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New Approach to Modeling a planar flexible continuum robot simulating elephant trunk

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Abstract

Research on the modeling of continuum robots is focused on ways to construct the geometric models, while maintaining maximum specificities and mechanical properties of the robot. This paper presents a new approach of geometric modeling of continuum planar multi- sections robots, assuming that each section is curved in a circular arc, while having inextensible central axis of the structure. The direct geometric model is calculated analytically, whereas the extreme points (used in calculating the inverse geometric model) of each section are calculated numerically using a particle swarm optimization (PSO) method. One advantage of this method is to simplify the mathematical calculations and transform the complex problem into a simple numerical function; which allows the knowledge of the form of the central axis of the robot. Simulation examples using this method are carried to validate the proposed approach.

Keywords: flexiblecontinuum robot; central axis; PSO; Khalil Klifinger method.

1. Introduction

Modeling continuum robots requires a continuous model of the central axis of the robot [1].Traditional approaches to modeling, in which the frames are associated with each joint, are inappropriate for the case of continuum manipulators, precisely because of the absence of discrete links in their architecture. A natural approach is to use a theoretical curve to model the axis of hyper-redundant robot. The fundamental question, concerning the modeling of the continuum robots, resides also in the infinity of the number of degrees of freedom which require the geometrical models in their continuous form.

However, the hyper-redundant robotic systems (figure 1), with discrete links or continuum cannot be controlled only considering a finite number of degrees of freedom. Thus admitting a reduced set of physical solutions. Among contributions on the geometric models of these structures, we can cite the model of [2, 3] use the Frenet-Serret formulas and modelise the central axis of the robot by a kinematic chain consisting of several rigid bodies.

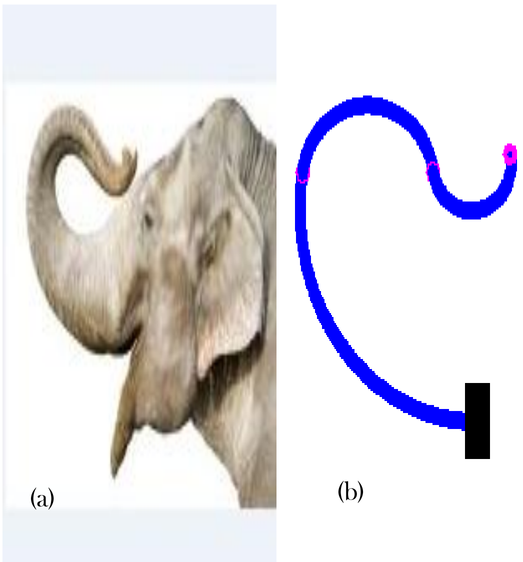

Figure 1: Simulation of the elephant's trunk; (a): the elephant's trunk. (b): the central axis o f the robot

[4, 5] assume that each section of a manipulator bends in an arc of a circle and that the central axis of the structure is inextensible. [5]Is based on modified Denavit-Hartemberg convention, the validation of this model has been done on a prototype robot called the 'elephant trunk'. Similarly [6] uses this assumption to study the kinematics of a snake robot. Furthermore, the inverse geometric model for the case of a multi-section is studied by [8], where the end points of each section are assumed to be known. The authors did not validate experimentally the model but they simulated the overall behavior using appropriate software. [9] Deals with the validation of the geometric model of a multi-section manipulator support by a mobile robot. [10] Has done enhancements on the inverse geometric model described by [4] for one bending section, the validation of this model has done on a micro-robot and showed that the model was not robust against uncertainties of environment and inaccuracies of materials. This inverse geometric model is formulated as an optimization problem with a cost function and constraints using the principle of interval analysis. Finally, a state of the art report in modeling these classes of robots is presented by [11]. The main contribution of this paper is described in two parts. The first presents the methodology follows to know the shape of the central axis of the robot, which represents the direct geometric model. This method relies on the assumption of a constant curvature and is based on knowledge of the angles between the end points of each section constituting the robot; these points will be determined by simple geometrical relations. The second part describes the inverse geometric model; where the extremes points of each section are calculated numerically by using optimization method, under the constraints of conservation of the length of each section. These geometric models presented are used to develop the kinematic and dynamic models for multi-section continuum robot.

