \quad (6)$$

The energy done by the tendons is equal to the distance that the certain tendon force has covered times the tendon force:

$$U_{tendons} = F_1 \cdot (\sum_{i=1}^{n} x_{1,0} - x_{1,i}) + F_2 \cdot (\sum_{k=1}^{n} x_{2,0} - x_{1,i}) \quad (7)$$

In order to model the contact force of the manipulator to the environment, another spring term is added to the energy equation. Each of the n segments are connected to the the m obstacles by variable stiffness springs. The stiffness of the spring becomes $k_{env} = 1 \cdot 10^5 N/m$ when the length of this spring from the point on the manipulator $P_{1,i}$ to the center of the circular obstacle is smaller than the radius of the obstacle r_{obs_j} and will be zero when it is in larger than the obstacle's radius.

$$U_{contact} = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{m} k_{obs_j} \cdot (P_{1,i} - r_{obs_j}) \quad (8)$$

Adding all the potential energy equations yields:

$$U_{total} = U_{spring} + U_{tendons} + U_{contact} \quad (9)$$

The contact force $F_{contact}$ is then calculated by:

$$F_{contact} = k_{env} \cdot u_{impression} \tag{10}$$

The force $F_{i,k}$ at an obstacle i with radius r_i and part on the manipulator k at a distance of $d_{i,k}$ of the point on manipulator to the center of obstacle yields the following equation:

$$F_{i,k} = k_{env,i} \cdot (r_i - d_{i,k}) \tag{11}$$

The equilibrium position of the system is then found by minimizing the potential energy function (9). This is done using a sequential quadratic programming (SQP) algorithm, by using the *fmincon* algorithm in MATLAB. This algorithm, which allows to solve a problem of optimization under linear and nonlinear constraints, is generally seen as the best general purpose method for constraint problems.

2.4.2 Simulation Model

In Working Model, a simulation model is made in order to evaluate the system and gain insight in the concept. In the dynamic model the advancement is done by a pushing forces attached to a linearly guided block generated by an actuator. The constant tendon force is generated by an actuator which is attached to a linearly guided block, on which the tendon is attached. Steering is done by switching the control tendon from one tendon to another by a timed on/off-control.

2.4.3 Prototype

A prototype and experimental setup were built, which is shown in figure 7, using the parameters of table 1. The link components of the prototype were made from acryllic links cut by a laser cutting machine. The links are hinged by bolts supported by plastic plain bearings. Two springs of 80.0 N/m are connected to each of the ends of the midsections. Two tendons were laced through each end of the segments. The number of segments is chosen to be 5, which is enough to show the basic properties of the underactuated manipulator.

Table 1
Parameters of manipulator used in the analytical model and prototype.

Parameter	Value	Dimension
Number of segments n	5	-
Spring constant k	80.0	N/mm
Width of base b	0.04	m
Length of link l	0.072	m

Experiment protocol: In figure 7 the experimental setup with the prototype is shown. The setup consists of two 90mm diameter disks representing the two circular obstacles. At one of these disks, two load cells are placed perpendicularly to measure the reaction forces on the disk in both x- and y-direction.

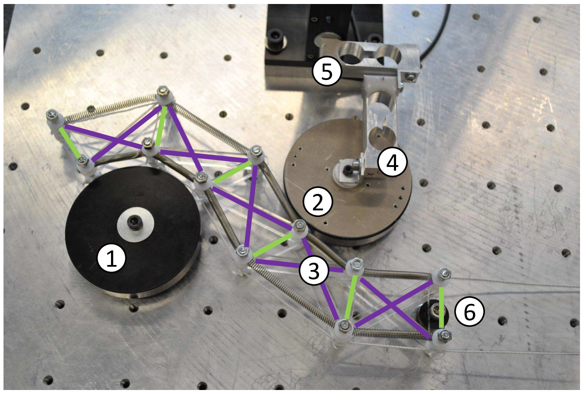

Figure 7. Experimental setup with prototype. The prototype (3) is mounted on a plate (6) and interacts with two obstacles (1 and 2). A variable force is applied on the tendons, while the x- and y- forces on one of the obstacles (2) was measured by two perpendicularly placed load cells (4 and 5).

The experiments were done in two configurations. In the first configuration the environment consists of two obstacles with at a between distance of 11cm at the centers and a manipulator of five segments was used. In these experiments the base of the manipulator is mounted on a plate at a fixed position and angle. During the experiment the tension force of one of the tendons is varied by hanging different weights on the tendons. Herewith the tension force of the tendons are varied from 0 to 10N with steps of 2N. Each measurement was done 5 times, and the experiments are repeated to measure the forces on the other obstacle. During these experiments the forces on the obstacle were measured in Labview and the angle of the distal segment of the manipulator was measured manually. Since many friction occured during the measurements the manipulator is helped finding its equilibrium position by softly ticking on the edges of the manipulator. These experiments are done in the simulation model Working Model, MATLAB and in the experimental setup at the same conditions w.r.t. object sizes, object locations and placement of the manipulator.

In the second configuration the environment consists of three obstacles placed in a row and an eight-segment manipulator is used. In this experiment the manipulator is manually pushed forward and steered in order to reach the target through the environment. It is checked whether the manipulator is able to reach the target and environmental forces are extracted from the simulation model.

3 Results

3.1 Results of one segment

Theoretically a maximum range of moment of each segment of $[-\pi, \pi]$ rad can be achieved. The range of motion that is measured in the prototype is $[-7/9\pi, 7/9\pi]$ rad, due to the obstruction of the own rigid links. In both the simulations as in the prototype an equilibrium position of one segment at $\theta = 0$ rad is found. This is found by minimizing the energy equation of one segment without force inputs.

3.2 Results of static experiments

The results of the reaction forces from the static experiments are shown in figure 8 for a varying right tendon force. A maximum difference between the matlab-model and simulation model of 0.06N was observed. The results from the experiments show that for both the reaction forces on obstacle one as obstacle two the same trend can be observed. The maximum difference of the simulation model and the experiments are 0.93N and 1.29N for obstacle 1 and 2 respectively. Figure 10 shows a typical result of an equilibrium position from the analytical model of the manipulator after minimization.

The results for the angle is shown in figure 9. The maximum difference between the results of the matlab-model and simulation model in Working Model is 0.01 rad. For the results of the experiment again the same trend can be observed. However, when the bending angle increases the difference between values of the model and the experiment increase. This way, the maximum difference between experiments and simulation models is 0.34 rad.

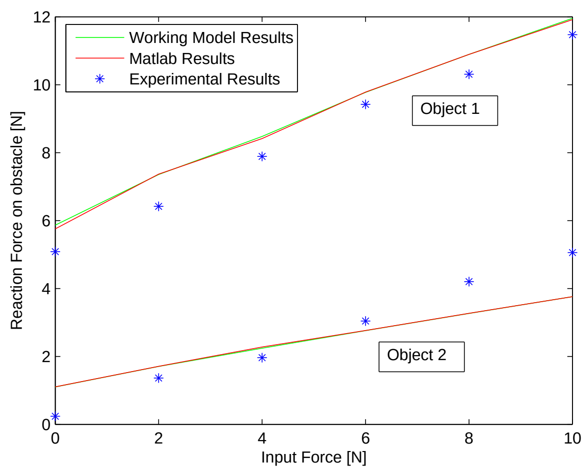

Figure 8. Results of the reaction forces of obstacle one and two measured from the experiment and from simulations. For the experimental results the average values are shown

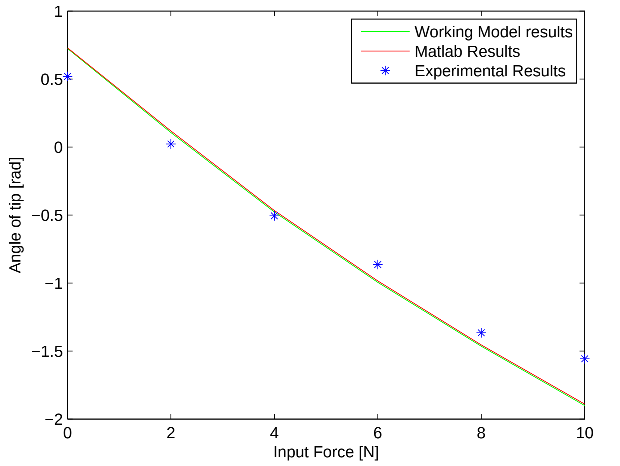

Figure 9. Angle[deg] of the distal segment of the manipulator plotted for different tendon input forces. For the experimental results the average values are shown.

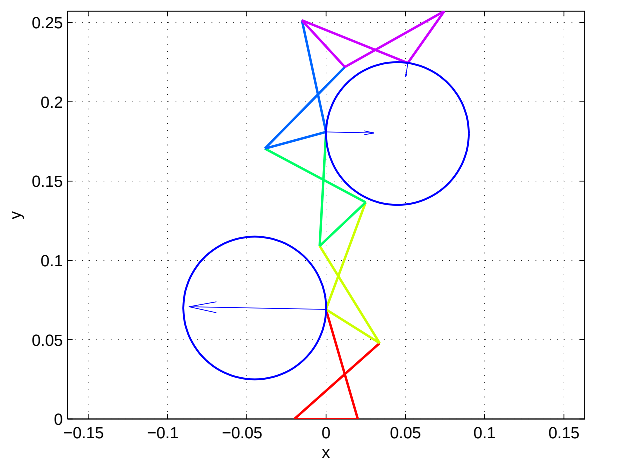

Figure 10. A typical result of a Matlab simulation of the manipulator interacting with two obstacles. This is the configuration that is used during the static experiments. From the figure it can be seen that the second segment comes loose from the object, which is a typical phenomenon in underactuated mechanisms.

