Kinematic Model Analysis and ROS Control of Cable Driven Continuous Robot Manipulator

Hernando Leon-Rodriguez[1,2] Yefry Moncada[1], Simon. Mosqueda[1], Cecilia Murrugarra[1], Michael Canu[1]

[1]*Electronics Engineering Department; El Bosque University, Bogota, Colombia.*

[2]*Bioengineering Department, El Bosque University, Bogota, Colombia*

{ hefrainl, ymoncada, smosqueda, cmurrugarra, mcanu}@unbosque.edu.co

Keywords: Continuous redundant robot, End effector, Mathematical model, cable robotic system.

Abstract: This paper describes the developed of cable continues redundant manipulator and its kinematic model analysis. The goal is to determine the accuracy of the experimental prototype with the constant curvature kinematic model. The experimental validation of the constant curvature kinematic model is evaluated to establish a relation between the mathematical model and continuum robot, and its feasibility of applying for any type of continuous redundant structure by computing the end effector trajectory based on the displacement of passive cables located along the structure. The continuous redundant prototype robot is composed by 2 segments with 7 modules sections powered by 6 driven cables where each segment is controlled with 3 lineal motors. The length of the segment is desired but it is also allows to add modular sections and connect them like serial chain. The radius of concave and/or convex curvature allows the robot manipulator to follow different trajectories and displacements in their workspace. The paper also describes the relevant components and the position feedback control implemented via ROS.

1 INTRODUCTION

The robotics field is always looking for different ways to provide solutions for specific requirements in industrial and medical applications. Initially, research was mainly focused in automated manipulators for dangerous work environments or manufacturing processes to replace human operator, especially in those with executed routines tasks. Industrial robots have traditionally open links with connected joints directly actuated (Pires, 2007). In addition, these types of robots have been proved to be useful in many industrial tasks, however, they have obvious weaknesses in more constricted spaces due to the lack of degrees of freedom (D.O.F.), low level of flexibility and in the real world the environment and task most of them are unknown for rigid link manipulator. (Li and Rahn, 2002)

Nowadays, some of these problems have been resolved through biologically inspired designs, which aim to reproduce the locomotion properties and adaptability of certain animal extremities such as octopus, or squid tentacles (Laschi et al., 2012), snake-like structures (Crespi et al., 2005), elephant trunks (Tiefeng et al., 2015) and others. This type of robotics mechanisms are known as a continuum or hyper-redundant robots where contrasts from traditional manipulators in the sense that they are capable of possessing a high range of flexibility and more degrees of freedom enabling them to traverse precisely through almost any ”space” and around many obstacles. I recent years, they have gained wide interest from the medical field (Burgner-Kahrs et al., 2015), specifically, in conducting Minimal invasive surgery (MIS) (Burgner et al., 2014). And also, in industrial applications they are considered to be ideal for probing cramped and hazardous industrial environments like inspect nuclear reactors (Ma et al., 1994), as well as confined spaces (Liu et al., 2016), to search and rescue in disaster situation (Meng et al., 2013); One of the best examples is been developed by a British company OC robotics (Robotics OC, 2016).

The research of multiple DOF are been proposal a few year back by mimicking a snake’s locomotion (Hirose, 1995), followed by the work of Chirikjian and Burdick that extended on this approach of fitting the hyper-redundant robot to analytical desirable mathematical curves by establishing them as the product of a Bessel function with trigonometric models (Chirikjian and Burdick, 1995b), moreover, they described the behaviour of the constant curving structure using the Frenet-Serret Frames equations (Chirikjian and Burdick, 1995a). Subsequently, the work of Walker (Jones and Walker, 2006), Zheng, Webster and Jones (Webster and Jones, 2010) allowed for the integration of these models, with the D-H parameters (Hannan and Walker, 2003), the integral representation and a product of exponentials (POE)(Li et al., 2017), to finally obtaining a reliable kinematic model derived to constant-curvature, which is capable to accurate describes the behaviour of any continuum robot and is one of the most well-known and used for modelling.

