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A Tendon-Driven Continuum Robot with Extensible Sections

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***Abstract*— Tendon-driven continuum robots offer increased dexterity and manipulability in comparison to conventional rigid link serial manipulators. Being able to conform to complex curves in 3D space, continuum robots are in particular useful for applications in restricted and hardly accessible environments. The workspace of a tendon-driven continuum robot depends on the number of sections, as well as the length of each section and its range of bending radii. Common tendon-driven robot designs have fixed section lengths such that deployment along a tortuous paths requires additional linear translation of the whole robot.**

In this paper, we propose a novel tendon-driven continuum robot with extensible sections. A telescoping backbone allows control of the section length during operation in addition to bending through tendon actuation. Thus, the arc length of a section can vary and the range of bending radii is enlarged. As a result, the novel robot design inherently allows for deployment along tortuous paths in a follow-the-leader fashion. We suggest the use of spacer disks equipped with permanent magnets with alternating pole orientation. The magnetic repulsion forces enable equidistant spacing of the disks at any lengths of a robot section. We prove the concepts of our novel design with experiments using a first prototype.

I. INTRODUCTION

Continuum robots are inspired by nature, e.g. snakes, tentacles, and elephant trunks. In comparison to conventional robots, continuum robots are not composed of concatenated joints and rigid links, but of one (or more) elastic continua (also referred to as backbone) which can bend at any point along the robot length. The continuous structure leads to increased dexterity and manipulability. Diverse continuum manipulator designs have been proposed thus far. A recent overview was provided by Walker [1].

Actuation of continuum manipulators can either be intrinsic to the structure (e.g. pneumatic or hydraulic [2][3][4]) or extrinsic through mechanical transmission (e.g. tendons [5][6][7][8][9]). All continuum manipulators have in common, that the higher the number of individually controllable sections is, the higher the variation of curvilinear backbone shapes can be. As a result, the dexterity and manipulability potentially increase as well.

Tendon-based continuum manipulators (e.g. in [7][8]) are considered extrinsically actuated. They are usually composed of a central backbone which resolves into a finite number of bending sections whose end points are defined by tendon termination positions. The tendons are usually routed through spacer disks per bending section. The length of a section determines the range of constant curvature arcs into which the section can be bend by tendon actuation (see Fig. 1). Inserting or advancing a tendon-driven continuum manipulator into an environment along a highly tortuous path, necessitates a custom manipulator with section lengths specifically chosen for the environment's constraints and explicit path planning techniques.

The range of achievable curvatures per section increases as section lengths can vary. This can be achieved by intrinsic actuation, such as fluidic or pneumatic actuators to realize extension and contraction of robot sections. The Octarm uses parallel McKibben actuators in 3 sections [10] with section diameters between 64-90 mm. Ranzani et al. introduced a soft continuum with diameter 32 mm using parallel fluidic actuators and granular jamming to achieve stiffening of individual section [11]. Maghooa proposed a combination of tendon- and pressure actuation and realized a prototype with 40 mm diameter at the base decreasing to 10 mm the tip. However, miniaturizing intrinsically actuated continuum robots is very challenging, as pneumatic and fluidic actuators require certain dimensions to allow for relevant extension/contraction. Thus, we are considering extrinsic actuation in this paper.

Concentric tube continuum robots are composed of precurved elastic component tubes which are arranged concentrically [12][13]. Actuation is extrinsic, as tubes are translated and rotated at their base. By telescoping from the most outer to the most inner tube, each segment of the backbone with constant curvature can be considered as a section. While the segment lengths can vary during actuation, the precurvature of each component tube and the

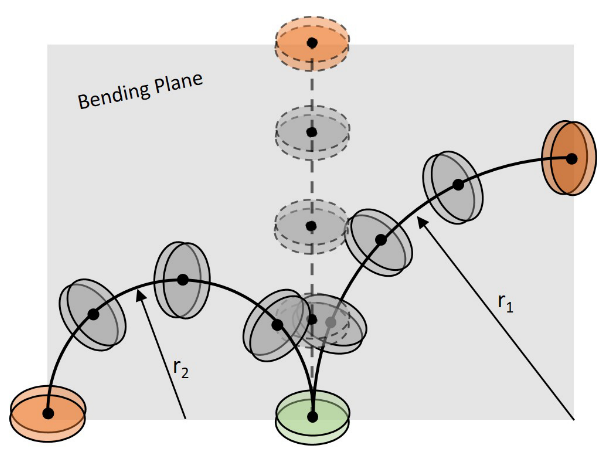

Fig. 1: Tendon-driven continuum robots bend with a finite range of bending radii, as the section length (i.e. arc length) is fixed. Example robot configurations with bending radius r_1 for bending angle 90° and r_2 for 180° are illustrated.