2. Direct Geometric Model

2.1. Problem statement

The direct geometric model consists of calculating the position and orientation of the platform n, with respect the base reference, depending on the lengths of cables (or tubes). In what follows, let us assume that each segment is curved in an arc of a circle, and that the central axis of the structure is inextensible. The first tangent of the curve is collinear with the initial ordered axis of each section (physical stress).

(a)

(b)

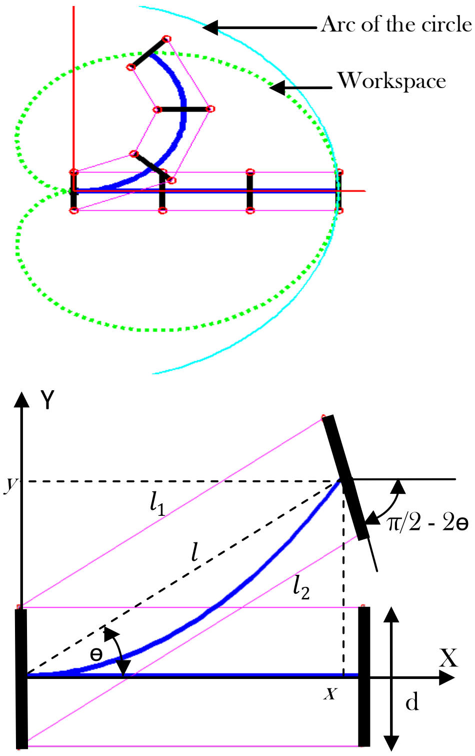

Figure 2: Geometrical parameters (a) Overview of the bending section; (b) A portion of the bending section.

Starting from the definition of arc length, where the curve is described with the arc length parameter: $f(s) = (x(s), y(s))$, then its derivative is a unit vector, so it can be set as a function of an angle α(s) [12]:

$$\acute{f}(s) = \begin{pmatrix} \acute{x}(s) = \cos(\propto(s)) \\ \acute{y}(s) = \sin(\propto(s)) \end{pmatrix} \quad (1)$$

From the figure 2(b) we have:

$$\begin{cases} x = l\cos(\theta) = l_1\cos(\theta) + \frac{d}{2}\sin(2\theta) \\ \quad = l_2\cos(\theta) - \frac{d}{2}\sin(2\theta) \\ y = l\sin(\theta) = \frac{d}{2} + l_1\sin(\theta) - \frac{d}{2}\cos(2\theta) \\ \quad = -\frac{d}{2} + l_2\sin(\theta) + \frac{d}{2}\cos(2\theta) \end{cases} \quad (2)$$

From equation (2) we find:

$$\sin(\theta) = \frac{l_2 - l_1}{2d} \quad (3)$$

$$\cos(\theta) = \sqrt{1-\left(\frac{l_2-l_1}{2d}\right)^2} \quad (4)$$

Therefore:

$$\theta = atan2\left(\frac{l_2-l_1}{2d}, \sqrt{1-\left(\frac{l_2-l_1}{2d}\right)^2}\right) \quad (5)$$

2.2. Calculating the angles function

Consider an inextensible section of length l, formed of (n +1) points (figure3). When using the arc length, the variation of angles $\alpha(s_i)$ is given by:

$$\alpha(s_i) = As_i + B \text{ ; i = 0, 1... n} \quad (6)$$

With the boundary conditions:

$$\begin{cases} \alpha(s_0 = 0) = 0 \\ \alpha(s_n = l) = 2\theta \end{cases} \quad (7)$$

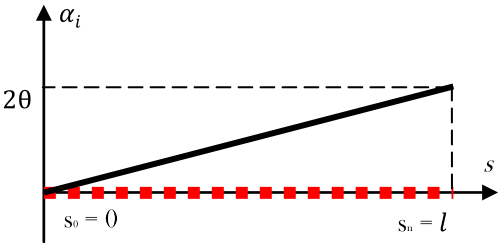

Figure 3: Variation of $\propto (s)$

After the development we find the expression of $\alpha(s_i)$:

$$\alpha(s_i) = \frac{2\theta}{l} s_i \ ; \quad s_i \in [0, l] \quad (8)$$

The equation (8) becomes:

$$\alpha(s_i) = \frac{2}{l} atan2\left(\frac{l_2-l_1}{2d}, \sqrt{1-\left(\frac{l_2-l_1}{2d}\right)^2}\right) s_i \quad (9)$$

2.3. Interpolation of the angles function

The interpolation of the function (9), with a natural cubic spline, gives:

$$\propto (s) = a_i\left(\frac{s-s_i}{h_i}\right)^3 + b_i\left(\frac{s-s_i}{h_i}\right)^2 + c_i\left(\frac{s-s_i}{h_i}\right)^1 + d_i \quad (10)$$

Where: a_i, b_i, c_i et d_i are parameters of the cubic spline, with $s_i \le s \le s_{i+1}$, $h_i = s_{i+1} - s_i$ and $i = 0, \dots, n-1$.