3.3 Results of multiple segments in motion

The manipulator can be modified in multiple ways, e.g. by adjusting lengths of several parts of the manipulator and the amount of segments. In figure 13 an example is given of the designed manipulator with multiple segments moving through a channel, which has three contact obstacles. The manipulator is moved forward by a single pushing force on a linear guide, and the steering is done by tensioning left and right tendon alternately. The figure shows that the manipulator is able to reach the target. The input force that is applied to the left and the right angle is shown in figure 11. The reaction forces on the object are shown in figure 12. It shows that tendon input forces of 2N and 4N are required to move to the environment and a maximum pushing force of 4N is required. The maximum force on environment of 1.6N is measured.

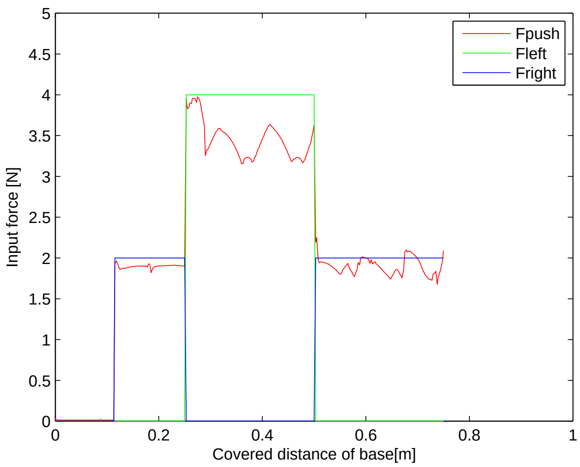

Figure 11. Input forces required for controlling the device.

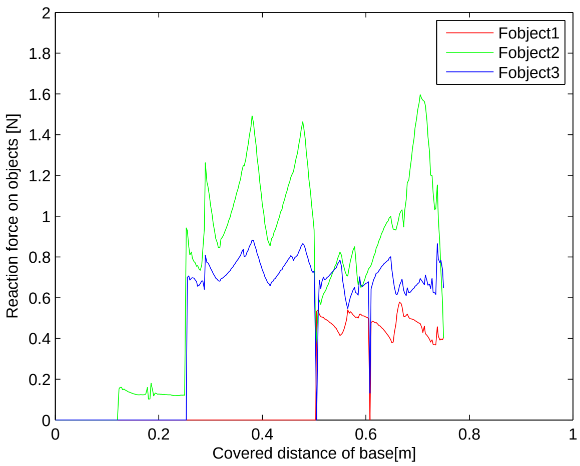

Figure 12. Reaction forces on the three objects, which the manipulator interacts with.

4 Discussion

4.1 Interpretation of results

The results obtained from Matlab and Working Model at the experiments of the static configuration show minimal difference, as indicated in the results. Therefore it can be assumed that the simulation model is validated. The results obtained by the experiments show that similar trends can be observed, but still minor difference occurs between simulation model and experiments.

The described differences between the experimental results and the simulation model can be declared by the capstan effect, known from ropes wrapped around a capstan. This effect states that the friction at the connection points of the tendons increase exponentially for an increasing angle θ and is not included in the simulation models. When the system is in bending, the tension in the cables are decreasing exponentially for increasing angle of θ. This reduced tendon force causes the individual segments to deflect less. This declares that the difference between angle of the experiments and angle of model increases, when the angle is further increased. Also, due to this reduced angle, the forces on the obstacles are smaller.

The results of the simulations from Working Model show that the manipulator is able to reach its target within the benchmark environment. The input forces that are required to control the device are shown in figure 11. It shows that only small forces are required to navigate the device and control is reduced to an on/off control. Since no friction is applied in the working model, the required advancement force stays below the tendon force for steering. This is declared by the fact that during the motion the manipulator takes off on the environment caused by the reaction forces done by the steering mechanism. The difference in range of motion of the prototype due to the obstruction of the own links should not be a problem, since reaching $7/9\pi$ is an exceptional angle.

The environmental forces on the three objects during the simulations are shown in 12. The reaction force on an obstacle starts when the manipulator has reached the obstacle and forms around it. The peaks in the figure are caused by the dis-continuous segments that are interrupting a continous motion.

After the tip of the manipulator reached an obstacle, at the non-contact state the bending goes at a higher rate, because there are no obstructions. At the point that the tip of the manipulator reaches the obstacle, the bending of the tip goes at a lower rate. Simultaneously, the tip of the manipulator looses its contact at the second segment, while the tip point slides along the obstacle, see figure 10. This effect is described as ejection [23], which is a typical phenomenon for underactuated mechanisms.

4.2 Comparison with related systems

In table 2 the proposed design is compared with current state of the art underactuated fingers and continuum manipulators, on range of motion, control and their environmental interaction. When the proposed design is compared to underactuated fingers, it can be seen that this manipulator has an increased range of motion since the it can move with an angle of π rad in two directions per segment.

If this manipulator would be compared with state of the art continuum manipulators it is seen that

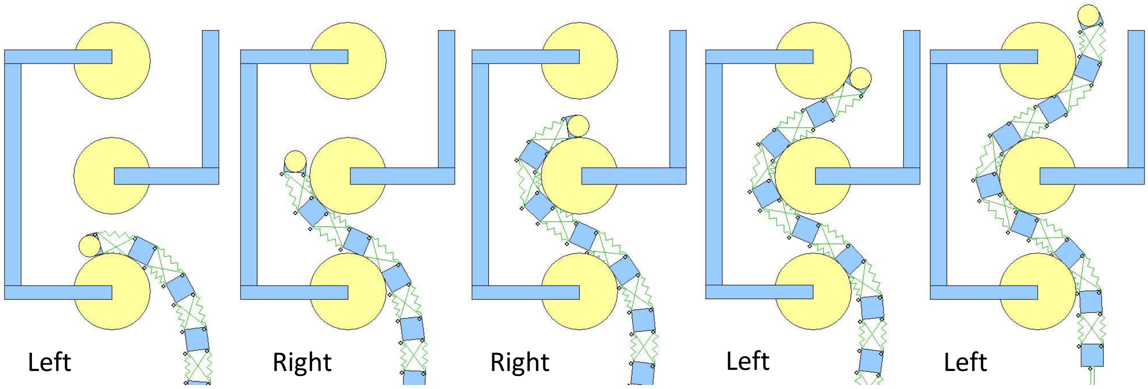

Figure 13. Sequence of the manipulator for moving through a three-obstacle obstacle environment. The control is reduced to a single pushing force and a left or right tendon force, which is indicated in the figure.

this type of manipulator does allow contact with the environment while others don't. Also, by doing this, a lower computational power is required, since only a binary control system is needed. The focus of this manipulator is not on accuracy, but on reaching a high reachability. The manipulator presented in this paper is unique in the sense that it has a range of motion compared with other designs from continuum manipulators and underactuated fingers. It uses underactuation principles to move forward using a simple control system. The manipulator can shape around any object regardless of the amount of obstacles that are already interacted with.

The energy approach is used to evaluate the kinematic behavior of the system and is validated by Working Model. The analytic model can be used as a mathematical framework for optimization when the model is designed for a specific application. Parameters are easily changed.

4.3 Recommendations

The proposed design consists of an actuation system with three actuators, but can be further reduced to two actuators if the variable stiffness is discarted. This manipulator would be preloaded by springs on one side and actuated by one tendon located on the other side. The equilibrium position of this system would be in the upper left/right position, and when pulled the manipulator moves to the other direction. A drawback of this solution is that it is hard to find a straight position, since the equilibrium position is in its upper left/right position.

This manipulator is developed for a 2D environment without gravity, in order to reduce complexity of the system. This is also done because the principles of the new approach of a continuum manipulators that uses environmental interaction becomes clearer when it is presented in a 2D environment, than when the system is designed in a 3D environment with gravity. However, the developed analytical model can be easily extended to a model that includes gravity, by adding the gravitational potential energies to the energy function. Extension to a 3D model is possible when segments are used that have each three crosslink segments formed in a triangular shape connected by ball joints, this would require three additional springs and 1 additional tendon. Still, a high range of motion will be achieved. This is subject for further research.

The friction of the cables within the manipultor could be reduced when pulleys are used, or lubricants are applied. Also the friction of the manipulator on the environment are not included in the model. Therefore the model could be further improved when these effects are included.

Since the manipulator is in contact with the environment, there is a contact force of the manipulator on the environment. Since the proposed manipulator consists of discrete segments it can easily hitch to corners, which can cause peaks in the required pushing force. This effect could be reduced by placing wheels on each side of the manipulator, which changes sliding contact into rolling contact force and therefore reduces the friction. Other possibilities are the placement of a rubber cover around the manipulator, for a smoother exterior. This cover could also function the springs in the cross-links mechanism to equilibrate the manipulator at 0 rad.