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elastic interaction between the tubes determines the range of achievable curvatures. This can be a limiting factor, if concentric tube robots are considered for operation in hardly accessible environments which require deployment along tortuous paths, since follow-the-leader insertion is not inherent to most component tube precurvatures. In fact, it can only be achieved with very limited curvature and actuation requirements [14].

In this paper, we propose a novel extensible tendon-driven continuum manipulator design. Our design considerably increases the reachability and range of curvatures for each section of the manipulator. The design combines a telescoping backbone with tendon-driven actuation, such that the resulting manipulator benefits the advantages of both types. We introduce the manipulator design, present the first prototype, and experimental evaluation results to prove the concept.

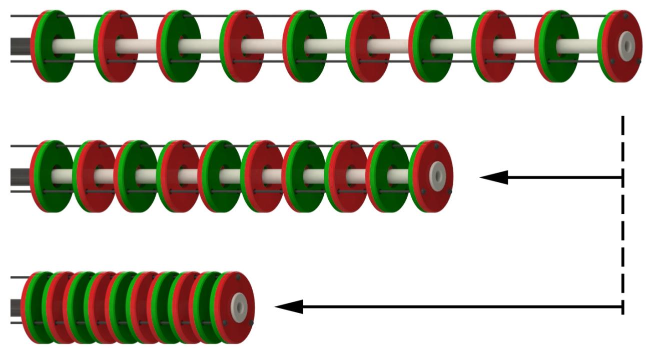

Fig. 2: Magnetic spacer disks are loosely distributed along the backbone of an extensible section with alternating pole orientation. They distribute with equidistant spacing due to magnetic repulsion forces at any section length.

II. ROBOT DESIGN

The design requirements are derived from applications in restricted and hardly accessible environments, which require deployment of the manipulator along tortuous paths. Such applications include (but are not limited to) medical interventions, such as minimally-invasive surgery through natural orifices, or industrial inspection tasks. We considered the following design requirements:

- Extensible continuum manipulator
- Controllable section lengths during operation
- Overall manipulator diameter $< 10\,\mathrm{mm}$
- Bending through extrinsic (tendon) actuation
- Adjustable section stiffness

A. Extensible Section Design

Each section is composed of an elastic backbone, i.e. a straight tube made from NiTi (alloy from Nickel and Titan) in its austenite phase (recoverable strain 8 %). An end disk is rigidly attached to the tube tip. While conventional designs feature spacer disks rigidly attached to the backbone with equidistant spacing in order to assure quasi constant curvature bending, our design requires spacer disks that distribute with even spacing for any backbone length during operation. Thus, we propose spacer disks loosely floating along the backbone. We equip those spacer disks with permanent magnets and arrange them with alternating magnetic pole orientation. As a result, magnetic repulsion forces keep the spacer disks evenly distributed along the backbone. This concept is illustrated in Fig. 2. Each disk features an embedded circular permanent neodymium magnet with a central circular recess, which has a larger diameter than backbone.

The maximum extension of a section is limited by the tube length. The minimum length is defined by the number of space disks and the disk's thickness (as illustrated in Fig. 2 bottom).

B. Manipulator Design

A continuum manipulator can be composed of n extensible sections. The backbone is composed of n telescoping tubes, which is inspired by concentric tube continuum manipulators. The main difference is, that the tubes used for our manipulator are straight rather than precurved. Sections are numbered from 1 to n with 1 being the section closest to the actuation unit. The backbone tube of section 1 has the largest diameter as the backbone tubes of all further sections pass through concentrically. The composition of backbone tubes for $n = 3$ sections is illustrated in Fig. 3a.