The constraints of the natural cubic spline are:

- Interpolation at the points:
  $\propto (s_i^+) = \propto_i$, $\quad i = 0, \dots, n-1$
  $\propto (s_i^-) = \propto_i$, $\quad i = 1, \dots, n$
- Continuity C^1 :
  $\propto' (s_i^+) = \propto' (s_i^-), \quad i = 1, \dots, n-1$
- Continuity C^2 :
  $\propto'' (s_i^+) = \propto'' (s_i^-), \quad i = 1, \dots, n-1$
- Minimization of energy:
  $\propto'' (0) = 0 \ \ et \propto'' (l) = 0$

2.4. Integration of the angles function

Once the function of the angles $\propto (s)$ determined, we can find the solution by integration of the equation (1), by using Simpson's numerical method. The function solution represents the shape of the central axis of the robot:

$$f(s) = \begin{pmatrix} x(s) = \int_0^s cos\left(\propto (s)\right) \\ y(s) = \int_0^s sin\left(\propto (s)\right) \end{pmatrix} \quad (11)$$

2.5. Applications

a. One section

Consider a bending section of length $l = 200\,mm$. Increasing l_1 and l_2 with $\Delta l = 0{:}10{:}30$, such as: $l_1 = l - \Delta l$ and $l_2 = l + \Delta l$. The robot configuration is shown in figure 4 and the curves of the associated angles functions of each movement are shown in figure 5. The position and orientation of the superior platform with respect to base reference is given by equations (11) and (5) for $s = l$.

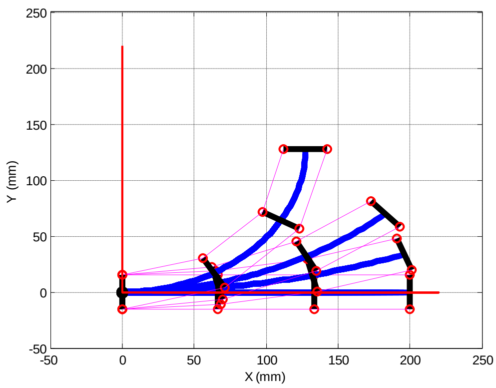

Figure 4: Planar robot with a single section

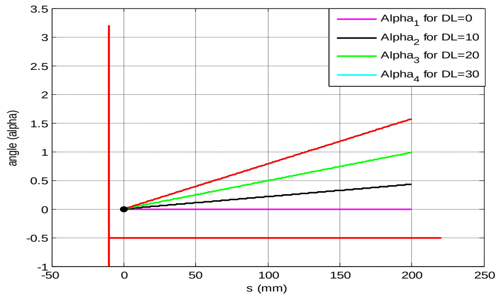

Figure 5: Functions of the associated angles

b. Three sections

Consider a robot formed with three sections of length $l_1 = 200\ mm$, $l_2 = 150\ mm$ and $l_3 = 100\,mm$. The position and orientation of the platform j with respect to base reference for a variation of the cables $l_{i,j}\,(l_{1,1} = 170, l_{2,1} = 230, l_{1,2} = 170, l_{2,2} = 130, l_{1,3} = 130, l_{2,3} = 70)$; is given by equations (11) and (5)

- Platform 1: $\begin{cases} f(l_1) = \begin{cases} x_1 = 165.40 \\ y_1 = 95.49 \end{cases} \\ \theta_1 = \pi/3 \end{cases}$
- Platform 2: $\begin{cases} f(l_1 + l_2) = \begin{cases} x_2 = 294.05 \\ y_2 = 133.97 \end{cases} \\ \theta_2 = -0.486 \end{cases}$
- Platform 3: $\begin{cases} f(l_1 + l_2 + l_3) = \begin{cases} x_3 = 382.77 \\ y_3 = 158.08 \end{cases} \\ \theta_3 = \pi/3 \end{cases}$

