Prototype of an affordable continuum robot-based IoT accelerometer and its kinematic modeling

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***Abstract*—The continuum robot-based IoT has been the focus of researchers over the last decades because of its affordability cost-less manufacturing. To this end, in this paper, continuum robot's design is briefly described. Then the forward kinematic modeling (FKM) for a single section continuum robot is derived and from which a new empirical formula for the FKM is proposed to simplify its mathematical complexity. After that, Particle swarm optimization (PSO) is adopted to figure out the inverse kinematic model of a single section continuum robot. To verify the reliability of the proposed empirical formula as well as PSO efficiency, a graceful prototype of continuum robot coupled with data logger named accelerometer 345 is attached on the robot's end-effector to record its positions for given bending angles. Finally, the obtained robots end effector positions from the accelerometer are used as inputs to PSO and its found that the resulting bending angles from both PSO and the angle meter are overlapped. It is noteworthy to say that the proposed technique of logging data-based accelerometer for tracking continuum robot is considered for the first time as an alternative technique to perfectly track the robot's motion.**

***Index Terms*—accelerometer , ADXL345 , continuum robot , robotic , Internet of Things**

I. INTRODUCTION

The first apparition of industrial robot was developed by Grifith P. Taylor in 1937, establishing the start of robotics [1]. Recently, a new type of robot has been emerged which is called continuum robot. They are biologically inspired, their shapes are way similar to elephant trunks and tentacles [2], [3]. Basically, continuum bionic robots are composed of a flexible backbone, disks, cables and a rigid base, which holds the control system. These robots are particularly used for exploration in labyrinth-like paths and confined environments [4]. Generally, there are single and multi-sections continuum robots [5]. For variable curvature continuum robots, there is a very few works which proposes models for the forward kinematics of conical shaped continuum robots. The previously developed forward kinematic models exclusively address a specific type of robot [6]–[9]. From an analytical point of view, the inverse kinematic model (IKM) is not that easy to solve, for this particular reason, researchers justifiably turned into meta-heuristic approaches [10]–[12], neural network [13] and so forth. In [8], the authors solved the IKM using particle swarm optimization (PSO). Their model provides with accurate results and the error is less than 0.0008 rad during trajectory tracking. Their main idea resides in developing an objective function which relates the robot's end effector and the prescribed trajectory. In [11], authors used genetic algorithm (GA) and particle swarm optimization (PSO) for solving the IKM of a continuum robot with constant curvature (CC). They followed the same idea as in [14].

The accelerometer in a sensors classified as an microelectromechanical system can translate dynamics quantities such as displacement, velocity and acceleration to electrical data [15]. To this end, in this paper, we present a data logger is attached on the end-effector of a continuum robot's prototype to record its positions and the resulting bending angles are measured using an angle meter. After that the obtained robots end effector positions from accelerometer are used as inputs to PSO and the resulting bending angles from both PSO and the angle meter are compared for the sake of validate the simulated model. To emphasize the contribution in this paper can be summarized as follows: a brief state of art for continuum robot, a newly proposed prototype for a constant curvature continuum robot, novel affordable technique to measure the robot's end tip using accelerometer. The rest of paper is organized as follows: Section II describes a conical as well as a cylindrical continuum robot. On the basis of CCKA, the forward kinematics models are developed in section III - IV. In section V , the particle swarm optimization is devel-

TABLE I
NOMENCLATURE

i	: cables $i = 1, 2, 3$	$(x, y, z)_{j,k}$	: local coordinate frame
j	: units $j = 1, 2, ..., 5$	$(X, Y, Z)_k$	: global coordinate frame
k	: sections $k = 1, 2$	$\theta_{j,k}$	: bending angle
$\ell_{i,j}$	: non-conic unit cable length	φ_k	: is the orientation angle
$\hat{\ell}_{i,j}$	: is the conic unit cable length	κ_j	: curvature
$l_{j,k}$	: central axis' length of the unit j	$r_{j,k}$	: Disk diameters

oped to solve the inverse kinematic model of single section continuum robot where provides with the robot's positions then they are used as an input to PSO. In section VI, an accelerometer coupled with an angle meter is used to obtain the robot's end effector positions as well as its bending angles, respectively. Then, the simulation and the experimental results obtained from accelerometer are compared. Finally, the paper is concluded with most important findings as well as future works for modeling continuum robots.