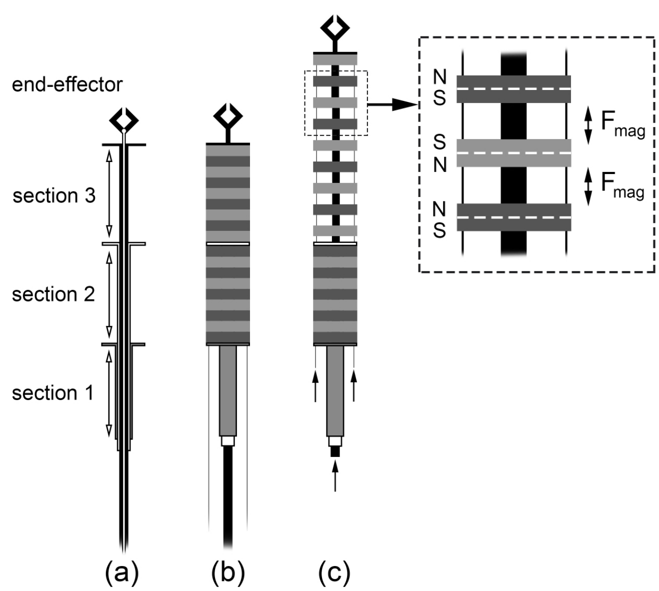

Fig. 3: Principle design of a tendon-driven continuum robot with 3 extensible sections. (a) The backbone is composed of 3 telescoping tubes with a rigidly attached end disk. (b) Section 2 and 3 at minimum length with spacer disks. (c) Section 3 extends. Magnetic spacer disks distribute equidistantly along the length.

1) Extension and Retraction: The length of a section is defined as the distance between the end disks of two consecutive sections. The length of section 1 is the distance between the restrained outlet of the manipulator from the actuation unit and the end disk of section 1. The maximum length of each section is limited by the length of the extensible part of the respective backbone tube.

The length of a section is controlled by extension and retraction of the backbone tube. When the backbone length changes, the spacer disks distribute with equidistant spacing along the length of backbone thanks to magnetic repulsion forces as a results of alternating polarity orientation of the magnets. This ensures that the segment bends with quasi constant curvature. Fig. 3b illustrates a continuum manipulator with three sections with section 2 and 3 at their minimum length. Fig. 3c shows the same manipulator where the backbone tube of section 3 is extended. The magnetic spacer disks keep equidistant spacing through magnetic repulsion forces between the alternating magnetic poles.

2) Bending: The curvature of each section of the continuum manipulator is controlled by tendon actuation. Tendons are routed through the spacer disks of a section and fixed at the section's end disk. The number of tendons can be chosen according to the specific requirements of the application. Here, we use a variant with 3 circumferential tendon routing channels with an offset of 120°. Each spacer disk features a circular recess to accommodate the permanent magnet. The spacer disk design is depicted in Fig. 4.

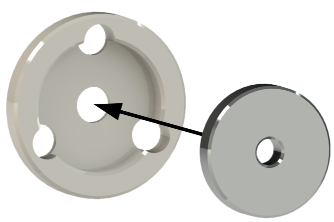

Fig. 4: Spacer disks design accommodating a permanent circular magnet with central recess for the backbone. 3 tendon routing channels on the circumference of spacer disks are offset by 120°.

By controlling the section length and tendon force for each section, the manipulator can conform to any curvilinear shape in Cartesian space, where the range of curvatures per section is defined by the minimum and maximum section length (i.e. arc length). Fig. 5 illustrates a continuum manipulator with three extensible sections in its straight configuration (top) and in a 3D curvilinear configuration (bottom) with varying section lengths.

