Robotics and Computer Integrated Manufacturing 56 (2019) 107–116

Contents lists available at ScienceDirect

Robotics and Computer Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Active uncoiling and feeding of a continuum arm robot

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ARTICLE INFO

Keywords:
Coiling
Continuum
Control
Robot
Tip Following

ABSTRACT

Continuum arms are becoming more popular for use in inspection and repair of hard to reach environments, typically in-situ. These applications characteristically have less space outside the scenario as well as internally. Previous approaches require a significant footprint in this area, potentially limiting the possible exploitations. The algorithm reported within this paper demonstrates a method to actively coil / uncoil a continuum arm on a helical drum, which can be applied to multiple trajectories within a practical computation time. Deviations from desired trajectory are below 3 mm or 1°, individual steps calculated on average in 0.031 s, or complete computation for new trajectory within 170 s.

1. Introduction

Continuum arms are a subset of hyper redundant manipulators that use flexible sections rather than discrete joints. This allows them to be resilient to collision with other objects and be more adaptable to complex environment geometry. Several examples have been demonstrated [1–3], demonstrating various sizes, designs and strengths.

There are two popular scenarios that are specialized to the high degrees of freedom in hyper redundant manipulators: Grasping and Snaking. Grasping systems replicate the motions of an Elephants trunk or a tentacle [4,5]. Whereas Snaking systems use longitudinal navigation to enter confined and restrictive spaces to perform inspection or other tasks [6].

This navigation has been implemented and reported in literature before. Chirikjian and Burdick [7] demonstrated a planar obstacle avoidance algorithm, Choset and Henning [8] uses Generalized Voronoi Graphs to achieve the follow-the-leader approach, and [9] adapts an obstacle avoidance algorithm from rigid-link robots with the aid of sensors. This manuscript assumes the use of the Tip Following technique [10] which uses an optimization routine to minimize the deviations from the path. This is dependent on the forward kinematics of the system, which assume each section performs a bend of constant curvature. For an N-section arm, the positions of each section in Cartesian space can be determined by

$$\begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix} = R_n \begin{bmatrix} \frac{S_n}{\theta_n}\cos(\phi_n)(1-\cos(\theta_n)) \\ \frac{S_n}{\theta_n}\sin(\phi_n)(1-\cos(\theta_n)) \\ \frac{S_n}{\theta_n}\sin(\theta_n) \end{bmatrix} + \begin{bmatrix} x_{n-1} \\ y_{n-1} \\ z_{n-1} \end{bmatrix} \tag{1}$$

and

$$R_n = R_{n-1} Rot_z(\varphi_{n-1}) Rot_y(\theta_{n-1}) Rot(-\varphi_{n-1}) \tag{2}$$

where S_i, θ_i, and ϕ_i are the section length, bending angle and direction respectively, with the subscript indicating which section. R is the rotation matrix at the end of the previous section and "*Rot*" represents a function which returns the rotation matrix of the desired angle around the subscript axis. Eqs. (1) and (2) are setup recursively such the $[x_0\ y_0\ z_0]$ are at the origin and R_0 is an identity matrix (unless a different starting pose if desired).

To achieve the longitudinal navigation, the Tip Following and other techniques rely on a feed-in action, a motion that pushes the active length into the environment. The typical method to create this has been to use a secondary actuation system. For example, the OctArm has been demonstrated on a TALON chassis [11], OC Robotics present their explorer arms on a KUKA robot [12], or on a linear track [2]. The drawback of these approaches is that the feed-in action becomes isolated from the navigation. This limits the navigation to linear advancement, and in most cases the algorithm is completely ignorant to the process used; this is not to mention the added complexity and loss of compactness of such systems.

Another approach has been to use the body of the manipulator to move the unused sections of the arm to create a loop [7] or series of loops [13] which can be re-shaped to cause the desired movement.

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https://doi.org/10.1016/j.rcim.2018.09.003
Received 5 August 2017; Received in revised form 19 June 2018; Accepted 5 September 2018

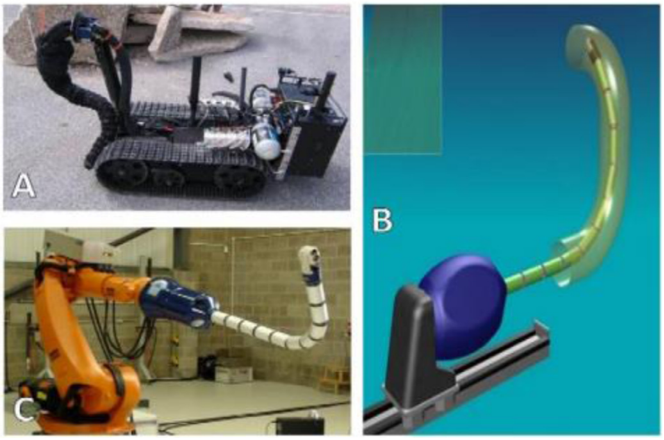

Fig. 1. Feed-in actions using secondary hardware: a) OctArm on TALON [11], b) OC Robotics Snake Arm on KUKA Robot [12], c) OC Robotics Snake on Linear Track [2].

