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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], [3] . These increased dof makes them promising for being applied as rescue robots, inspection devices and minimally invasive surgery devices. This type of manipulator 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 [3].

The concept of many simply actuated bending modules forming a backbone In the past decades an increasing number of continuum manipulators has been proposed using many different actuation principles. These include tendon-driven [4], [5], [6], pneumatically driven [7], [8] and a combination of both tendons and pneumatics [9], [10] 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 [5]. Another oftenly used approach is the cosserat rod method [8] [11], which determines the shape of the manipulator using force-torque balance equations [12]. Using this approach a positioning error of upto 1.7% can be achieved [6]. 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 [13], [3].

The main advantage of a continuum robot compared with a rigid link robot is that their inherent compliance can be used to actively engage with the environment, by whole arm grasping or environmental navigation. In many applications continuum robots have contact with their environment as they are deployed [14], [3], [15]. An example where the environment is actively used to navigate through an environment can be found in [16], where a continuous robot can move through an environment by a peristaltic wave motion.

A 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 [17], [18], [19]. If there is environmental contact involved, this is done in a preknown environment and requires a computationally intensive algorithm [20].

From previous research it can be found that researchers are 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. 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 actively used to navigate through an environment. 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 [21], [22], [23], 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.

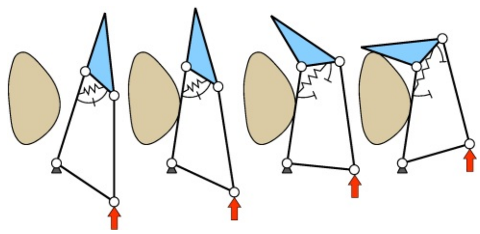

Figure 1. Closing sequence of an underactuated 2dof finger adapting to an object using a single actuator. Figure adopted from [23].

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 number 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.

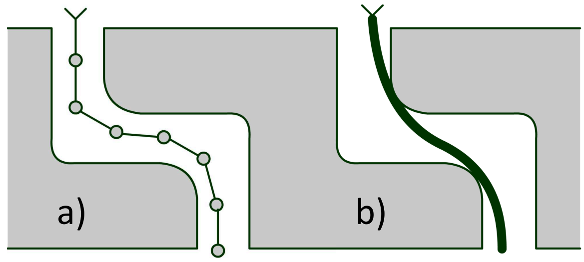

Figure 2. An environmental interaction case: (a) Discrete manipulator with obstacle avoidance (b) Continuum manipulator with environmental interaction

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 number 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 manipulator 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 continuum manipulator to be designed 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 reproducible 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.

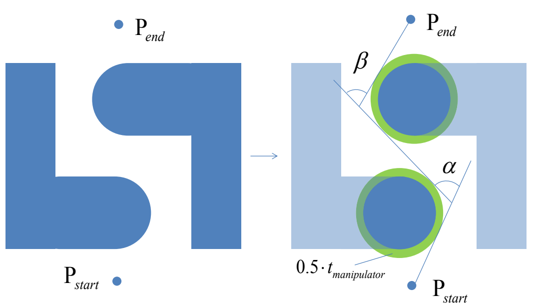

Figure 3. (a) An environment in which the manipulator navigates from a starting point P_{start} to a target point P_{end}. (b) The environment can be reduced to a two-obstacle field with a minimum required range of motion of the manipulator of α and β dependent on the width of the manipulator, $t_{manipulator}$

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 are within the range of motion of each segment of the manipulator. The range of motion of one segment, $RoM_{segment}$, is determined by the maximum and minimum rotational displacement per segment, θ_{max} and θ_{min} respectively, and is given in equation 1.

$$RoM_{segment} = \theta_{max} - \theta_{min} \tag{1}$$

The RoM of a system RoM_{system} with n segments is defined by equation 2.

$$RoM_{system} = n \cdot RoM_{segment} \tag{2}$$

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 manipulator through the environment with obstacles. Two forces are distinguished:
   a) The force required to steer the manipulator into the right direction.
   b) 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 [24], 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.