The proposed design can be used towards the design of a compliant manipulator. Since each joint within the crosslink joint has a limited rotation, the mechanism would be suitable to be converted into a compliant mechanism. The application of compliant mechanisms has many advantages as it is compatible with many fabrication methods, reduces assembly time, have friction free and wear free motion and provide high precision and high reliability and can integrate multiple functions into fewer components. [24]

This proposed manipulator serves as a research model for a general purpose. Many different applications can be thought of; i.e. rescue robots, inspection devices or cleaning devices for channels. When it is designed for a specific application, the design needs to be further developed and optimized. The developed analytical model is suitable for serving as a framework for optimizing the system towards a specific

Table 2
The proposed design compared to underactuated fingers and continuum manipulators at their current state of research about environmental interaction, faced obstacles, range of motion and control effort

	Underactuated finger	**Proposed manipulator**	**Continuum manipulators**
Environmental interaction type	Adapting to obstacles	Adapting to obstacles	Avoiding obstacles
Number of obstacles confronted with	One	Multiple	Multiple
Range of motion	$[0, \pi]$	$[-\pi, \pi]$	[-0.5 $\pi, 0.5\pi$]
Control effort	Low	Low	High

application. Some of the modifications that can be done are:

- Increasing the stiffness of the springs in the segements of the manipulator: This would increase the overall stiffness of the manipulator and increase the forces on the environment.
- Changing the amount of segments n: This will increase the overall range of motion and reachability of the system.
- Changing this l/b ratio: This influences the rotation characteristics of the segments.

Also these changes can be applied in each of the segments seperately, in order to change the overall behavior of the system as force output or manipulator's shape. This way the shape of a bending can be changed.

The designed underactuated system is in this purpose used for a manipulation task. However, the designed mechanism could also be applied to underactuated grasping purposes. Due to the increased range of motion per segment, it could lead to promising opportunities.

5 Conclusion

This research proposes a novel design of a continuum manipulator that is able to navigate through an unstructured environment by passively adapting to the obstacles. The concept consists of a sequence of cross-linkage segments with springs attached to the end of each linkage. The system is highly underactuated, since only the small amount of three actuators are needed to control the manipulator: one for pushing the manipulator forward, and two for actuating the antagonistic pair of tendons. These tendons are laced through each end of the segments and can bend by a varying force on the tendons. A simulation model is developed and validated, which can be used for optimizing the device towards a specific application.

Due to the variable instantaneous center of rotation of the cross-link mechanisms a range of motion per segment of theoretically $[-\pi, \pi]$ rad can be achieved. Applying the cross-linkage segments in a sequence results in a unique underactuated manipulator that can navigate through an environment with obstacles. Using this properties the manipulator is able to reach highly constrained areas. Results from simulations and a prototype show that the manipulator is able to reach its target though an environment with multiple obstacles, using a simple binary control system with a small control input.

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Appendix A

Concept Development

A-1 Design Method

This part will give a further elaboration on the design of an environmentally interactive continuum manipulator. First an extended method will be described. In figure A-1 a flowchart is shown about the used method. First from a literature study, see appendix C, it is detected that research on environmental interaction within the field of continuum manipulators is underexposed, which led to a new approach in navigating through an environment. Following from this specific approach the research objective, requirements and approach were defined. In order to develop these requirements, first an analysis is done on different types of environments, and how continuum manipulators can interact with the environment.

Following from the requirements, approach and environment, the design of the manipulator is done. The final concept development is done using two different processes, which are done simultaneously and interactively. The first process, shown in green on the left side of the figure, is the conceptual design based on the Pahl and Beitz method. This process subdivides a main task into subtasks. For each of these subtasks subsolutions were developed leading to many possible solutions. These solutions are combined into concepts and evaluated on predefined evaluation criteria. This led to a final design. Simultaneously two models are developed to simulate the concepts. These simulations are needed to evaluate the concepts and give insight in the working principles.

Next, after several iterations, the final design is decided and manufactured into a prototype and tested in an experimental setup. In the next phase the results of these experiments are evaluated and compared with results from several simulations. This leads to a discussion and a conclusion. This is an iterative process which means that several cycles may be runned through before getting the final design. Eventually the research is written in a scientific paper, which acquires new literature and makes the loop complete.

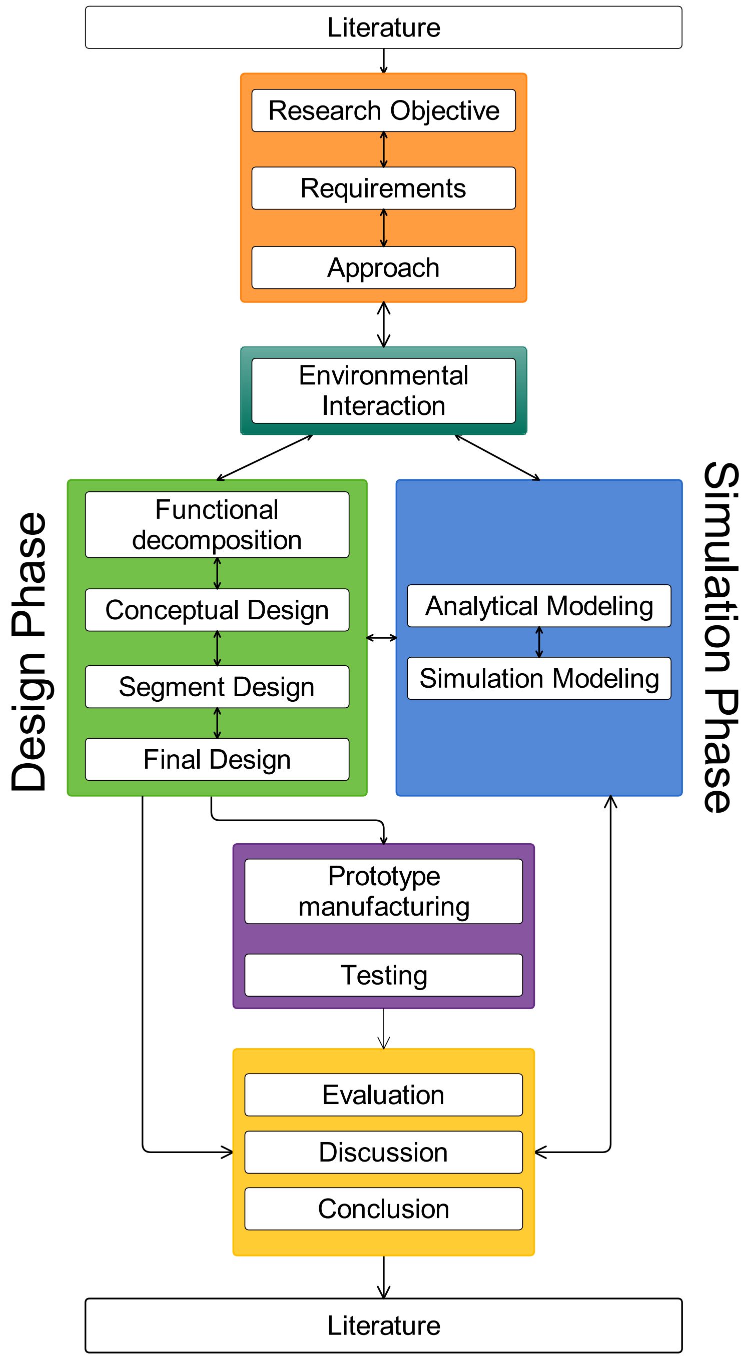

Figure A-1: Method of Research

A-2 Function Analysis

The main function for the continuum manipulator is to move the tip of the manipulator through an environment with obstacles from a position a to a position b_1 or b_2 as depicted in an environment with obstacles, such as a channel as depicted in figure A-2. This main function can be subdivided into two subfunctions, which are indicated in the figure.

1. Advancement: This means that the tip of the manipultor should be able to move forward in order to reach a certain target.
2. Active steering: This means that the manipulator has to be able to actively choose a direction.
3. Passive steering: This means that the manipulator should be able to follow a path regardless of the position in which the manipulator is.

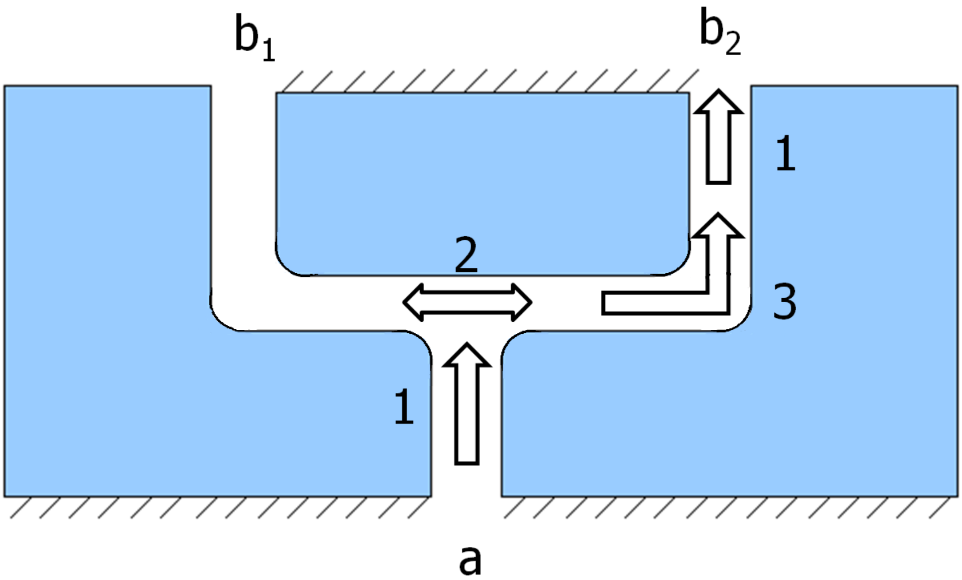

Figure A-2: A typical environment in which the manipulator has to move from a point a to a point b_1 or b_2. The subfunctions are indicated in the figure: 1: Advancement, 2: Choosing a direction and 3: passive steering

A-3 Evaluation Criteria

Subsolutions of the design are evaluated on the following criteria. Concepts are evaluated on a scale of [- -, -, 0, +, ++], where - - is the worst case and ++ is the best case. For each case the worst and best cases are described as a reference.