These methods and the use of secondary robots all require significant space outside the environment entrance, such as the examples in Fig. 1. Considering most scenarios where such continuum robots need to be utilized involve constrictive space, it is often likely that there is limited space outside the environment.

The solution is to create a system that coils around the actuation pack. This makes the footprint of the hardware much smaller, meaning less space needed in operation and the transport and storage easier. Passive systems have already been presented in this manner. NASA's Tendril Robot [14] has a long passive length that is coiled in a drum pack.

However, for adaptability, an actively coiled system is ideal. In this field however, very little has been published in terms of coiling these styles of manipulators, save for the grasping strategies of the OctArm [11]. Other work has been presented for bio-inspired robots of climbing snakes [15] and tendril-based plants [16].

To address these challenges, this paper presents an active coiling approach to determining the posed required to smoothly coil a continuum arm on a drum while compensating for the pitch and effects of the coiling process. With this in mind the paper is organized into 8 chapters as follows:

Section 2 provides brief specification of the robotic prototype this work was intended for. Section 3 explains the process for calculating the coiled profile. Section 4 depicts the possible trajectories for uncoiling. Section 5 calculates the motion for one trajectory. Section 6 converts these calculations into a function. Section 7 demonstrates the results, followed by the conclusions in Section 8.

2. Short specification on the design of the continuum robot

The continuum arm on which the feeding motion will be presented has been designed based on compliant joints that allows coiling around a drum which contains the whole actuation pack as shown in Fig. 2; full information about the construction of this robot can be found in [3,17]. The actuation pack of the robot houses all the motors and control systems used to run the 24 degrees of freedom (DoF) of the robot and a rotation stage to turn the drum. The only external connections are an ethernet cable and power. The size and weight of the hardware was restricted by another robot which this system can be combined with [18,19]. The arm itself is 1256 mm long and comprised of 12 sections, each capable of bending 90°. The sections vary in length and diameter, as described in Table 1, to provide greater stiffness when fully extended.

Table 1
Section length and diameter of prototype.

Section	Length (mm)	Diameter (mm)
1, Base	144	40
2	144	40
3	146	40
4	122	22
5	122	22
6	122	22
7	102	20
8	102	20
9	102	20
10	50	13
11	50	13
12, Tip	50	13

A helical channel was added to the design of the actuation pack to support and protect the body of the arm during transport and storage. This recess provides the specification for the coiling profile required from the process. The helix has a diameter of 275 mm and a pitch of 42 mm, consequentially, this means there is 1.452 revolutions required to completely coil the length robot.

3. Coil shape

Provided with the shape of the helix and the geometric behaviour, it is possible to find a configuration for the continuum arm that matches the channel. In the reported design, there is a maximum of 2 mm clearance between the diameter of the arm and the shape of the recess, therefore any path deviation must be below this value. Initial evaluation of the profile used an approach based on the forward kinematics to find a suitable pose.

For a homogenous arm, that is one with same size section lengths, a helical pose can be created by having the same bending angle for each section determined by the desired radius, r_{helix}, using

$$\theta = S/r_{helix} \tag{3}$$

while the direction angle follows the rule

$$\phi = [a + a_0\ ,\ \ 2a + a_0\ ,\ \ \dots\ ,\ \ na + a_0] \tag{4}$$

where a_0 is the starting direction and a is the pitch angle of the coiling drum. To align with the current helical profile $a_0 = 180°$ and $a = 1.92°$, for a continuum arm with twelve sections of $S = 100$ mm and θ is 41.67°.

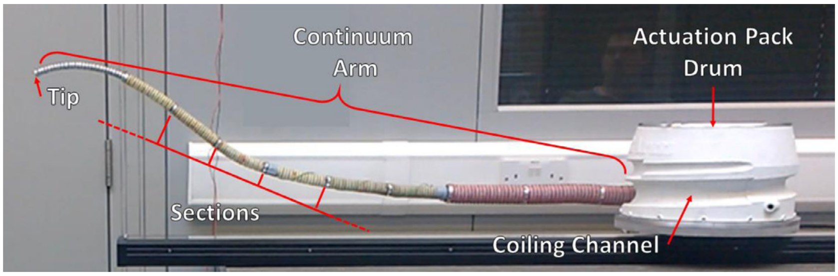

Fig. 2. Annotated image of the MiRoR: SeRArm prototype.