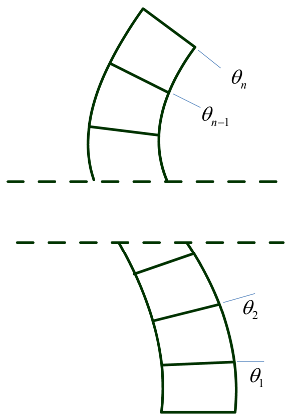

Figure 4. A general model consisting of n segments, where each relative angle is denoted by θ_i

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.

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 without crosslinks, 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 while maintaining balance between the whole driving forces and contact forces. This final concept will be further analyzed in the next sections.

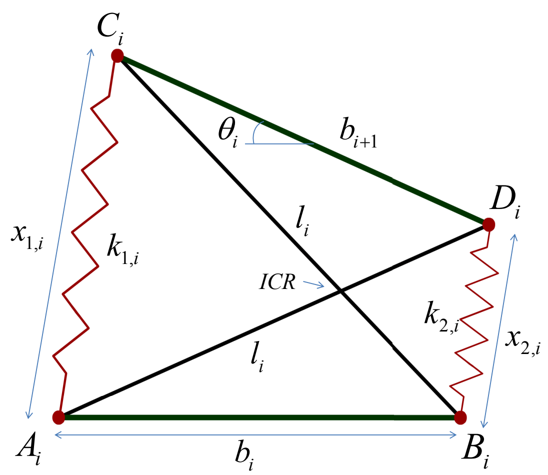

Figure 5. Schematic representation of the ith cross four-bar segment shown at a random θ. Bar CD rotates at an angle θ by the 4 revolute joints A, B, C and D. The Instantaneous Center of Rotation (ICR) is located at the intersection of the two cross links.

2.4 Modeling

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

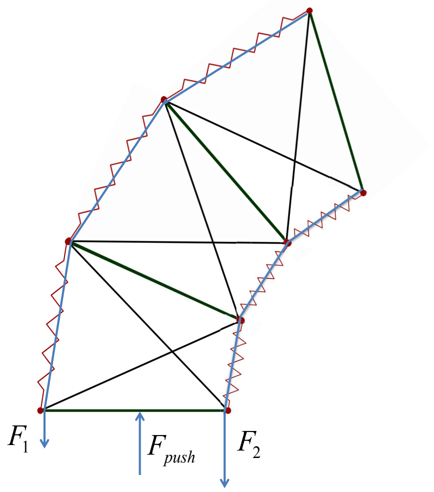

Figure 6. Schematic representation of a small sequence of cross segments. The force inputs F_1 and F_2 are used to bend the manipulator. F_{push} is used to move the manipulator forward.

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 [25], [26]. The model will be used to calculate the actuation forces and the forces on the environment. The mathematical model will give us 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 [26], 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 [25]. 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 separate joints at a segment i with an angle of θ_i are determined using trigonometric equations.

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 3. In this equation $x_{1,i}$ and $x_{2,i}$ are the length of the springs.

$$U_{spring} = \frac{1}{2}\sum_{i=1}^{n}(k_{1,i} \cdot (x_{1,i})^2 + k_{2,i} \cdot (x_{2,i})^2) \tag{3}$$

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 4. 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.

$$U_{spring} = \sum_{i=1}^{n} k_i \cdot (l_i^2 - b_i^2 \cdot cos(\theta_i)) \tag{4}$$

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

$$U_{tendons} = F_1 \cdot (\sum_{i=1}^{n} x_{1,0} - x_{1,i}) + F_2 \cdot (\sum_{k=1}^{n} x_{2,0} - x_{2,k}) \tag{5}$$

In order to model the contact force of the manipulator at the environment, the environment is modeled as a spring with a stiffness of $k_{env} = 10^5$ N/m. This spring becomes only active at the points where the manipulator is in contact with the environment. The energy done by the environmental springs is defined in equation 6. The compression that the manipulator makes on the environment at contact point j is denoted by u_j.

$$U_{contact} = \frac{1}{2}\sum_{j=1}^{m} k_{env} \cdot (u_j)^2 \tag{6}$$

Adding all the potential energy equations yields:

$$U_{total} = U_{spring} + U_{tendons} + U_{contact} \tag{7}$$

The contact force $F_{contact,j}$ at contact point j is then calculated by the equation:

$$F_{contact,j} = k_{env} \cdot u_j \tag{8}$$

The equilibrium position of the system is then found by minimizing the potential energy function 7. 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 acrylic 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.