- Control Effort: The amount of effort it takes to control the device should be low. The control effort is dependent on the amount of actuators and the complexity of the control system. [- -] for high control effort, [++] for low control effort.
- Range of motion: The minimum and maximum angle which one segment can move measured from its equilibrium position. [- -] for low range of motion, [++] for high range of motion.
- Required actuation force: This is dependent on the friction force on the environment. [- -] for high required actuation forces, [++] for low estimated actuation forces.
- Friction loss: This criterion is evaluated by the estimated loss done by friction. [- -] for many estimated friction, [++] for few estimated friction.
- Mechanism characteristics (mech. char.): This criterion evaluates the characteristics of the mechanism evaluated by the equilibrium position of the system and how it rotates. [- -] for bad characteristics [++] for good characteristics.
- Robustness: Since the manipulator is used in wide range of types of environments the manipulator should be robust enough to withstand different forces of the variable environmental influence. [- -] for a low robustness, [++] for a high robustness.
- Force transmission: This criterion evaluates the force transmission of actuators on segments, considering buckling and force transmission. [- -] for a bad force transmission, [++] for a good force transmission.

A-4 Concept Generation

For each of the subfunctions multiple subsolutions were developed and evaluated here.

A-4-1 Advancement principles

- Pushing the arm at the base: In this concept the manipulator is moved forward by a single force that is applied at the base of the manipulator.
- Extensible mechanisms: These subsolution provide solutions which are in a way extensible. It means that the arm reaches its target by changing its length. This can be done in multiple ways:

  Unfolding scissor lift mechanism: In this concept the manipulator moves forward by extending a scissor lift-like mechanism.

  Telescope arm: In this concept the manipulator is moved forward by parts that can be pushed into one another as a telescope.

  Inflation: The manipulator is moved forward by an inflatable hose, which moves forward by inflation.

A-4-2 Choosing a direction

Considering a flexible beam choosing

- Changing the lengths of the sides of the manipulator. This can be done in several ways:

  Pulling cables: Applying force on the cable transmits the force into

  Pushing flexible rods: This subsolution can provide

  McKibben actuators: This subsolution uses two pneumatically driven Mckibben actuators which can independently change in size. A difference in length of the McKibben actuators leads to a rotation of the total system.
- Locally weakaning and stiffening the system: This steering system is based on passive adaption to the environment. The manipulator is moved forward, while the manipulator adjusts its stiffness of the manipulator when it has to make a bending.
- Using bi- or tristable elements: In this subsolution each segment is made bi- or tristable and each segment is controlled individually in order to reach the right shape. When the bi-/tristable element comes in contact with the environment, the segment automatically form towards the environment. It is reset by the mechanism.

A-4-3 Segments solutions

- Cross linkage segment: This mechanism consists of antiparrallel fourbar mechanism which can move over a high range of motion due to a variable instantaneous center of rotation

- Single joint mechanism: This mechanism consists of a fixed single joint which connects all the segments together.
- Fourbar-mechanism: This mechanism is applied in many underactuated mechanisms and consists of a four-bar mechanism with a smaller topbase then a downbase. The mechanism moves by rotating one of the outer links.

A-4-4 Subsolution Selection

Translation:

Table A-1 shows the evaluation of the translation principles. The control effort of the pushing principle is low, has low friction and is a robust system. All the extensible solutions will have many moving parts that are sliding along each other. Because of the many moving parts friction increases. Also it is hard to implement a steering mechanism that can adjust to the length of the manipulator at that. As for the inflation the, the Therefore the extensible mechanisms will be not taken into consideration at the concept development part for the advancement of the tip. Pushing the arm at the base: This would require a low control effort since it is only dependent on a single pushing force. Since no additional mechanisms are put in this model, this turns out to be a good subsolution.

Table A-1: Evaluation of translation principles.

Subsolution	Control	Friction in system	Robustness
Pushing the arm at the base	+	+	+
Unfolding scissor mechanism	+	-	-
Telescope Arm	+	-	-
Inflatable arm	-	0	-

Evaluation of Steering Principles

Table A-1 shows the evaluation of the translation principles. The control effort of the pulling cables are low, since only 1 forces is required for steering the system. The same holds for pushing rods, where only 1 pushing force is required. As for the force transmittance, the pulling cables are most effective, since cables can easily transmit forces without buckling. Pushing rods can be used, but can buckle if the manipulator is in a constrained position. Locally weakening and stiffening the system: This would require a complex control system which would determine the environment and can adjust its stiffness. Also it would require a second mechanism to actively steer the system. Using bi- or tristable elements: This solution would adapt to the environment require many independently controlled segments, which will take a high control effort. Therefore this subsolution will not be taken into consideration for the concept development. From this small analysis it appears that steering by pulling cables is the most promising to be applied in the designed manipulator.

Table A-2: Evaluation of steering systems

Subsolution	Control Effort	Friction	Force transmittance
Pulling cables	++	+	++
Pushing rods	++	+	0
McKibben actuators	+	+	+
Locally weakening the system	-	0	0
Bi- or tri-stable mechanism	-	0	0
Actuators in each joint	−	+	0

Evaluation of Segment designs

Table A-3 shows the evaluation of the translation principles. The crosslink segment shows to have a high range of motion due to the moving instantaneous center of rotation. Also it has good characteristics, since it has its equilibrium position at $\theta = 0$ rad and converges to this point over the whole range of motion. It is suitable to be converted to compliant mechanisms, because of the low rotations in the joint. The revolute joint mechanism has a high range of motion, since it can can move over a high range. However, it is restricted by their own links, and the mechanism characteristics are not ideal. It can have a equilibrium position at $\theta = 0$ rad, but does not converge to the $\theta = 0$ rad equilibrium position over its whole range of motion. Instead, it has two extra equilibrium positions which are reached when the θ is over a certain angle. This mechanism is also less suitable to be converted into a compliant mechanism, since the individual joint has a large rotation. This subsolution has low friction since it can be easiliy beared. 4 bar mechanisms, as applied in underactuated graspers, have a lower range of motion if they are applied in continuum manipulators. The mechanism characteristics are also not ideal since also three equilbrium positions can be found which are converted to if θ falls within the certain region. For convertability and friction the same values of crosslink mechanims hold. From the table it appears that the cross-link segment shows to be the most promising to be applied in the underctuated manipulator.

Table A-3: Evaluation of different segment designs

Subsolution	Range of motion	Mech. Char.	Convertability	Friction
Cross linkage mechanism	++	++	+	0
Revolute Joint	+	+	0	+
4 bar mechanism	0	-	+	0

A-5 Final Concept

The final prototype concept is the combination of the subsolutions as shown in table A-4 and a first prototype is made in construction tool *k'nex*, shown in figure A-3. Further elaboration on the design is found in the main paper.

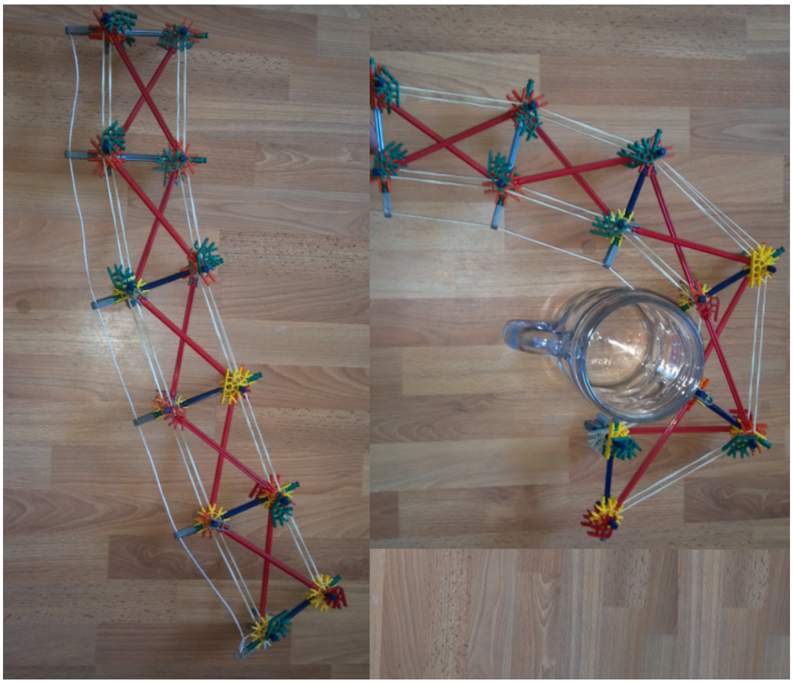

Figure A-3: First prototype made in k'nex.

