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Kinematics and performance analysis of a novel concentric tube robotic structure with embedded soft micro-actuation

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ABSTRACT

Continuum robots have shown astounding abilities to assist surgeons reaching confined spaces in the human body. Thus, accurate control of these manipulators, and particularly concentric tube robots, is required in order to achieve intracorporeal microrobotic interventions. We present hereby an improvement of this kinematic structure based on embedded soft micro-actuators. Two models for single and double direction curvature control are introduced. We demonstrate that kinematics are enhanced with respect to the standard approach in terms of holonomy, actuation redundancy and workspace covering. Further kinematic analysis enables the detection of singular configurations. The number of the end-effector pose occurrences that can be reached in a given volume (one cubic millimeter) are computed as well. Finally, the advantages of the novel structures are proven using performance indices.

1. Introduction

Observing the wondrous abilities of some natural creatures has always been motivating as well as inspiring, particularly for researchers. Concerning soft structures, one of the most fascinating is the elephant's trunk. Notwithstanding its flexibility, which would trivially mean its weakness, that appendage is able at one moment to show great strength and power when lifting heavy loads as tree trunks. It can also present delicacy and precision when eating or interacting with their calves. Fig. 1 shows elephants at almost the same trunk configuration performing different tasks with varied effort and stiffness requirements.

1.1. Continuum robots

One can distinguish the continuum robots from the "traditional" hard robots with the absence of rigid links and joints for the latter. Typically, the former presents a distributed deformation performed by scattered actuators throughout the structure. Trivedi et al. [65] suggested a different approach, classifying them into a subset of hyper-redundant robots. However, the difference between hyper-redundant and continuum manipulators is subtle. Thus, it is challenging to provide a clear classification. Hyper-redundancy implies the presence of discrete elements within the backbone. The continuity of the robot shape, regardless of its structure, is not necessarily the suitable criterion to consider a robot as continuum. For instance, early prototypes including snake-like robots developed by [38] and elephant trunk robots developed by [66] present a continuous shape but they

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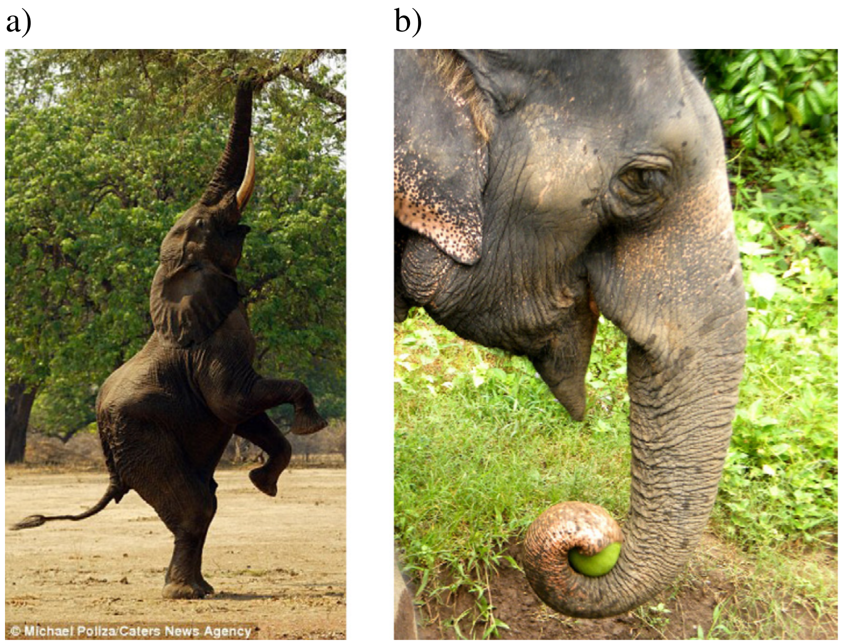

Fig. 1. Almost the same position and shape of an elephant trunk a) wresting a tree branch, which requires high forces (Michael Poliza/Caters News Agency ©2011), and b) picking a mango with the appropriate delicacy (Josh Urich/Canva Photographers ©2015).

are considered hyper-redundant robots. These robots are considered as bio-inspired as they mimic animal parts or movements. Observing the abilities and the performances of hydroskeletons and muscular hydrostats, other bio-inspired prototypes have been developed later. One can cite the starfish-like gel robot developed by [52], octopus-like robot (OctArm) developed by [44], elephant trunk-like robot developed by [74], and snake-like robot developed by [63]. The latter brought an enthralling classification. It is based, notably, on the actuation technique, whether it is continuous or discrete. In order to actuate continuum robots, different techniques have been used, such as

- cables along the backbone, equally distributed around the tubular robot diameter as proposed by [2] depicted in Fig. 2a [22,31,36] and [14] depicted in Fig. 2b or elastic rods to raise the rigidity of the robot to permit transmission of compressive forces as used by [54, 63, 75],
- fluidic (pneumatic and hydraulic) actuators by [7, 15, 21, 39, 42, 44],
- Shape Memory Alloy (SMA) based actuators by [35, 40, 47, 49],
- Electro-Active Polymer (EAP) based actuators by [8, 20, 45, 48, 61], and
- concentric tube robots depicted in Fig. 2c by [27, 28, 71, 73].

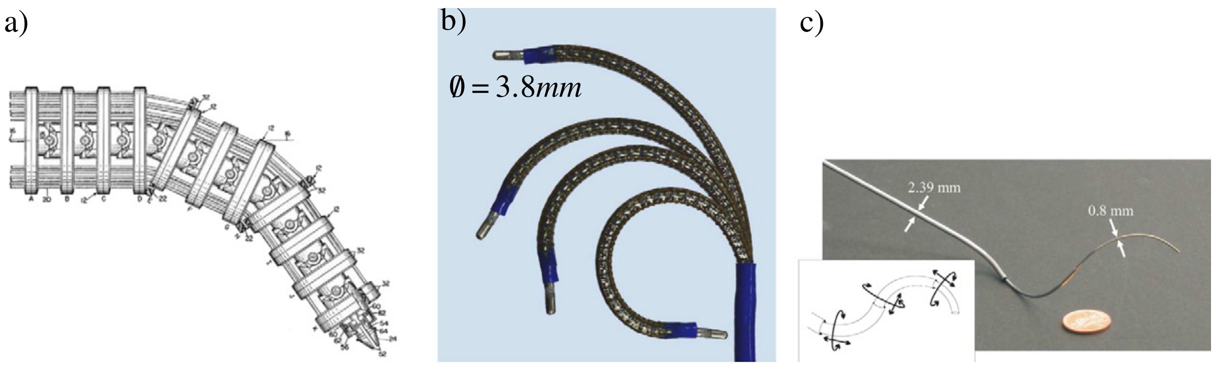

Fig. 2. a) The Tensor Arm of [2], considered as the continuum robot ancestor. b) The Hansen Medical Sensei® system described mechanically and kinematically by [14]. c) The concentric tube robot developed by [73].