The experiments were done in two configurations. In the first configuration the environment consists of two obstacles with a distance of 11cm between the two centers. 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

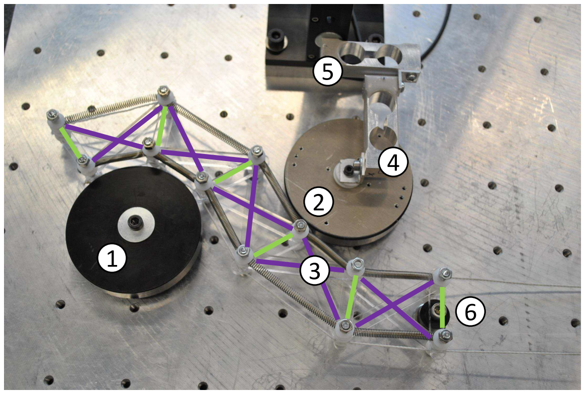

Figure 7. Experimental setup with prototype. The prototype (3) is mounted on a plate (6) and interacts with two obstacles (1 and 2). A variable force is applied on the tendons, while the x- and y- forces on one of the obstacles (2) was measured by two perpendicularly placed load cells (4 and 5).

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.

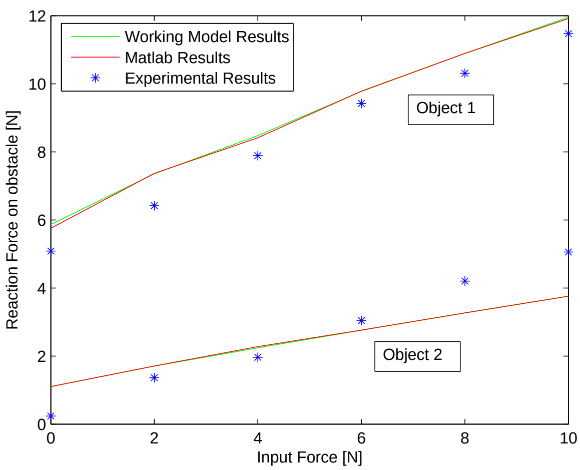

Figure 8. Results of the reaction forces of obstacle one and two measured from the experiment and from simulations. For the experimental results the average values are shown

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

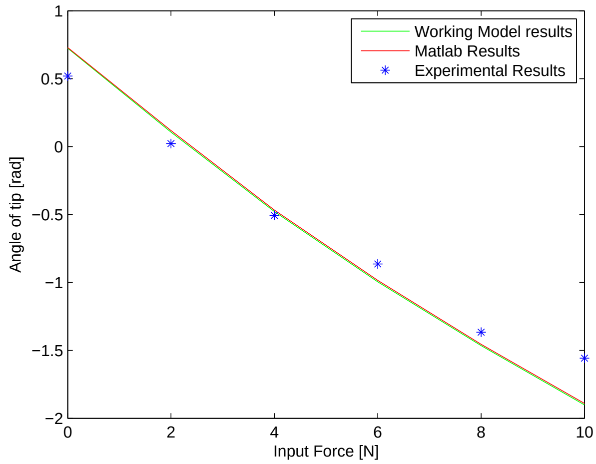

Figure 9. Angle[deg] of the distal segment of the manipulator plotted for different tendon input forces. For the experimental results the average values are shown.

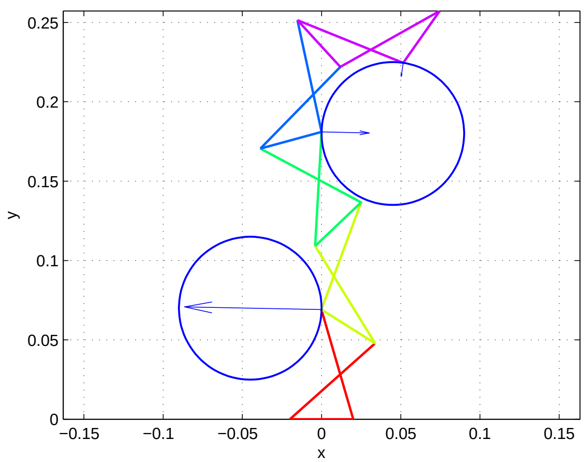

Figure 10. A typical result of a Matlab simulation of the manipulator interacting with two obstacles. This is the configuration that is used during the static experiments. From the figure it can be seen that the second segment comes loose from the object, which is a typical phenomenon in underactuated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

environment and a maximum pushing force of 4N is required. The maximum force on environment of 1.6N is measured.