Table A-4: Final concept by chosen subsolutions.

Subfunction	Choice of subsolution
Translation	Push at base
Steering	Pull cables
Segment	Cross-linkage

Appendix B

Analytics

B-1 Characteristics of segments

In this section x_1 and x_2 and V of a general cross-linkage segment are derived using parameters from figure B-1. Points A,B,C and D describe a quadrilateral having diagonals L_1 (length AD) and L_2 (length BC), and two sides B_1 (length AB) and B_2 (Length CD). x_1 and $x2$ are of the side AC and side BD respectively. θ is the angle of the base 1 with base 2. In this mechanism known are diagonals L_1, L_2, and baselengths L_3 and L_4. The mechanism is determined by an input angle θ_1. θ_3, θ_4 and θ_5 correspond to angles CAD, CAB and DAB respectively.

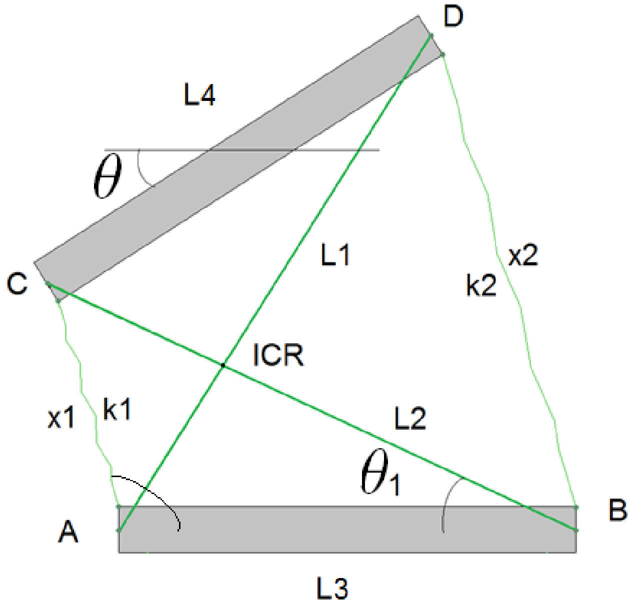

Figure B-1: General model of a crosslink segment with parameters used in the derivation of x_1, x_2 and V

By applying the cosine rule length:

$$x_1 = sqrt(L_1^2 + L_4^2 - 2 * L_4 * L_1 * cos(\theta)) \tag{B-1}$$

by applying cosine rules:

$$\theta_3 = acos((x_1^2 + L_1^2 - L_4^2)/(2 * x_1 * L1)); \tag{B-2}$$

$$\theta_4 = acos((x_1^2 + L_3^2 - L_2^2)/(2 * x_1 * L_3)); \tag{B-3}$$

$$\theta_5 = \theta_3 - \theta_4; \tag{B-4}$$

Knowing θ_5 and θ_1, the x and y coordinates of C and D were calculated:

$$C_x = B_x - L_4 * cos(\theta); \tag{B-5}$$

$$C_y = B_y + L_4 * sin(\theta); \tag{B-6}$$

$$D_x = A_x + L_3 * cos(\theta_5); \tag{B-7}$$

$$D_y = A_y + L_3 * sin(\theta_5); \tag{B-8}$$

Finally θ and x_2 were calculated by:

$$\theta_{kop} = atan2((D_y - C_y), (D_x - C_x)); \tag{B-9}$$

$$x_2 = sqrt(L_1^2 + L_3^2 - 2 * L_3 * L_1 * cos(\theta_5)); \tag{B-10}$$

where $atan2$ is the four quadrant inverse tangent function with range $[-2\pi, 2\pi]$.

Considering a special case where $B_1 = B_2, L_1 = L_2$: In this case a direct function of θ can be derived, by solving two functions derived by the cosine rule. x_1, x_2 and θ can be derived by solving this system:

$$\begin{aligned} S = solve((2*a^2)*(1-cos(th)) - x1^2, (2*(a+B)^2)*(1-cos(th)) - x2^2, \\ a^2 + (a+B)^2 - 2*a*(a+B)*cos(th) - L^2, x_1, x_2, a) \end{aligned} \tag{B-11}$$

$$subs(S.x1, B, L, th, 2, 4, 0.0001) \tag{B-12}$$

In both cases the energy function can be derived as follows:

$$V(\theta) = k_1 \cdot (x_1 - x_0)^2 + k_1 \cdot (x_2 - x_0)^2 \tag{B-13}$$

Figure B-2 and B-3 show some of the characteristics of the segments. It can be seen that the energy behaves as a cosine, and has a continuous motion over the whole range of [-pi,pi] rad. The energydiagram has its minimum value at 0 rad, which means that the equilibrium position is at 0 rad.

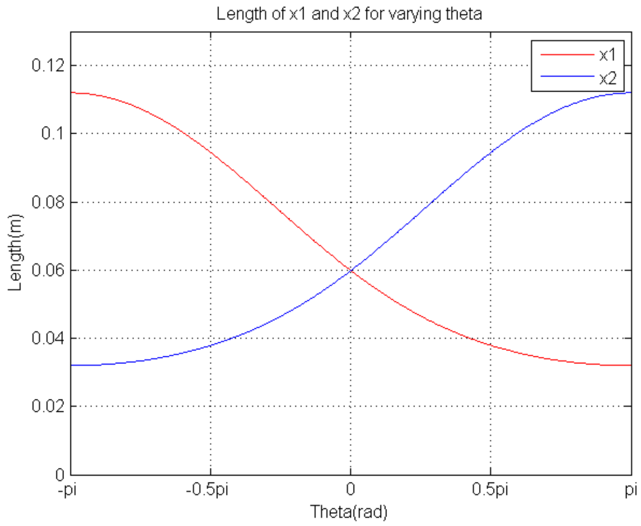

Figure B-2: Lengths of springs x1 and x2, for varying θ

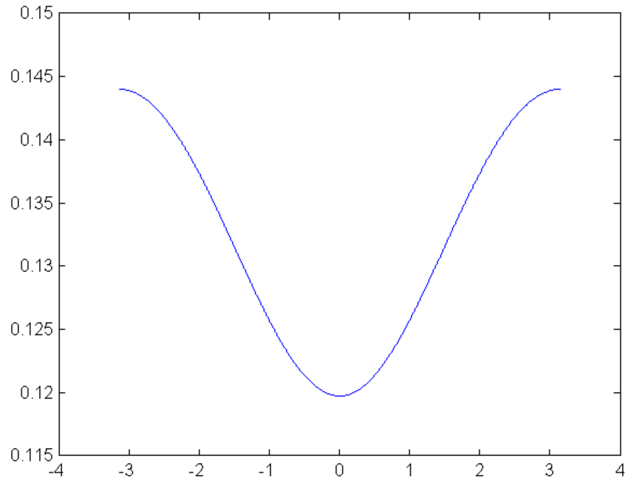

Figure B-3: Energy diagram of segment design

B-2 Experimental setup and prototype manipulation.

More details about the measurement setup are found in figure B-4 and B-5. In these figures it can be seen that the obstacle on which measurements are done is loose from the ground. Figure B-6 shows the measurements of an eight-segment prototype moving through a three obstacle environment. In this figure it can be seen that the manipulator is able to reach a target in an environment with three circular obstacles.

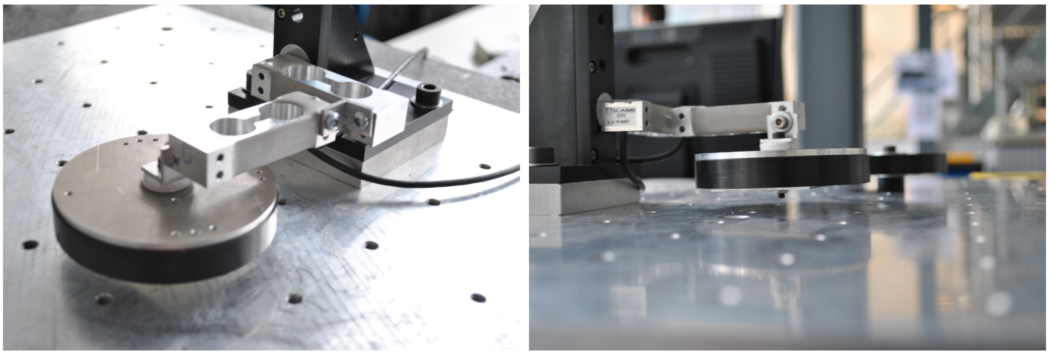

Figure B-4: Details about the measurement setup.