II. DESCRIPTION OF CONTINUUM ROBOTS' DESIGN

Cable driven continuum robots are mainly composed of a set of disks which are held by a flexible backbone as it is described in [4], [7] and can also be actuated pneumatically as in [14]. Each disk has three holes through which the cables go through and used to manipulate the robot's movement. To the best of our knowledge, there are two approaches of modeling cable driven continuum robot, namely constant and variable. Constant curvature continuum robot (see Fig. 1a) is typically known by its cylindrical shape and each of its sections are governed by the same bending angle. Noticeably, the constant curvature (CC) continuum robot's section units has the same bending angle. The kinematics nomenclature of the robot are given in tab I

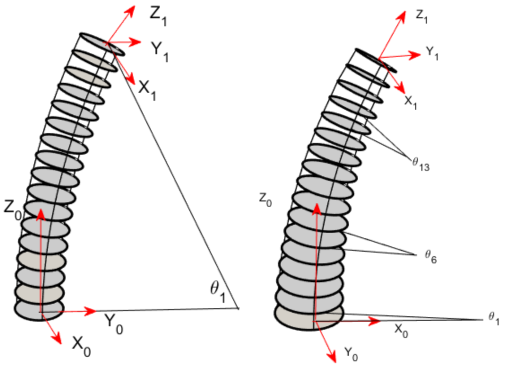

Fig. 1. (a) Constant curvature continuum robot; (b) Variable curvature continuum robot (conical shape)

However, VC continuum robot's (Fig. 1b) backbone consists of serially connected units where each unit is governed by its own bending angle. Furthermore, variable curvature (VC) continuum robot's each unit has an upper and lower disk with different diameters forming a conical shape. A detailed description of the robot's unit with CC and VC is illustrated in Fig. 2.

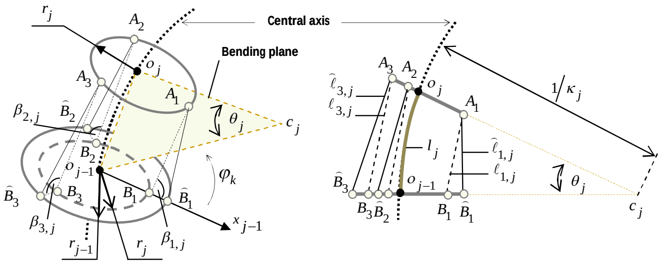

Fig. 2. Kinematics nomenclature of a single conically and cylindrically shaped unit

III. FORWARD KINEMATICS MODELING OF CONSTANT CURVATURE CONTINUUM ROBOT

The constant curvature kinematic approach (CCKA) is the most commonly used in modeling continuum robots [8] due to its simplicity yet it does not properly describe the geometry of variable curvature continuum robots. In General, this approach can be performed in two steps: a specific transformation between the configuration space followed by an independent transformation between the actuator space and the configuration space. In the following analysis, the orientation angle is considered to be equal to zero (i.e. in planar projection). The specific kinematic mapping gives the arc parameter as a function of the actuators cable. Therefore, the bending angle be expressed as follows:

$$\theta_j = \frac{2}{3}\frac{\ell_{1,j} - \ell_{2,j}}{r_j} \tag{1}$$

While the independent kinematic mapping expresses the relationships between the operational coordinates and arc parameters. More generally, this mapping can be described by the following homogeneous transformation matrix :

