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Continuum Robot Cables and Hoses for Adaptive Inspection and Pumping

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Abstract: This study aims to describe the development and application of novel long, continuous backbone hose and cable robots. These continuum robots can actively control the bending along their compliant backbones. This feature allows them to both enter into and maneuver and operate within tight spaces that neither conventional robots nor people can access. Equipped with cameras and other sensors, these robots provide new capabilities in remote inspection, and when used as hoses, enable novel applications in dirty and dangerous environments. This paper discusses the design and implementation of two such types of novel robots: (1) a long, thin tendril cable robot for remote visual inspection; and (2) a novel active hose robot for pumping viscous fluids. The deployment of the cable robot in novel applications, including inspection of equipment racks on the International Space Station, is reviewed. Application of the hose robot to novel robotic 3D concrete applications and the effects of the pumping dynamics on the operation of the hose robot are also discussed. Owing to the developments in robotics, this study has provided useful insights and opened up various avenues for further exploration.

Keywords: *Continuum robot, hose, cable, inspection*

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I. INTRODUCTION

Current robots and unmanned systems are well-suited to preplanned tasks in structured environments (manufacturing, assembly). However, they are generally poor in adapting in real-time to unforeseen situations, and have been unable to transition successfully to unstructured environments. The serial rigid link structure of traditional robot manipulators hinders their ability to enter tight spaces. Humans remain the go-to solution for inspection and repair in unstructured environments, as well as in many industrial applications such as the construction industry. However, their ability to enter and operate in small and narrow spaces is inherently restricted by their size and mobility, by their stamina, and additionally by safety considerations in dangerous environments.

The cable and hose robots described in this paper have capabilities "dual" to conventional robot technology: 1) their core structures are compliant rather than rigid, and 2) they adapt to their environment instead of requiring their environment to be adapted to them. They are most effective in unpredicted situations in cluttered environments, rather than for preplanned repetitive tasks in engineered, largely open, spaces.

The concept of building compliant biologically inspired robots is not new [1]. However, in the last few years, advances in robotics and sensor technology have made the concept feasible [2, 3, 4]. In particular, continuum "tongue, trunk, and tentacle" robots are characterized by smooth compliant backbones which bend, and sometimes also extend, at all points along their structure [3, 4, 5]. These highly maneuverable backbones provide capabilities beyond those of conventional rigid link

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robots, notably nondestructive penetration of and operation within congested environments, and additionally adaptive whole arm grasping [3, 4]. Continuum robots have been strongly inspired by structures in nature [1, 2], notably elephant trunks [6], octopus arms [7, 8], and more recently plant stems [9, 10].

The field of continuum robots has seen a surge of research in recent years. Inspired by several early exploratory hardware prototypes [1, 2] and core foundational theory [3, 4], researchers over the past twenty years or so have established a range of practical approaches to creating continuum robot hardware [1, 2, 3, 4, 11, 12]. Advancements in modeling initially lagged behind the numerous hardware realizations, mainly due to the complex kinematics and dynamics associated with compliant continuous structures. However, in recent years, formal approaches to modeling of continuum robots have been established in the literature. Continuum robots have been successfully applied in a range of medical procedures, notably endoscopy and minimally invasive surgery [11].

Fig. 1. Continuum robots: shape versatility [8, 9]

Continuum robots, when deployed on a mobile platform and demonstrated in field trials (see Fig. 1), significantly enhance the ability of unmanned systems to maneuver through complex obstacle fields and manipulate objects over a wide range (orders of magnitude) of size and weight, of many different shapes, and with widely different physical characteristics (rigid, soft, flexible..). This capability is particularly important in the unstructured environments typically encountered in military and inspection operations.

In this paper, we discuss the potential for continuum robots to perform a remote inspection (section II) and, in particular, to act as active robotic hoses (section III). Conclusions are presented in section IV.

II. ROBOT CABLES FOR INSPECTION

Continuum robots, particularly in long thin cable-like variants, can be used to access and sense areas in deep and complex environments. We have recently, under NASA funding, developed and demonstrated cable-like continuum tendril robots for remote inspection [10]. See Fig. 2.