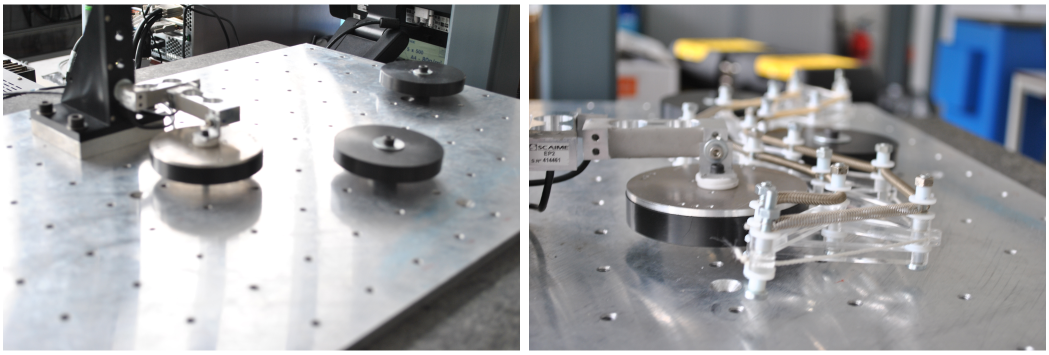

Figure B-5: Details about the measurement setup.

B-3 About the Optimization Algorithm

To perform the optimization the optimization solver, fmincon, of MATLAB is used which is able to handle multi-variable, non-linear, constrained optimization problems. The ability of handling constrained optimization problems and the relatively easy implementation are the main reasons for choosing this algorithm. For solving the constrained non-linear multi-variable optimization problem, fmincon uses SQP, Sequential Quadratic Programming. The SQP algorithm can be summarized in the following steps, see Papalambros and Wilde [2000]:

1. Take the initial point x_0 and estimates the initial multiplier λ_0
2. Set up the matrices for the QP subproblem
3. Solve the QP subproblem, using the Newton method, to determine s_k and λ_{k+1}
4. Set $x_{k+1} = x_k + s_k$
5. Check convergence criteria, no termination? Back to step 2.

In these steps represents x_0 the set of starting design variables, λ_0 contains the initial Lagrange multipliers describing the sensitivity of the objective to changes in the constraints, s_k is the set representing the search direction, λ_{k+1} is the set of new Lagrange multipliers and x_{k+1} is the set of new design variable. The algorithm is called SQP since the result is obtained by solving a sequence of quadratic programming subproblems. SQP is generally seen as the best general-purpose method for constrained problems.

The limitations of the fmincon algorithm, important for the current optimization problem, are: fmincon is a gradient-based method such that the objective and constraint function should be both continuous and should both have continuous ïňĄrst derivatives. fmincon might only give local solutions. When the problem is infeasible, fmincon attempts to minimize the maximum constraint value.

The constraints are based on based on angles of θ and prevent the manipulator from finding a minimum outside the boundaries of the obstacles.

B-4 Choice of Simulation Program

The simulations of the type synthesis were executed with the 2D simulation program Working Model (WM) from MSC Software. WM allows the user simulates the behavior of different bodies interconnected by mechanical components like joints, springs and actuators. The program is therefore suitable for simulating the movement of a simplified flexible structure in contact with the environment. WM can extract the kinematical and dynamical data from any component. Furthermore, WM can export these data such that it can be used for further analysis e.g. in Matlab. Forces were applied by using a pneumatic actuator that can simulate a constant force.

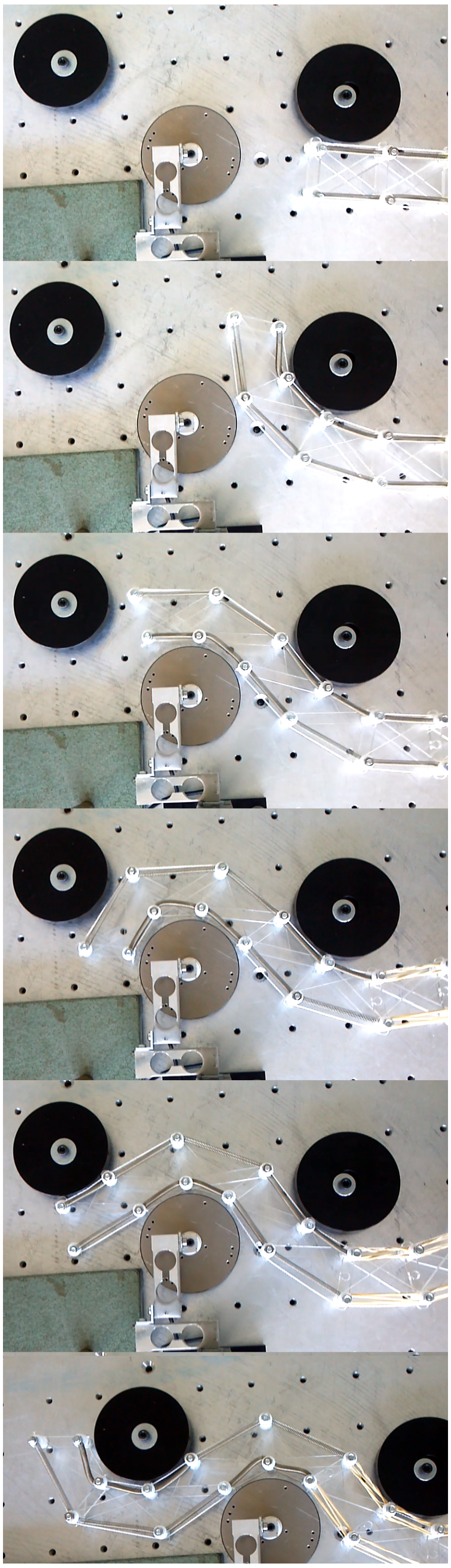

Figure B-6: Manipulator consisting of eight segments moving through an environment of three circular obstacles.

B-5 Compliant Mechanisms

Compliant mechanisms provide significant benefits for motion applications. They can be compatible with many fabrication methods, may not require assembly, have friction-free and wear-free motion, provide high precision and high reliability, and they can integrate multiple functions into fewer components. The major challenges associated with compliant mechanisms come from the difficulty associated with their design, limited rotation, and the need to ensure adequate fatigue life. It is likely that compliant mechanisms will see increasing use in mechanical systems at all size scales and in many application domains as more people understand their advantages and have tools available for their development. [Compliant Mechanisms, Howell, 2001]

Appendix C

Literature Study: A Literature Review on Continuum Manipulators and Environmental Interaction

A Literature Review on Continuum Manipulators and Environmental Interaction

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Abstract—
This paper presents the results of a literature search about continuum manipulators and their environment interaction. Continuum manipulators are large or infinite degrees of freedom structures that can be used for navigating through an environment with obstacles by a limited amount of actuators. In this type of task environmental interaction is inevitable, but a clear overview of how they can interact with eachother is missing. Therefore the environmental interaction will be studied. Through a literature search it is found that three sub research areas of continuum manipulators can be distinguished: Mechanical design, kinematic modeling and path planning. For each of these research areas it is examined how they interact with the environment and what the interrelations of the sub areas are. The results show that many models of continuum manipulators do not take into account the environmental interaction, but rather focus on accuracy. Also in most path planning algorithms obstacles are avoided instead of allowing any contact with the environment. Therefore environmental interaction is an underexposed research area. A new approach, where environmental contact on continuum manipulators is emphasized, could bring promising possibilities.

Keywords: Continuum Robotics, Kinematic Modeling, Environmental Interaction, Path Planning

1 Introduction

Industrial 6 degrees of freedom robots are suitable for accurate positioning tasks as pick and placement in structured environments. However, this type of robot is not suitable for reaching in confined environments. A better alternative for this kind of tasks is the use of a hyper-redundant manipulator, a manipulator with a large or infinite degrees of freedom that can use their redundancy to improve their reaching performance in complex and cluttered workspaces [1]. Hyper-redundant manipulators can move similar to the shape of snakes, elephants trunks or octopus' tentacles, due to their increased degrees of freedom and flexibility. The emerging field of hyper redundant manipulators can be divided into continuum, discrete or variable geometry truss (VGT) structures depending on their degrees of freedom and structure, see figure 1. Discrete manipulators use rigid links and joints and have a finite degree of freedom. The VGT models consist of a longitudinally repetition of octahedral truss modules. Continuum robots use flexible elements and have a large or infinite degrees of freedom. A continuum manipulator, which consists of a linkless compliant structure, can move by elastic deformation of the manipulator [2]. The use of compliant mechanisms has many advantages such as reduction of friction, backlash, wear, lubrication, fabrication costs, maintenance and weight compared to rigid link mechanisms [3]. Applications for continuum robots include search and rescue robots, inspection robots and minimally invasive surgery devices. Nature shows that these manipulators can be very suitable for moving through obstacles or grasping objects. See table 1 for a short comparison between industrial robots and continuum robots.

The ability to interact with the environment is often mentioned as being a promising feature for continuum robots. However, few research has been done in this area. In the development of continuum manipulators the main focus is control and accuracy rather than how they interact with the environment. Also in the development of path planning algorithms the focus is on obstacle avoidance rather than environmental contact. Environmental interaction is an under-

Table 1
Comparison of Industrial versus Continuum manipulators

	Industrial Manipulators	**Continuum Manipulators**
Degrees of Freedom	≤6	Large or infinite
Environment Type	Structured, spacious, pre-known	Unstructured, with obstructions, unknown
Tasks/Applications	Accurate positioning	Approximate positioning
	Pick and placement tasks	Whole Arm Grasping
Suitable for environmental contact?	No	Yes
Suitable for obstacle Handling?	No	Yes

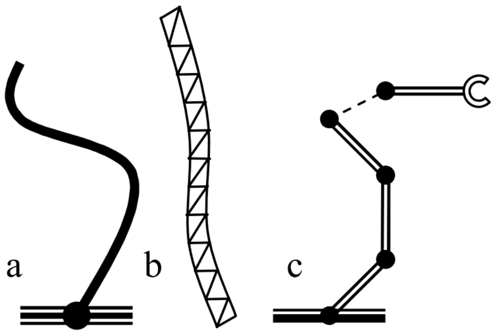

Figure 1. Different morphologies of hyper-redundant manipulators: a) Continuum manipulator, b) Variable geometry truss, c) Discrete manipulator. Figure extracted from [4].

exposed subject and therefore topic of this study.