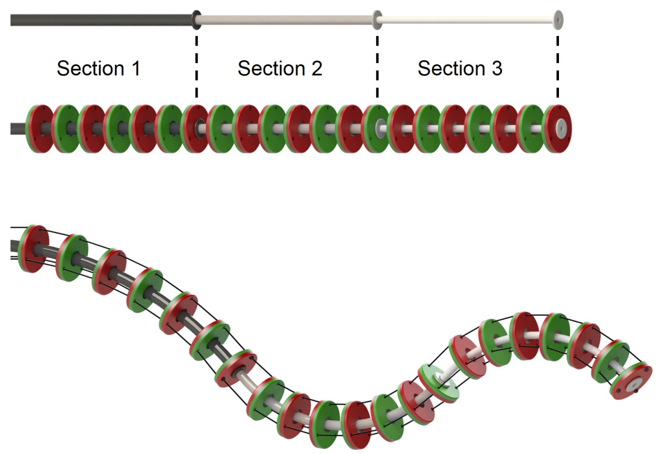

Fig. 5: Manipulator composed of 3 extensible sections. By controlling the section length through extension and retraction of the respective backbone tube (top) and by controlling the tendon forces, the manipulator can conform to any curvilinear shape (bottom).

C. Actuation Unit Design

In order to achieve actuation of a tendon-driven continuum manipulator with extensible sections, an actuation unit is required to control the tendon forces for each tendon and to control the translation of each component tube of the backbone. We propose an actuation unit design for a maximum of 3 extensible sections (see Fig. 6): The basic assembly for a single section requires 4 motors: One motor generating the extension/retraction of the section through a rack and pinion drive on a linear stage and three motors for controlling individual tendons. Transmission of tendon actuation is achieved by a worm gear attached to each motor shaft driving a gear wheel which winds up or unwinds the tendon. The main motor rim can accommodate up to 9 motors for the maximum of 3 sections. By enlarging the diameter of the rim, the design could be extended to actuate more than 3 sections.

The linear stages are mounted onto the linear extension of the main motor rim. The concentric tube backbone of the manipulator passes through the central shaft of the motor rim and takes a turn of 120°. Each tube is attached to a linear translation stage which controls the extension and retraction of the respective section using rack and pinion actuation.

As the telescoping tubes are subject to interaction forces dependent on the section curvature, we introduce an anti-

Fig. 6: CAD rendering of an actuation unit for a tendon-driven continuum robot with 3 extensible sections.

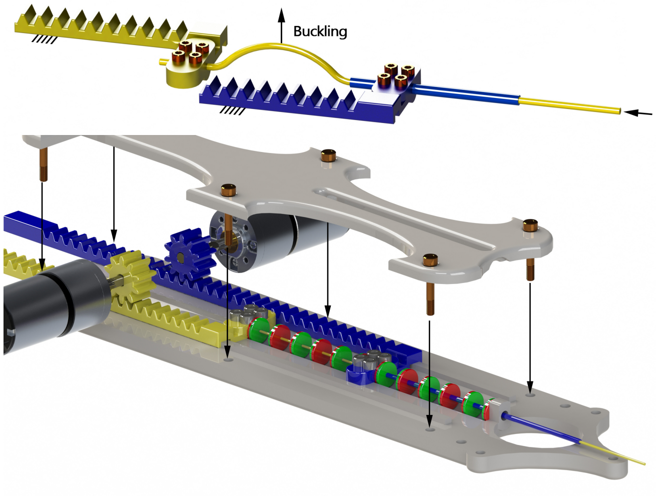

Fig. 7: CAD drawings of the anti-buckling jig (bottom) to prevent the tubular backbone from buckling (top).

buckling jig to the linear stage in order to prevent tube deformation (see Fig. 7). As the critical axial load a tube can carry without buckling is dependent on the unsupported length of the tube, we introduce magnetic spacer disks distributed loosely along the backbone tubes hold in place by a semicircular top and bottom bracket on the linear stage (see Fig. 7 bottom). The concept of alternating polarity is applied here as well, such that the disks distribute with equidistant spacing thanks to magnetic repulsion and thus reduce the unsupported tube length.

III. PROOF OF CONCEPT

A. Magnetic Spacer Disks

We used a NiTi tube equipped with 10 Neodymium magnets (grade N45, diameter 5 mm, thickness 1 mm, central recess diameter 1.5 mm, Curie temperature 80 °C) and adjusted the length manually with an overtube from both ends, in order to qualitatively determine equidistant spacing behavior. Fig. 8 shows photos of the magnets distribution at various lengths and bending radii. We can observe that they distribute with equidistant spacing.