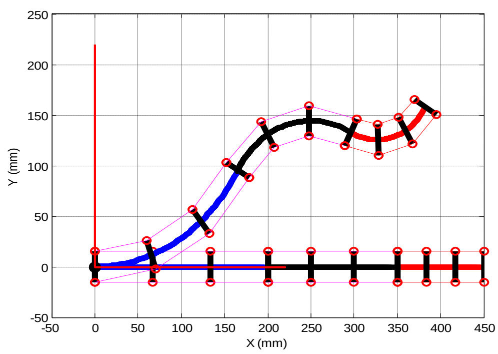

Figure 6: Initial and final position of the robot with three bending sections

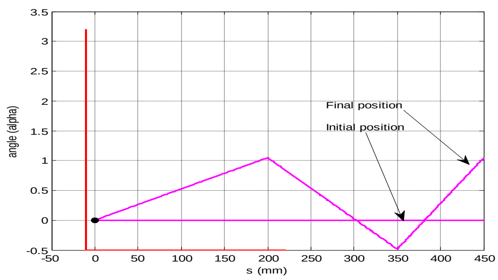

Figure 7: The function of the associated angles

3. Inverse geometric model

3.1. Inverse geometric model for one section

One bending section of a continuum manipulator is modeled by an arc of circle with one end point o fixed at the origin of the reference frame; the other end point P is located anywhere in the workspace. This section of continuum manipulator is parameterized by lengths, its curvature κ, and its orientation θ as shown in figure 8. These parameters are given by:

$$\theta = atan2\,(y, x) \tag{12}$$

$$\kappa = \sqrt{\frac{2(1-\cos(2\theta))}{\sqrt{x^2+y^2}}} \tag{13}$$

$$s = \frac{2\theta}{\kappa} \tag{14}$$

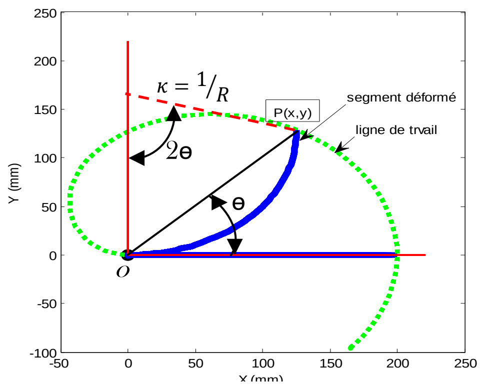

Figure 8: Circle arc parameters

3.2. Inverse geometric model for multi-sections

The inverse geometric model presented in the previous section can be iteratively applied to several sections in serial connection to model a continuum manipulator of n sections.

The operational coordinates of the origins of the intermediate platforms (x_i, y_i) of each sections, are calculated numerically by the PSO method, using constraints on the conservation length, such that $l_i = \sqrt{((x_i - x_{i-1})^2 + (y_i - y_{i-1})^2)}\,\theta_i / \sin(\theta_i)$, with $\theta_i = atan2((y_i - y_{i-1}), (x_i - x_{i-1}))$, for $i = 1, \ldots, n$. Where (x_i, y_i) are the Cartesian coordinates of the origin of reference frame R_i in the frame R_{i-1}. The algorithm for computing the inverse geometric model of the overall structure is presented in figure 9.

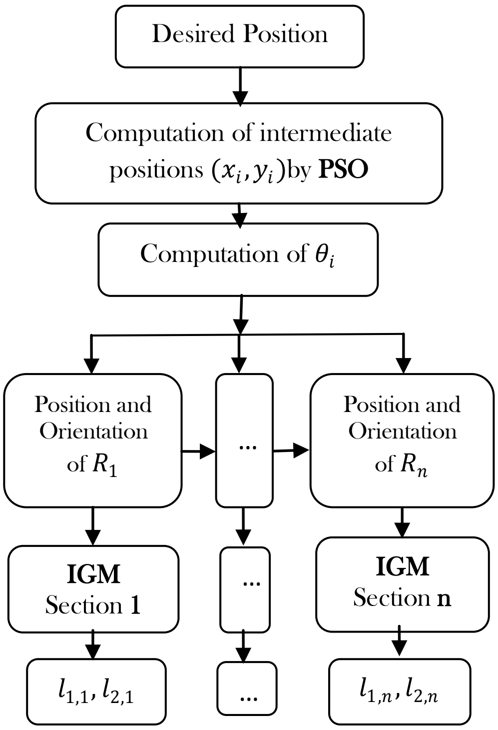

Figure 9: Algorithm for computing the inverse geometric model of a *planar flexible continuum robot*