$$\mathbf{T}_n^0 = \prod_n^0 \mathbf{T}_{j,k}^{j-1,k} \tag{2}$$

in which

$$\mathbf{T}_{j,k}^{j-1,k} = \left(\begin{array}{c|c} \mathbf{R}_{j,k}^{j-1,k} & \mathbf{P}_{j,k}^{j-1,k} \\ \hline \mathbf{0}_{1\times 3} & 1 \end{array}\right) \tag{3}$$

where $\mathbf{R}_{j,k}^{j-1,k}$ and $\mathbf{P}_{j,k}^{j-1,k}$ are the rotational matrix and the vector position, respectively. They can be expressed as a function of arc parameters as follows:

$$\mathbf{R}_{j,k}^{j-1,k} = \mathbf{rot}(Z_{j-1,k}, \varphi_k)\cdot\mathbf{rot}(Y_{j-1,k}, \theta_{j,k})\cdot\mathbf{rot}(Z_{j-1,k}, -\varphi_k) \tag{4}$$

and

$$\mathbf{P}_{j,k}^{j-1,k} = \begin{cases} \frac{l_{j,k}}{\theta_{j,k}}(1-\cos(\theta_{j,k}))\cos(\varphi_k) \\ \frac{l_{j,k}}{\theta_{j,k}}(1-\cos(\theta_{j,k}))\sin(\varphi_k) \\ \frac{l_{j,k}}{\theta_{j,k}}\sin(\theta_{j,k}) \end{cases} \tag{5}$$

IV. FORWARD KINEMATICS MODELING OF VARIABLE CURVATURE CONTINUUM ROBOT

To derive the Forward Kinematic Model (FKM) of the conical-shaped unit by applying the CCKA [8], Equation (1) has to be expressed as a function of the cables length $\overset{\frown}{\ell}_{i,j}$ instead of $\ell_{i,j}$ (for more details refer to [16]). The relationship between the cable lengths can be expressed as follows [16]:

$$\overset{\frown}{\ell}{}^2_{i,j,k} = \ell^2_{i,j,k} + (r_{j-1,k} - r_{j,k})^2 - 2\ell_{i,j,k}\,(r_{j-1,k} - r_{j,k})\cos(\beta_{i,j,k}) \tag{6}$$

With :

$$\cos(\beta_{i,j,k}) = \sin\left(\frac{\kappa_{j,k} l_{j,k}}{2}\right)\cos\left(\frac{2}{3}\pi\,(k-1) - \varphi_{j,k}\right)$$

After solving equation (6), the cables' lengths $\ell_{i,j,k}$ can be expressed as follows:

$$\ell_{i,j,k} = \sqrt{\overset{\frown}{\ell}{}^2_{i,j,k} - (r_{j-1,k} - r_{j,k})^2 + (r_{j-1,k} - r_{j,k})^2 \cos^2(\beta_{i,j,k})} + (r_{j-1,k} - r_{j,k})\cos(\beta_{i,j,k}) \tag{7}$$

According to (7), the cables' length $\ell_{i,j,k}$ is in function of the cables' length $\overset{\frown}{\ell}_{i,j,k}$, the variation of the diameters of each units' disks $(r_{j-1,k} - r_{j,k})$ and angle $\beta_{i,j,k}$. The diameters of the continuum robot's disks can be calculated using the following equation [8]:

$$r_{j,k} = r_{\max,k} - \frac{j}{m_k}(r_{\max,k} - r_{\min,k}) \tag{8}$$

$$\gamma_i = \frac{2(i-1)\pi}{3}, i = 1, 2, 3 \tag{9}$$

However, due to the coupling of cables length and bending angle, Equation (5) does not have an analytical solution. To derive an analytical-approximate solution, the bending angle θ_j is firstly estimated as a function of a given driving cable length $\overset{\frown}{\ell}_{i,j}$ using particle swarm optimization where the objective function is to make the root attain specific position using the same cable length for each unit. For this optimization problem, the appropriate cost function to be minimized can be formulated from Equation (5), where the unknown variable to be searched is the bending angle θ_j. Secondly, the obtained bending angle θ_j is expressed mathematically as a function of $\overset{\frown}{\ell}_{i,j}$ using Cubic Polynomial Fit (CPF). illustrates the geometric parameters of the considered CDCR. it is noteworthy to say that the developed work in this paper is strongly related on the work done by Bousbia et al.