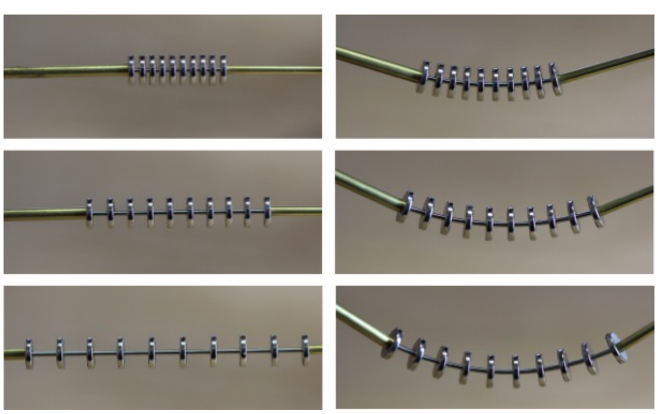

Fig. 8: Neodymium magnets distributing with equidistant spacing along sections of various length and bending states.

B. Robot Prototype

We constructed a tendon-driven continuum robot prototype with extensible sections according to the design described above. The prototype is composed of 3 sections from which 2 are extensible. Fig. 9 shows the prototype.

Section 1 is a section with fixed length 100 mm. 15 spacer disks (thickness 8 mm) are rigidly attached to this section with equidistant spacing. The backbone tube is fabricated from polycaprolactone (PCL), a flexible thermoplastic material. With the elastic, yet stiffer backbone tube, section 1 is build such that it provides structural stiffness for the extensible sections for the experiments outlined in the remainder of this paper.

Section 2 and 3 are composed of NiTi tube backbones and are both extensible. Each section is equipped with 10 spacer disks (outer diameter of 8 mm and 1.4 mm height). Neodymium magnet are embedded into the spacer disks (see last section). As a result, Section 2 and 3 have a minimum length of 14 mm and a maximum length of 70 mm. The parameters of the 3 section are summarized in Table I.

TABLE I: Backbone tube parameters: material, outer diameter (OD), wall thickness (WT), minimum and maximum section length (ℓ). All values in mm.

	Section 1	Section 2	Section 3
Material	PCL	NiTi	NiTi
OD	2.8	1.2	0.8
WT	0.7	0.16	0.13
min ℓ	100	14	14
max ℓ	100	70	70

Each section is actuated by 3 tendons (Dyneema, diameter 0.3 mm). The spacer disks and all structural parts of the prototype are fabricated of Polyactide (PLA) using fused filament fabrication (Replicator 2, MakerBot Industries, LLC, New York City, NY, USA). 11 DC motors (25 6V/14RPM) with a gear ratio of 1:478 and maximum torque ±8 kg/cm were used for the proof of concept experiments outlined below.

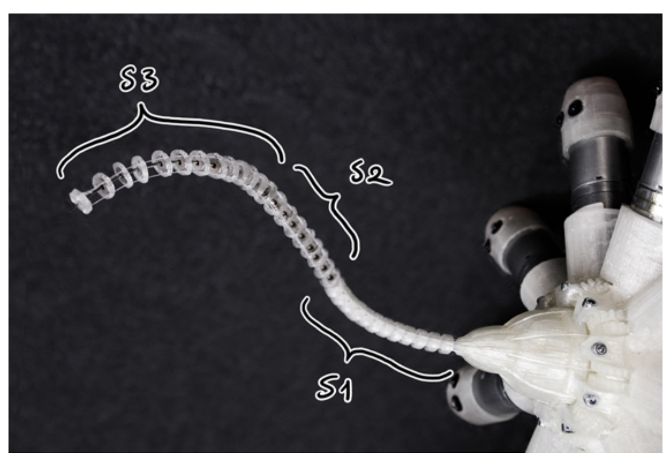

Fig. 9: Tendon-driven continuum robot prototype with three sections (S1-S3). S2 and S3 are extensible.