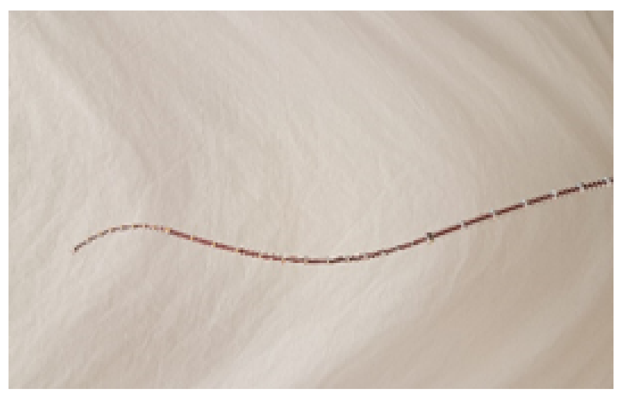

Fig. 2. Cable-like tendril robot [9, 10, 13]

These robots were designed based on spring-loaded concentric tube backbones. The tubes were made from carbon fiber. The tubes were actuated, in bending and extension, via remote tensioning of cables by D.C. motors (see Fig. 3). The overall robot was built of three serially connected three degrees of freedom sections (Fig. 3). Springs along the sections allowed the local length of the backbone to be varied by increasing or decreasing the tension on the set of tendons actuating that section.

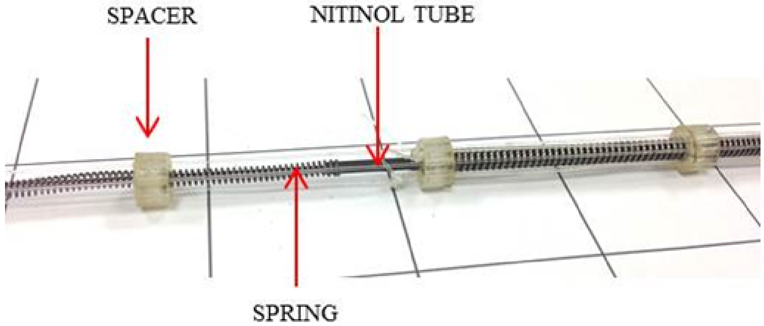

Fig. 3. Tendril robot design

We focused on the specific application of inspection between, behind, and within the equipment racks in the International Space Station (identified as a target application for that project by technical project managers at NASA). A formal demonstration of the developed tendril robots performing the inspection within equipment racks in an International Space Station Mock-up environment was conducted at the NASA Johnson Space Center in June 2017 [10]. In that demonstration, the ability of the robot to access and image equipment within, and material behind, the racks were established. We additionally conducted research on the use of the robots in more general inspection and monitoring operations [9, 10, 13].

III. ROBOT HOSES FOR PUMPING

An alternative morphology for continuum robots is as hoses [14, 15]. Deployed as hoses, continuum robots have the potential, for example, to deploy concrete-delivery hoses in congested spaces and support a novel application: 3D printing of concrete. Traditionally, concrete placement has been treated as a "low-tech" and an extremely individualistic endeavor - and hence as manual-labor intensive. 3D concrete printing exploits the ability to couple computer-aided design modeling with robotic-controlled precision layer-by-layer deposition of engineered concrete mixture.

However, current approaches are restricted to layered printing (along the vertical, or z-direction) and lack the dexterity to work around existing obstacles (e.g. rebar) or in close-proximity to humans. Proposed systems can be categorized as gantry-based [16], and arm-based [17]. Gantry-based systems can be further decomposed as D-shape [18], contour crafting [19, 20, 21, 22], and cable suspension systems [23]. Initial efforts have printed walls [24] and simple structures [25], [26], with further efforts developing suitable materials [27, 28, 29]. The ability to print large structures has been proposed [30], [31] and demonstrated [32, 33].

Motivated by the concrete pumping application, we created an extension of the tendon-driven design summarized in section II. Specifically, we designed and constructed a prototype hose robot, as detailed in the following. A specially-designed cable-harness was attached externally to an existing hose, to render the overall system robotic. Each harness was comprised of n circular collars clamped at predetermined locations along with the hose, connected by 3n cables guided by intermediate circular spacers (see Fig. 4). Each collar was designed to have a set of three cables, spaced 120 degrees apart, terminated at it, with the other ends actuated by D.C. motors.