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

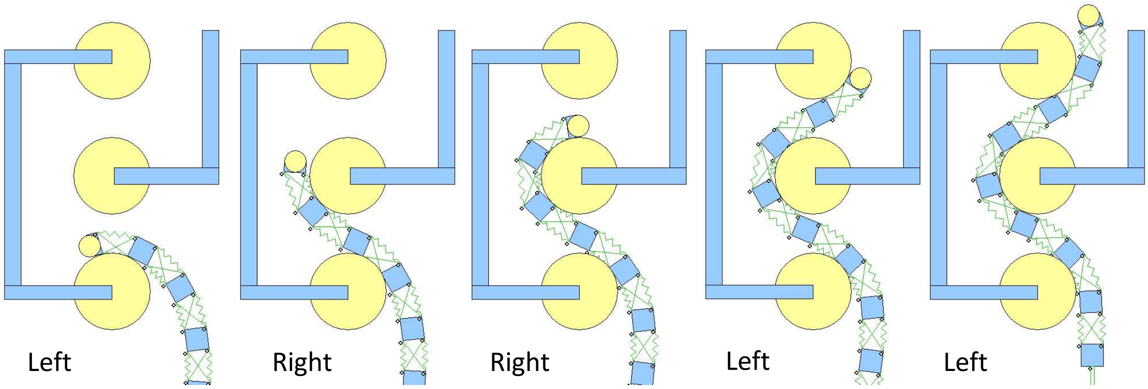

Figure 13. Sequence of the manipulator for moving through a three-obstacle obstacle environment. The control is reduced to a single pushing force and a left or right tendon force, which is indicated in the figure.

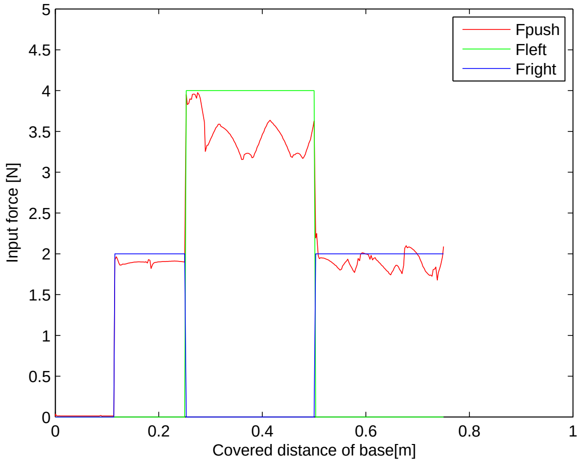

Figure 11. Input forces required for controlling the device.

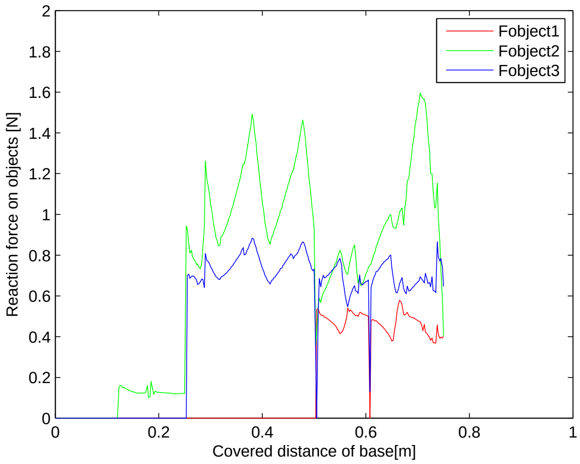

Figure 12. Reaction forces on the three objects, which the manipulator interacts with.

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 [27], which is a typical phenomenon for underactuated mechanisms.

4.2 Comparison with related systems

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 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 this type of manipulator has been actively designed to take advantage of sliding over environmental features, while others have not. 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 discarded. 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. [28]

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 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 these 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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