C. Actuation Forces

The tubular telescoping backbone structure of the proposed robot leads to different section stiffness'. In order to evaluate the actuation forces needed to actuate bending of the sections at varying length, the setup depicted in Fig. 10 was used. The manipulator (5) is rigidly attached to a base (6, 7) secured by 4 screws (4). A single tendon (2) of a section is guided through a pulley (3) and mounted on a grip. The grip is attached to a force/torque sensor (1) (Mini 40, ATI Industrial Automation Inc., Apex, NC, USA) such that the tendon tension force acts in one direction (perpendicular to the sensor surface). Tension forces are measured continuously while manually operating the linear stage by turning a handle until the segment deflects from the initial straight configuration with the desired bending angle.

We evaluated 45° and 90° bending angles for both extensible sections of the manipulator. Bending angles were measured in respect to a rectangular grid. Each section was evaluated at its maximum length 70 mm and half length 35 mm. The manipulator final configurations are illustrated in Fig. 11. The maximum tension force was acquired for each trial. For each pair of bending angle and section length the measurement was repeated 10 times. The mean tension force was calculated. Higher tension forces were determined for section 2, as the stiffness of the backbone is higher. The mean tension force for section 2 ranges from 10 to about 14 N. Section 3 could be operated with mean tension forces ranging from 4 to about 7 N.

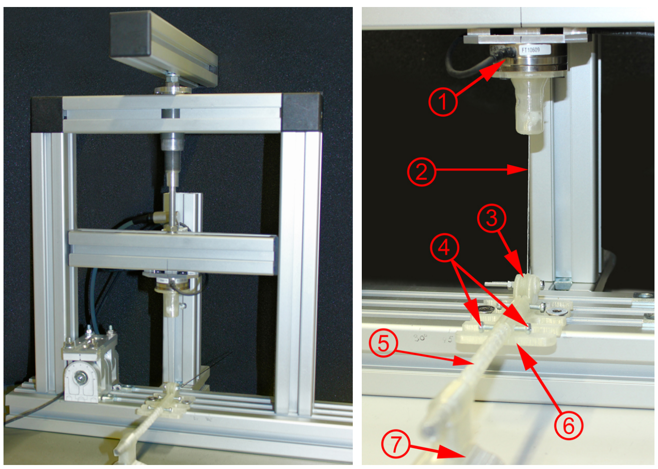

Fig. 10: Setup for measuring actuation forces. The tendon is fixed to a linear stage equipped with a force/torque sensor.

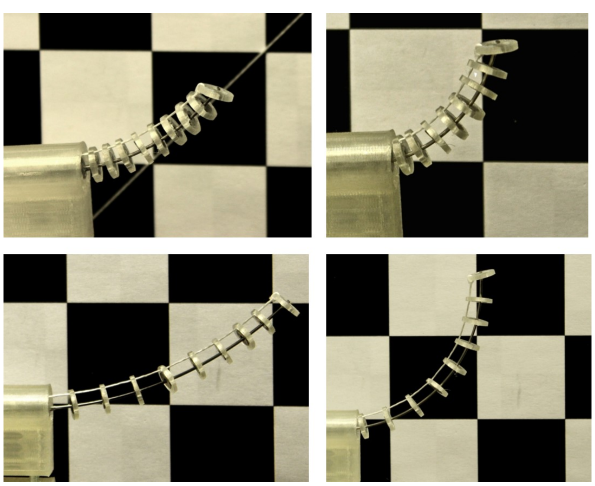

Fig. 11: Planar bending of a section into 45° (left) and 90° (right). Section length of 35 mm (top) and 70 mm (bottom).

D. Deployment Scenario

To illustrate the characteristics of our new tendon-driven continuum manipulator with extensible sections, we conducted a deployment experiment. The environment is shown in Fig. 12. The manipulator has to navigate along a planar tortuous path in order to reach a target position. Section 1 was used to position the manipulator relative to the entrance of the tortuous path and remained in a straight configuration. The robot prototype was deployed in the following sequence (depicted in Fig. 12): (a) Section 2 and 3 are fully retracted with section 2 slightly bend, (b) Section 2 is extended and bend successively to make the turn, and (c) Section 3 extends to its full length during bending in order to reach the target position.