For further use, let's calculate the first bending angle θ_1 of the robot section. For instance, the estimated bending angle θ_1 of the first bending section as a function of a given driving cable length $\overset{\frown}{\ell}_{i,j}$ is shown in Fig. 3. From this Figure, one can observe that the errors are negligible. By using the Cubic Polynomial Fit (CPF), the obtained bending angle can be approximated as follows:

$$\theta_1 = 1.8912{\cdot}10^{-4}\,\overset{\frown}{\ell}{}^3_{1,1} - 1.068{\cdot}10^{-2}\,\overset{\frown}{\ell}{}^2_{1,1} + 2.4\,\overset{\frown}{\ell}_{1,1} + 4.9872{\cdot}10^{-4} \tag{10}$$

TABLE II
GEOMETRIC PARAMETERS OF THE PROPOSED PROTOTYPE

Description	section length	number of units	r_{min}	r_{max}
value	300 mm	5	20	31

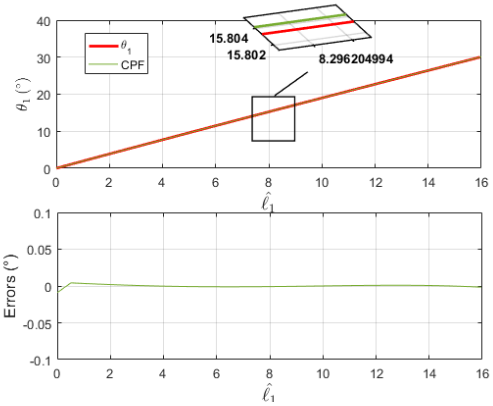

Fig. 3. Cables length in function of the first bending angle and their errors

A. *Forward kinematic of a single continuum robot section*

As an open kinematic chain of serially connected units, the forward kinematic of a continuum robot section can be obtained according to the homogeneous transformation matrix as follows:

$$\mathbf{T}_n^0 = \prod_n^0 \mathbf{T}_{j,k}^{j-1,k} \tag{11}$$

In which the FKM of each conical-shaped unit can be derived following the same procedures described in the previous subsection. However, in order to reduce the number of variables involved in the model, the rest of bending angles θ_j with $j = 1, 2, 3$ will be approximated as a function of the first bending angle θ_1 using CPF. The bending angles θ_j of the continuum robot section, composed of five units, can be expressed as follows:

$$\theta_j = c_{1,j}\theta_1^3 + c_{2,j}\theta_1^2 + c_{3,j}\theta_1 + c_{4,j} \tag{12}$$

where the coefficients $c_{1,j}$, $c_{2,j}$, $c_{3,j}$, $c_{4,j}$ are given in tab three.

V. PARTICLE SWARM OPTIMIZATION (PSO)

PSO was mainly developed by Kennedy and Eberhart in 1995 [17]. This method is inspired from the remarkable movements of the flock of birds. It has become omnipresent