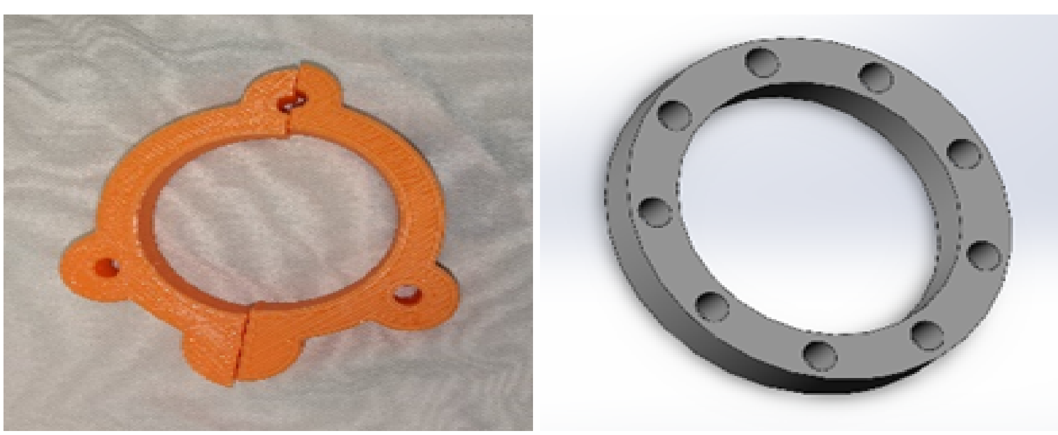

Fig. 4. Two collar designs

This arrangement can be expanded to create a *n*-section continuum robot, with the section ends defined by the collars; each section is able to bend in two dimensions via differential cable-actuation operating against the hose stiffness. Such an approach has the advantages of being both mechanically simple and inexpensive, and also requires only a simple retrofit to the existing concrete pumping hardware to render it robotic. The ability to, for a given pumping scenario, choose the lengths of the sections (clamping locations of the collars) to fit the environmental constraints (task needs) is quite novel.

An initial prototype of this above design is shown in Fig. 5. This represents a single section, i.e., a single set of three actuated tendons, of the design.

Fig. 5. Initial prototype

Fig. 6. Refined prototype

Previous efforts to realize continuum-robot-based active-hoses [12-13] neglected (potentially very significant) dynamic effects of pumping and were never fully-realized. In order to evaluate the magnitude of these effects and their potential to hinder robotics concrete pumping, we conducted a series of experiments with the above prototype.

Initially, we chose a sump pump hose for our prototype (Fig. 5) due to its flexible nature and large diameter which would be easy to adapt to other fluids in the future. As we conducted initial experiments with the prototype, we found that while the flexibility was necessary to the movement of the hose, it allowed for the weight of the pumped fluid to affect the mobility far too much to obtain reasonable results. We concluded that for our uses, we needed a stronger hose, more collars, and possibly more tendons.

Consequently, a refined prototype was created using a heater hose with a smaller, 3/4 in diameter. We increased the number of collars on the hose from five to nine but still used three tendons to control the hose. We conducted experiments with this design, with the hose initially in bent configurations, and with the hose initially in a straight-line configuration. The goal of these experiments was to study how the fluid mechanics of the water running through the hose affected the amount of force needed by the tendons to keep the hose in the aforementioned configuration. Through each experiment, it is observed that the major effect that needed to be counteracted on by the tendons was the mass of the fluid being pumped. This was in contradiction to the hypothesis that the dynamic effects of pumping would prove significant, with respect to the mass effect. It is additionally observed that due to the alignment of the tendons around the hose, these effects of the mass caused uneven stress amongst the three tendons, causing difficulties in potential control strategies for the robot.

IV. CONCLUSION AND RECOMMENDATIONS

This research has discussed the potential of continuous backbone continuum robots for remote inspection and robotic pumping. We reviewed the use of tendon-driven thin tendril continuum robots for remote inspection, using as an example case the inspection between equipment racks on the International Space Station. The design, construction, and testing of an extension of the tendril design, a tendon driven continuum hose robot, focused on 3D concrete pumping applications are investigated and described in detail. Th effects of pumping dynamics were explored and discussed.

Declaration of Conflicting Interests

The authors state that there are no conflicting interests associated with this work.

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