This optimization method is inspired by the social behavior of some biological organisms, especially the group's ability of some animal species to locate a desirable position in the given area. This method uses the simple rules of displacement in the space of the solutions, where the particles can progressively converge to a local minimum. For each iteration t, the velocity changes by applying equation (15) to each particle.

$$v_i(t+1) = \omega v_i(t) + c_1\varphi_1(P_{ibest} - x_i) + c_2\varphi_2(P_{gbest} - x_i) \quad (15)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (16)$$

Where ω is called the inertia weight, c_1 and c_2 are weighting factors and φ_1 , φ_2 are random variables uniformly distributed within interval [0, 1]. P_{ibest} and P_{gbest} represent the best position visited by a particle and the best position visited by the swarm till the current iteration t. The position update is applied by equation (16) based on the new velocity and the current position. The calculation steps are given by the following algorithm:

- *For the time step t*

  For each particle

  For each dimension d

  Modify the velocity:

$$\begin{cases} v_d(t+1) = \omega v_d(t) + \\ aleatory.[c_1\varphi_1](P_{i,d} - x_d(t)) + \\ aleatory.[c_2\varphi_2](P_{g,d} - x_d(t)) \end{cases}$$

- *Move* $x(t+1) = x(t) + v(t+1)$

3.3. Application

Knowing the general movement of the platform *n* generated by the operational coordinates (x_n, y_n) we determine the displacements of the actuators and the mobile platforms. To illustrate this inverse geometric modeling, we applied it on a planar robot consisting of two bending sections of length $l_1 = 140\ mm$ and $l_2 = 120\ mm$, for the following settings of the trajectory in operational space:

$$\begin{cases} x_2 = 260 - 15 \times t \\ y_2 = 15 \times t \end{cases}$$

Where *t* is time variable varying from 0 to 8 sec, with a step equal 2 sec .

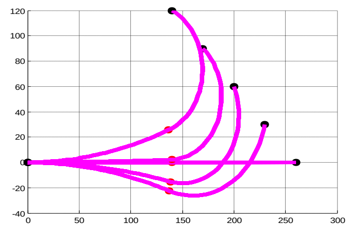

Figure 10: The virtual axis of the robot

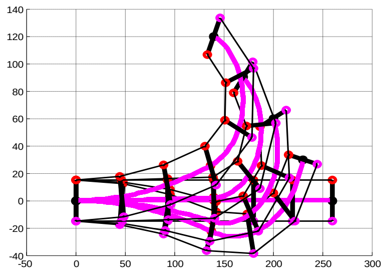

Figure 11: Robot with two bending sections describing a linear path

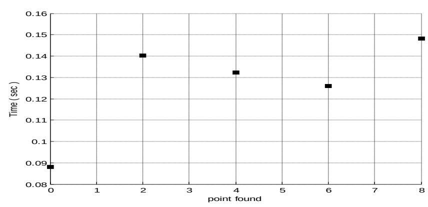

Figure 12: The execution time of the optimization algorithm for each point found.

The simulations were done on a PC with a processor i3 3.30 GHz. the execution time of the optimization process for each point found is shown in figure.12. The average time is equal to 0.128 sec.

Conclusion and future works

In this paper, a new approach of modeling of the planar flexible continuum robots is presented. We have detailed the methodology to formulate the function describing the curvature of the central axis of the robot. The principal idea of our work is based on rebuilding of curves work starting from the tangential data developed in [12]. Mathematical formulations of a planar continuum robot are given; these formulations provide the calculation of the cables lengths of the robot for of a given point in the workspace and vice versa. The operational co-ordinates of the intermediate platforms origins, used in the calculation of the inverse geometric model, are calculated by a numerical method where the space of search for this method is arbitrarily selected. Future work is to improve the execution time, one taking the space of research in the workspace of each section, in order to find a solution close to real time. To have the uniqueness of the solution the introduction of other constraints is necessary. Also the generalization of the approach in the three-dimensional is projected.

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