TABLE III
COEFFICIENTS OF THE CUBIC POLYNOMIAL FIT

Bending angles	$c_{1,j}$	$c_{2,j}$	$c_{3,j}$	$c_{4,j}$
θ_2	$3.0495 \cdot 10^{-6}$	$-3.608 \cdot 10^{-4}$	1.0898	$1.101 \cdot 10^{-4}$
θ_3	$7.899 \cdot 10^{-6}$	$-9.079 \cdot 10^{-4}$	1.1997	$3.371 \cdot 10^{-4}$
θ_4	$1.584 \cdot 10^{-5}$	$-1.759 \cdot 10^{-3}$	1.3226	$8.109 \cdot 10^{-4}$
θ_5	$2.940 \cdot 10^{-5}$	$-3.099 \cdot 10^{-3}$	1.4984	$1.799 \cdot 10^{-3}$

in engineering problems since it can easily help to figure out them efficiently. The first step in PSO is the random generation of particles. Each particle P is updated at every single iteration by two best values: (1) the position vector of the best solution which has been achieved so far by the particle and can be denoted as $P_{pb(t)}$, and (2) the general best value obtained by any particle is also considered to be another overall best value which can be called $P_{bg}(t)$. Furthermore, at each iteration, the PSO algorithm randomly changes the velocity of each particle towards $P_{pb}(t)$ and $P_{bg}(t)$. Then select the best one of them which matches with the tackled operation. (13) and (14) depict, respectively, the updating velocities $v(t)$ and positions $P(t)$ of each particle. PSO stops operating at the maximum number of the given iterations.

$$v_p^{t+1} = \omega v_p^t + c_1 \rho_1 (P_{pb}^t - x_p^t) + c_2 \rho_2 (P_{bg}^t - x_p^t) \tag{13}$$

$$x_p^{t+1} = x_p^t + v_p^{t+1} \tag{14}$$

where v_p^t is the particle velocity; x_p^t is the particle position; ω is the inertia weight; c_1 and c_2 are constants; ρ_1, ρ_2 are random numbers uniformly distributed within the interval $[0, 1]$; P_{pb}^t represents the local best position; P_{bg}^t represents the global best position.

A. *Objective function and problem formulation*

The objective function is the distance between the robot's end effector and the position on the prescribed trajectory. The lowest distance can be considered as a solution to a given position. Basically, PSO finds the bending and angles to attain the desired position. The process of PSO for solving the inverse kinematic model of the considered robot consists in randomly generating the bending angles thus the robot's end effector has random position according to the desired position yet the randomly generated angles which ensure the lowest distance between the robot's end effector and the needed position is considered as a solution to IKM. Since the cables length are in function of the bending and orientation angle, the cables length allowing to reach out the needed position can be obtained. The whole process is performed through a set of iteration and the obtained angles are sent to the FKM in order to visualize and confirm the tracking at each iteration.

$$F = (P_{x_i} - X_{c_i}) + (P_{y_i} - Y_{c_i}) + (P_{z_i} - Z_{c_i}) \tag{15}$$

where X_{c_i},Y_{c_i}, and Z_{c_i} represent the spatial coordinates of a located position on the prescribed trajectory. P_{x_i}, P_{y_i}, and P_{z_i} represent the position of the robot's end tip for each specific position of the prescribed trajectory. The robot's end-tip pose is obtained from the FKM. Explicitly, its position present the three first components of the fourth column of the matrix which is defined by (3), similarly its rotation is also obtained from (3). The obtained positions are used as an input to PSO, which generates the needed bending angles according to the given robot's end effector. Accordingly, the generated bending angles from PSO and those obtained from FKM are compared as it is shown in figure **??** and which can be summarized as follows:

$$\begin{cases} \theta, \phi \xrightarrow{FKM} (X, Y, Z) \\ (X, Y, Z) \xrightarrow[PSO]{IKM} \theta, \phi \end{cases}$$

VI. SIMULATION ANALYSIS

In this section, simulation analysis is carried out for a single section continuum robot for the sake of validating the developed mathematical formula in this paper. In the first simulation a variable curvature continuum robot with one section follows arc-like trajectory. The particle swarm optimization is supposed to find the necessary robot's bending angle allowing its end effector to attain to each position on the arc like trajectory. where the objective function defined by equation (15). is used in the MATLAB code as the distance between the robot's end effector and the position on the prescribed trajectory.