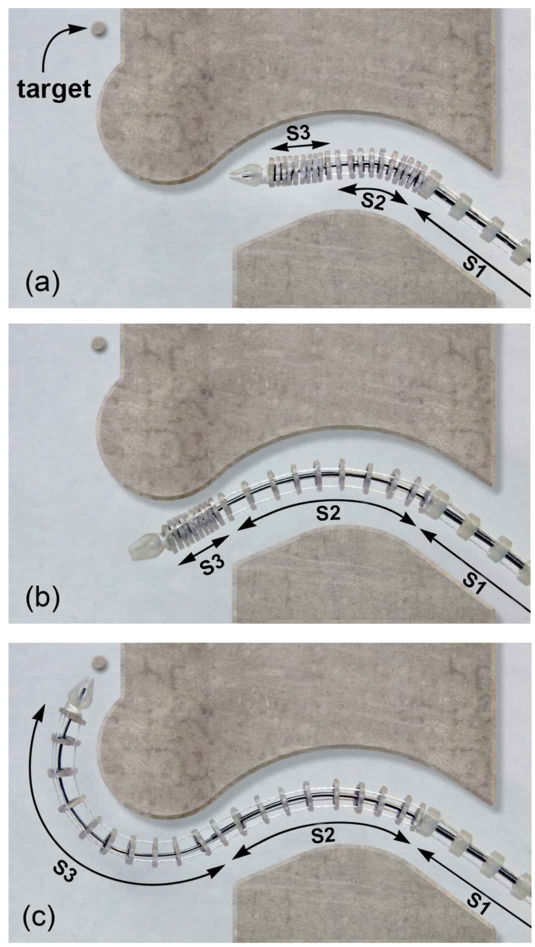

Fig. 12: Deployment of the continuum robot prototype with extensible sections along a tortuous paths with follow-the-leader motion.

IV. DISCUSSION

The proposed extensible section continuum manipulator design is the first design combining a telescoping backbone with tendon-actuation. As a result, the manipulator enables control of the section length during operation in addition to bending. Compared to conventional tendon-driven continuum robots, our design does not only allow to control the bending radius of a section by tendon actuation, but to further control the arc lengths of the bending section. Thus, the dexterity is highly increased. As we have seen in the deployment scenario (Fig. 12), the controllable section lengths further enable deployment along a tortuous path in a follow-the-leader motion.

In order to guarantee quasi constant curvatures for the sections, we propose magnetic spacer disks which distribute equidistantly along the section length by magnetic repulsion forces, as the polarity orientation alternates. Neodymium magnets allow for high forces at a small scale, such that the diameter and thickness of spacer disks can be realized at small scale as well, reducing the overall size of the manipulator. Magnetic repulsion forces of Neodymium magnets are consistent over a long period of time unlike mechanical components like spring which have been proposed for variable section length in continuum manipulators with larger diameters (e.g. in [15][16]). Magnetic spacer disks might be problematic for those applications in environments with ferromagnetic components. We note, that by increasing the diameter of the spacer disks and thus increasing the diameter of the circular recess accommodating the magnet, lateral repulsion/attraction forces to external ferromagnetic objects can be reduced or prevented.

The proposed design allows to adapt the section stiffness of the manipulator, which is dependent on the backbone tube parameters (wall thickness and diameter) and the backbone tubes of the succeeding sections as those pass through the section's backbone tube. We have determined the tension forces to bend sections with different stiffness. Thus, task-specific design optimization of the backbone stiffness, adaption of spacer disk size and magnet selection make this manipulator design versatile for a variety of applications.

Our prototype manipulator is 8 mm in diameter, which enables applications in hardly accessible environments such as minimally-invasive surgery through natural orifices. Thanks to extrinsic actuation, the manipulator is smaller in diameter than existing intrinsically actuated manipulators. The combination of tendon actuation with a telescoping backbone is novel. Existing kinematic models for tendon-driven continuum robots can be adapted for our tendon-driven continuum manipulator with extensible sections [15][17][18].

V. CONCLUSION

The proposed a tendon-driven continuum manipulator design with extensible sections. This design allows for more dexterous applications involving deployment of the manipulator into hardly accessible environments on tortuous paths. At the same time the size in terms of the manipulators diameter is considerably smaller than for extrinsically actuated continuum robot with extensible sections.

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