The objective of this literature research is to identify the main research areas that are involved with the design and control of continuum manipulators and how the different areas interact with eachother. A second objective is to identify how these seperate research areas deal with environmental interaction. A third objective is to identify promising research opportunities, based on these results.

This paper is structured as follows. In section 2 the method is explained, by showing the search method and how the results are selected. In section 3 the results of the literature survey are analysed and presented by categorizing it in three main areas. In the discussion, section 4, the results will be discussed, interpreted and a future research direction is proposed. Finally, the conclusions are presented in section 5.

2 Method

In this section a search method is presented and a classification is made for the research of continuum robots.

Literature is found for the area of continuum or soft robotics. The results show that within this research area three sub research areas can be distinguished. These main research areas are: Mechanical development, kinematic modeling and environmental interaction. Mechanical development is defined as the research about mechanical design and working principles of a continuum robot. Kinematic modeling is defined as the study for modeling the continuum robot in order to estimate the positions of the manipulator at a certain force input. Environmental interaction is the research area where algorithms are developed for path planning.

Articles are selected using the keywords and combinations of keywords as shown in table 2, and found by using the search engines for scientific articles Scopus and Google Scholar. Each research area has several related keywords, since each research area can be defined in multiple ways. In the found literature relevant references were used to find new articles and to redefine the search terms. The found articles are restricted to designs, concepts and developments of continuum robotics. Also research work that is related to or applied for continuum robotics is included. The latter also contains modeling theories, control theories and path planning algorithms of continuum manipulators.

In order to investigate the environmental interaction of each of the research areas, for each of these areas state of the art research will be presented and will be evaluated on their environmental interaction.

3 Results

As mentioned in section 2 three main research areas can be identified based on the gathered papers:

1) Mechanical design, focusing on the physical development of the continuum manipulator.

Table 2
Keywords and associated terms used for literature search. Keywords are used and combined to find relevant literature in the field of continuum robotics and environmental interaction.

Main Keyword	Related Keywords
Continuum manipulators	Soft OR continuum OR flexure AND robot OR robotics OR manipulator OR arm
Environmental interaction	”Environmental interaction” OR ”path planning” OR ”obstacle avoidance”
Environmental contact	Compliant OR environmental OR obstacle AND contact OR interaction
Kinematic modeling	Kinematics, flexure modeling, cosserat rod OR beam, pseudo rigid body model, constant curvature

2) Kinematic modeling, focusing on development of mathematical models of continuum manipulators.
3) Environmental interaction, focusing on how continuum manipulators can interact with the environment.

For each research area the state of the art developments will be listed and it will be determined how the different areas are related to environmental interaction.

3.1 Mechanical Design of Continuum Robots

This section presents the recent developments of continuum robots and their applications. Table 3 shows a selection of state of the art continuum manipulators. For each manipulator the main properties are listed. Applications for development are general purpose [5], [6], [7], [8], [9], biomimicry: [10], [11] and applied for surgical tools [12], [13], [14].

A large variety of continuum robots has been developed using many different actuation principles. These different actuation forms can be classified into three categories according to the method and location of actuation [2]:.

1) Extrinisic actuation, which uses remote actuation. The actuators are located outside the manipulator and the motion is transferred via a mechanical linkage. An example is a tendon driven manipulator.
2) Intrinsic actuation, where the actuators are on the device and form part of the mechanism. This can be pneumatics, hydraulics or motors placed in different stages on the manipulator.
3) Hybrid actuation, which uses a combination of both intrinsic and extrinsic actuation. An example is a manipulator that uses both pneumatics and tendon actuation.

Each of these groups can be further classified into planar and spatial devices. Planar means that the manipulator is used in a single plane only, whereas spatial manipulators can work in any direction perpendicular to their longitudal axis.

A few examples of state of the art continuum manipulators are threated next: In [10] a tendon driven soft manipulator is developed based on an octopus arm. The octopus tentacle is fabricated to work in water where buoyancy complements gravitational effects. With the kinematic model, based on cosserat beam kinematics, the shape of the manipulator is calculated based on input forces of the tendons. The kinematic model and the protoype results are compared and an position error of 6 % is measured. Another state-of-the art manipulator is the Octarm [17]. This manipulator is a pneumatically driven arm developed for the purpose of whole arm object grasping. A third example of a recent development in continuum robotics is [14]. This manipulator is able to sense forces that are applied on the robotic arm. The design of the continuum arm highly depends on the task that it should perform.

3.2 Kinematic Modeling

Since the presence of continuum manipulators many different flexure or kinematic models have been developed. These models estimate the position and shape of the manipulator based on the applied internal and external forces. The consideration for developing the models is to find an accurate model which is able to calculate the shape and positions of the manipulator as fast as possible. The models then will be used for being implemented in control schemes. In table 4 a concise overview is given on current flexure models and compared on accuracy, computational time and experimental method. In table 3 it is also shown what kinematic models is used for the particular design. Each model has different approaches and will be briefly explained with

Table 3
Overview of state of the art continuum manipulators

Name / Description Environmental Interaction	Ref. Application	Actuation type Evaluation	Kinematic Model Error
Artificial Muscle Continuum Robot	[5]	Pneumatic, McKibben	Mckibben force model
Octopus inspired Continuum Robot	[10]	Tendon	Cosserat beam
Octarm	[6]	Pneumatic, McKibben	Cosserat beam
Elephent's trunk manipulator	[11]	Tendons	Constant Curvature
Air-Octor	[7]	Tendons + Pneumatics	Constant Curvature
Planar continuum robot model	[8]	Tendons	Cosserat rod/string model
Airoctor + Octarm combi	[9]	Tendon + Pneumatics	Constant Curvature
Multisegment continuum robot	[13], [14]	Actuation rods	Virtual Work Model

Ref.	**Environmental Interaction**	**Application**	**Evaluation**	**Positioning error**
[5]	n/a	Exploration	Rotation, load capacity	n/a
[10]	n/a	Bio-inspiration	Accuracy	6%
[6]	Object grasping	Exploration	Accuracy	5%
[11]	Avoidance algorithm	Bio-inspiration	Accuracy	50%
[7]	Grasping objects	Exploration	Performance	n/a
[8]	n/a	General	Accuracy	1.70%
[9]	Contact force estimation	General	Accuracy	2.2% (no Gravity)
[13], [14]	n/a	Surgical tool	Force detection	n/a

Table 4
Overview of kinematics models used to model continuum manipulators

Method	References	Approach	Validation	Implemented in:	Error	Computation Time
Constant curvature model	[15], [6]	Geometrical representation	Experiment	[7],[9],[11]	50%	++
Cosserat rod model	[6], [8]	Newtonian formulation	Experiment	[6], [8], [10]	1.7 - 6%	-
Pseudo rigid body model	[16]	Mass-spring system	Simulation	n/a	1.2%	+

advantages and drawbacks. Also the model evaluation will be explained and compared in this part.

Each kinematic model is evaluated on accuracy by using the position error as a percentage of the total length. These error percentages are also shown in table 4 and 3. The percentages show a range of the best and worst case scenario of the experiments, depending on the load case. The errors are extracted by experiments after applying a tip-wrench on the manipulator. The end positions are measured and compared with the results of the exact finite element model, to estimate the error. Some of these results are based on physical models, others are based on simulations. This is indicated in the table.

An early developed kinematic model, the constant curvature model uses a geometrical approach that assumes a piecewise constant curvature shape of the backbones. In [18] an extended review on the constant curvature is given. The constant curvature model is a lower order model that is useful for fast computation of inverse kinematics [11]. However, because of this simplification, the constant curvature model becomes unreliable when it is applied to dislinerities as buckling and compression loads. Also gravitational effects of the model are not included in the model. The model has been implemented in several models as [11], [7], [9]. In a recent model [6] the constant curvature model is tested and compared with the exact model and shows a positioning error upto 50%. It is implemented in models as [15].

Other approaches that do incorporate dynamic effects are the smooth curvature model, the pseudo-rigid-body method and the cosserat rod model. These are based on physical methods as mass-spring system, Euler-Bernoulli equations and Newtonian equations respectively. These models show better accuraciy levels but are computationaly expensive.

Another kinematic model uses the pseudo rigid body (PRB)-model. Using the PRB-method a compliant structure is modeled as rigid mass elements connected by revolute joints and torsion springs [16]. The method uses Newtonian equations for approximating the displacements of the joints for any given tip wrench. In [16] the PRB model is implemented in a simulation model and compared with a tip-wrench simulation of a FEA model to determine the accuracy. The results show a maximum tip error of 1.2 %. Limitation of the model is that it is only valid for a limited range of motion and applied force. Also, the PRB model cannot calculate the shape of the manipulator, but is limited by the coordinates of the end position. Another limitation is that the PRB model is not suitable for real-time control [19].