A. *Verification of the newly proposed formula*

In this section, the proposed empirical formula (12) is used to generate the robot's end effector positions during trajectory tracking see Fig. 4. Basically, the obtained positions are used as an input to the optimization algorithm PSO. Then, the particle swarm optimization generates the needed bending angles according to the given robot's end effector. Accordingly, the generated bending angles from PSO and the obtained bending angles From FKM are compared as it is shown in Fig. 6.

Remarkably, based on Fig. 6, the obtained bending angles from the proposed formula and those generated from PSO are in a good match which proves the efficiency of the proposed model as well as the particle swarm optimization algorithm. To emphasize both codes are available, the former generated the robot's end effector positions and latter consists of using particle swarm optimization to solve the inverse kinematic model of the continuum robot's section proposed in this paper.

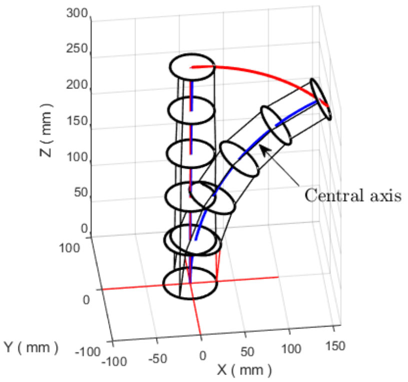

Fig. 4. The whole robot follows the arc-like trajectory

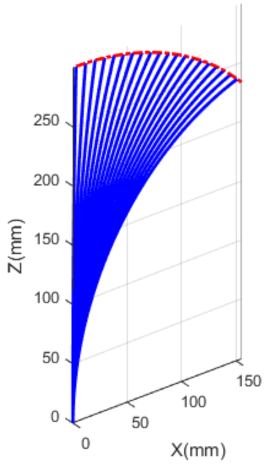

Fig. 5. The robot's central axis follows the arc-like trajectory

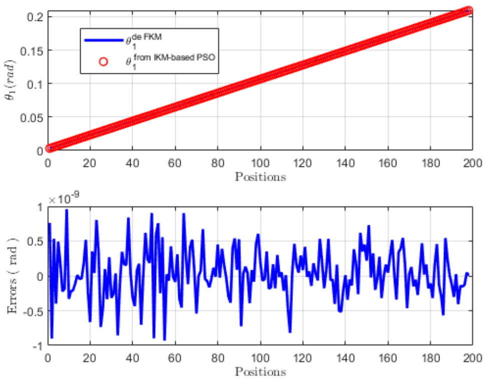

Fig. 6. The bending angle for the first five units of the first section and their errors

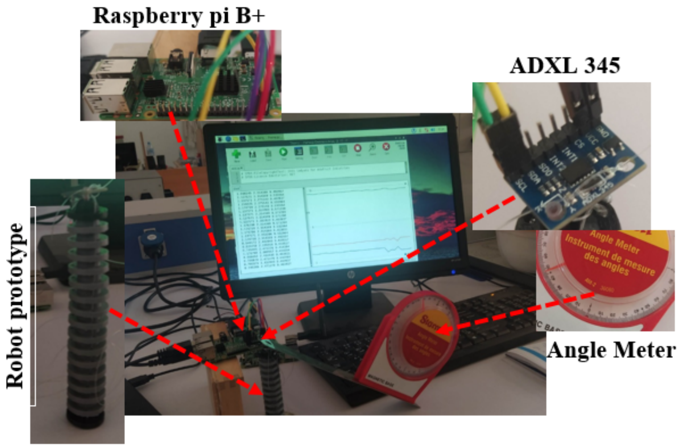

Fig. 7. Bench test which depicts the way to track the robot's end effector and the bending angles corresponding to each position