An other frequently applied method is the cosserat rod model. This model consists of a one-dimensional continuum body in which the generic material element is considered as an infinitesimal small rigid body which can rotate independently from the neighbouring fellows. The material element carries material and geometrical properties of the cross section. The cosserat model is implemented in [10], where kinematic equations are derived for different cable tensions. The prototype is tested for different tension forces and a maximum position error of 6% is measured. Another implementation of the cosserat model is in the Octarm [6] showing a maximum error of less than 5%. [8] introduces an extension of the cosserat rod model where tendon forces can be represented as a distributed load along the beam. It shows an error of 1,7 % based on tip load experiments.

3.3 Environmental interaction

The environment is regarded as the objects in the workspace of the manipulator at which the manipulator can interact. This environmental interaction can be either done by having contact with the environment or by obstacle avoidance. Both forms of interaction are often mentioned applications of continuum manipulators. The algorithms to move through a set of obstacles are called path planning algorithms. This can be done by having contact with the obstacles or avoid them. An overview of path planning algorithms is shown in table 5

3.3.1 Path planning algorithms

The application of avoiding obstacles is already mentioned in [20]. Since then many obstacle avoidance or path planning algorithms have arisen. In [11] a design is proposed that can avoid with obstacles using predefined curves. Another approach [21] is based on real-time adaptive motion planning (RAMP) and this algorithm is developed for a hyper-redundant manipulators to avoid any contact with obstacles. The algorithm is based on a dynamic environment where obstacles can move. For every timestep the algorithm calculates a collision free path. Reference [22] uses this algorithm and applies it for continuum manipulators. Previous algorithms as PRM and RRT planner are based on an offline environment with predefined obstacles. In [23] the authors show another dynamic obstacle avoidance algorithm. In table 6 the algorithms that are used are divided into unstructured and structured environment and known and unknown environment.

Table 6
Classification of path planning algorithms in environment type and contact allowance

	Allow Contact	Avoid Contact
Known Environment	[25], [26]	[23], [20], [24]
Unknown Environment	n/a	[22], [21]

4 Discussion

In this section the results will be discussed and interpreted by each of the three research areas. As stated in many papers continuum manipulators are promising to be applied in an unstructured environment [27]. After all, their flexibility allow them to move around obstacles to reach hard to reach places. It will be discussed to what extent the developments in the different fields of continuum robotics actually focus on this feature.

4.1 State of the Art Continuum Manipulators

The field of continuum robotics is a popular research field, where a large amount of papers can be found. It can be seen from table 3 that many of the found papers consider the accuracy of the models as the principle evaluation criterion. However, continuum manipulators are shown to be at a disadvantage for precision positioning tasks, unless they are instrumented with numerous sensors and equipped with sensor-based control strategies as stated in [1]. Also, in a study of [27] where continuum structures from nature and mechanical continuum manipulators are compared it is already observed that most developments have been motivated by the desire to precisely control their shape through the continuum, while in nature soft continuum limbs are used mostly for approximate positioning.

4.2 Accurate Modeling

Many different kinematic models have been developed to calculate the shape of the manipulator and end position. As can be observed from table 3, one of the major concerns in the development of kinematic models has been accurate positioning. As shown in table 4 kinematic model can reach a high accuracy upto a positioning error of 1 percent, but it still has some remarks. The positioning error results are based on simulations or experiments that are limited to tip wrenches and do not take into account any environmental effects. This is remarkable because in an unstructured environment the continuum arm will be exposed to multiple wrenches at multiple positions. The found position errors will be different when these multiple wrenches are applied. Another limitation is that models are often limited to a certain range of motion while the continuum robot goes beyond traditional mechanics. Non-linear effects are inevitable for continuum arms in unstructured environment, but these are often not included in the models. In case an accurate positioning device is required rigid link manipulators form a better alternative than continuum manipulators. In the case where environmental contact is involved, other factors become more important than accuracy, like: what is the force applied to the environment and what is the optimal way to control the device with a minimum amount of actuators.

4.3 Path Planning

As seen in the results, researchers have put many efforts in developing path planning algorithms that are able to navigate through obstacles or environment with a continuum structure, see table 5. The algorithms that are found can navigate in a preknown virtual environments. Most of these algorithms avoid any contact with the environment and only few include environmental contact. Obstacle avoidance algorithms can be useful when moving through fragile, unstable environment that can be damaged by the manipulator or that the environment is harmful for the manipulator, i.e. by sharp edges or hot surfaces. For the use in normal environment these situations are exceptional. Algorithms that do include environmental contact are based on virtual environments and require a preknown environment and are computationally intensive.

Table 5
Overview of path planning algorithms and their properties of the environment and the manipulator

			Environment Properties							Manipulator	
Ref.	Algorithm	Allows Contact	Known	Unkn.	Soft	Hard	Dyn.	Stat.	Cont.	Rigid
[21]	RAMP	No		x	n/a	n/a	x	x	x	
[23]	Mode shape function	No	x		n/a	n/a	x		x	
[22]	RAMP	No		x	n/a	n/a	x	x	x	
[20]	Geometry based	No	x		n/a	n/a		x	x	x
[24]	Potential fields	No	x		n/a	n/a		x	x	
[25]	Probalistic roadmap	Yes	x		x			x	x	
[26]	Probalistic roadmap	Yes	x		x			x	x	x

Current path planning algorithms are hard to implement in physical continuum arms. Most of these algorithms are based on a preknown environment, while in unstructered environments the environment is unknown. It will require many equipment to estimate the environment. Furthermore the avoidance algorithms are computationally expensive. As found in table 6 no path planning algorithms were found that can be used in an unknown environment where contact with environment is allowed. This is remarkable because it is found that continuum manipulators are especially suitable to be used in an unstructured environment with contact.

It is still found to be a difficult task to navigate through these obstacles. However moving such a device is a difficult task that requires a large computing power and a complicated mechanical design of the manipulator. Often, these algorithms are limited by simulations and are not applied on a real continuum manipulator. For obstacle avoidance you need an obstacle map and using that map the algorithm is applied.

Applying environmental avoidance in a continuum structure makes control unnecessairy complicated. It requires many d.o.f. to form the arm in complex shapes to avoid obstacles, while when obstacle contact is allowed, only 1 d.o.f. may be sufficient. In that case the arm can form around the as shown in using a coupled mechanism as shown in [11].

4.4 Interaction of Different Research Areas

Three different research areas were distinguished, being mechanical design, kinematic modeling and path planning. Ideally each of these three research areas would be used to optimally use every aspect of the manipulator. The interaction between mechanical design and kinematic modeling is the highest. This interaction consists of mostly model validation. The interaction between kinematic modeling and path planning is zero. There is no research found where the kinematics and path planning algorithms are combined where kinematic models are implemented in path planning algorithms. Also the interaction between path planning and mechanical development is minimal. There is only one model found where a path planning algorithm is implemented [11].

Having mentioned this shows that there is a need for the development of a new continuum mechanical model for the purpose of environmental interaction. As can be observed in this paper, development in continuum robotics hold on to criteria as accuracy for performance evaluation, which are often used in precision technology. But continuum robots have to cope with so many different aspects, that an accurate model is hard to realize. The interaction between the research areas of modeling and path planning is minimal. Prominent kinematic models are not used in path planning problems.

4.5 Future Approach

The previous parts indicate that a new approach is needed for continuum robotics where accuracy becomes a factor of minor importance and allowing contact has higher priority. This different approach of moving through obstacles could be not to avoid obstacles but have intentionally contact with the obstacles or environment. Applying intentional environmental contact has many advantages that can provide several new applications. Adding contact points to the manipulator can lead to steadier operation of the end effector, because the length of the loose end will decrease. Also the amount of actuators can be reduced for control of the manipulator. The optimal way to make use of environmental contact should be a topic of a next study.

Applications for continuum manipulators that make use of intentional contact are numerous. Applications that require manipulation behind a corner or manipulating through a multiple obstacle field belong to promising applications. In literature few is known about this intentional use of environment. The use of intentionally environmental contact brings new challenges for mechanical design and kinematic modeling of the continuum manipulator, and is subject for further research.

5 Conclusion

A literature review is done on continuum robotics and evaluated on how they interact with the environment. Continuum manipulators are mentioned to be promising for being used in an unstructured environment. These environments can consist of many obstacles where contact with the environment is inevitable. Through a literature search using Scopus and Google Scholar many papers were gathered. The results can be divided in three main areas: Mechanical design, kinematic modeling and obstacle avoidance. Many physical prototypes are developed for various applications as well as many models to describe the kinematics and forces of the continuum arm. Path planning algorithms are developed mainly to avoid obstacles. Results show that the main focus of research on continuum robotics is accurate positioning and avoidance of obstacles. Path planning algorithms are designed for avoiding obstacles while the reason of avoidance remains unclear. Research in continuum robotics that allow environmental contact is underexposed. A different approach leading to many advantages could be the use of intentional environmental contact, where the environment is actively used for moving through the obstacles. Using intentional environmental contact the continuum arm can get extra support, which can lead to a stabler movement of the end effector. Manipulating around corners and moving through unstructured environment belong to promosing applications. The intentional use of environmental contact brings new challenges for the mechanical design and kinematic modeling of the continuum arm and requires further research.

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