VII. EXPRIMENTAL VERIFICATION OF PARTICLE SWARM OPTIMIZATION THROUGH ACCELEROMETER BASED DATA

In this section, a prototype for a single section continuum robot is proposed and used to verify the accuracy of particle swarm optimization in solving the inverse kinematic model. Basically, to acquire the different data of the robot, namely the robot's end effector position as well as the bending angle corresponding to that position, we used the following equipment:

- Accelerometer ADXL 345 : is used to record the robot's end effector along X, Y, Z, which is a tiny, low power, 3-axis accelerometer with high resolution (13-bit) and measurement at up to 16 g. it also provides with digital outputs [18].
- Angle meter is used to measure the robot's bending angle
- raspberry pi 3 B+ a single-board computer's final revision with characteristics which can be found in detail in the manual [19] is used to run the accelerometer
- Python is the used language to program accelerometer and make it record positions.

Due to the basic used tools for measurements, we have only tried eight positions for the robot's end effector. Interestingly, the main idea is not only dedicated to comparing the obtained angles from PSO and those from accelerometer but it also focuses on using accelerometer as a costless tool to track the robot's end effector. With more accurate accelerometer models we can even come close to the theoretical obtained angles from PSO. Based on tab five , there is a difference between the obtained angles from PSO and those obtained from real measurements where the maximum error is less 3 degrees.

Basically, the main idea in this section is to show the utility of using accelerometer to track the the robot's end effector through costless tools without the need to implement extravagant high tech.

VIII. CONCLUSION

In this paper, the forward kinematic model of a single section continuum robot is derived and simplified by proposing a new empirical formula. Undoubtedly, the non-linearity of the inverse kinematic model presents an impediment to researchers which stimulate the use of meta-heuristic approaches to solve

TABLE IV
COMPARAISON BETWEEN THE OBTAINED ANGLES FROM PSO AND THOSE MEASURED USING AN ACCELEROMETER AND AN ANGLE METER

position from accelerometer (mm)	obtained angles from PSO (degree)	Measured angles (degree)
(1.9014,0,118.6489)	43.89	45.70
(2.9512, 0,116.5491)	40.52	41.57
(3.9996,0,115.4369)	38.61	40.80
(4.0463,0,114.3123)	36.93	34.55
(5.0156,0,113.3123)	34.50	35.60
(6.0463,0,112.3123)	30.68	32.50
(7.0463,0,111.3123)	28.90	31.55

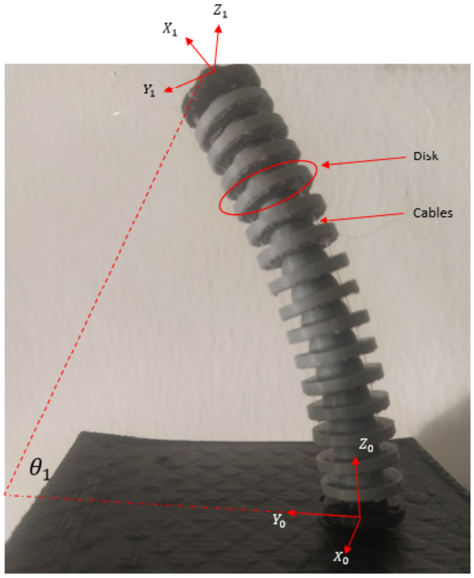

Fig. 8. The proposed single section continuum robot prototype

it. In this context, the particle swarm optimization is used to figure out the IKM. The IKM problem is formulated as an objective function which is the distance between the robot's end effector and the position on the prescribed trajectory. The generated bending angles from PSO and those obtained from FKM are in a good match. Experimentally, for the sake of verifying the efficiency as well as the accuracy of particle swarm optimization, we proposed a single section continuum robot's prototype, in which the bending angle of the prototype for each positions are recorded using an angle meter. Interestingly, accelerometer can be used as an alternative to identify continuum robot's end effector position instead of using expensive tools. However, in future works accelerometer needs to be furtherly improved to efficiently record data from continuum robots.

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