The classifications of type of robots by their defining feature are continuously curving back-bone or core. This backbone is known as continuous redundant and can be segmented and resembled to serial rigid-links, which together give the appearance of one continuous structure. The shape can be modified with diverse types of actuators, as example: pneumatic mechanism (Mahl et al., 2014), tendon mechanism (Li et al., 2016)

Most continuum redundant robots have a few actuators; these are also known under-actuated considering the number of DOFs produced. These under-actuated systems had a substantial simplicity on the control system, with some disadvantage in speed, strength and limited workspace due to the reduce dexterity. Nevertheless, these robots by their type of actuation and structure can be classified in three main categories, tendon-driven serpentine manipulators (TSM), Tendon-driven continuum manipulators (TCM) (Walker, 2013), and concentric tube manipulators (CTM) (Li et al., 2017).

This work presents the description of technical characteristics in the mechanical design, motion, electronic system and measurements. The paper is based in the evaluation of the relation between the mathematical models of continuous robot and some experimental measuring in the end effector in planar trajectory (S. Mosqueda et al, 2018). This work was done by tracking the displacement of passive cables located along the structure, with the purpose of estimating the resulting shape of the planar trajectory. The further research work and experimental validation implemented of the continuous redundant robot is presented by analysing two segments in a formal description of the Mathematical model and validation.

2 PROTOTYPE DESIGN

Figure.1 is showing a computer render and prototype of the continuous redundant manipulator; it is composed by 2 segments with 7 sections each and free joints between them. The bases are made in MDF in order to locate the manipulator on top of them and underneath are located the 6 lineal actuators. Each segment is power by 3 lineal motors where its mathematical model and analysis is presented in the next section.

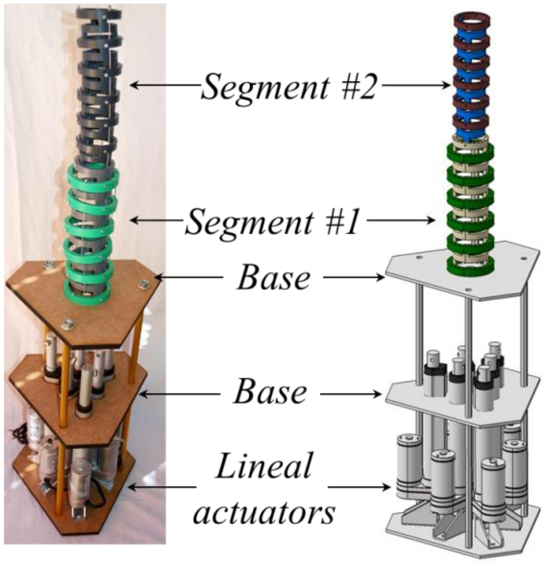

Figure 1: Prototype platform of continuous redundant robot composed by: 2 segments, 14 sections, 6 cables (3 for each segment), and 6 lineal actuators.

Figure 2 is showing the block diagram of the experimental prototype controller from the remote stations (ROS computer) to end up in the end effector.

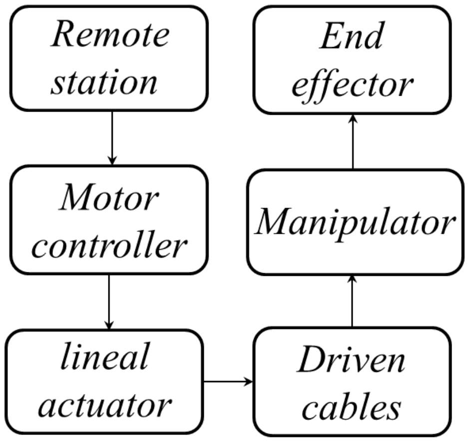

Figure 2: Block diagram of prototype platform for the continuous redundant manipulator.

The Continuous redundant Manipulator system showing in figure 3 was implemented to position the end effector in a determined 3D location by executed the following steps. The ROS software located in the remote stations send a specific position command through the motor controllers. The motors using the motor control boards until the lengths of the tension cables are reached. When the end effector is close as possible to the theoretical lengths the systems stops by compared the final position of the actuator through of lineal sensor located in the stroke of the lineal motor.

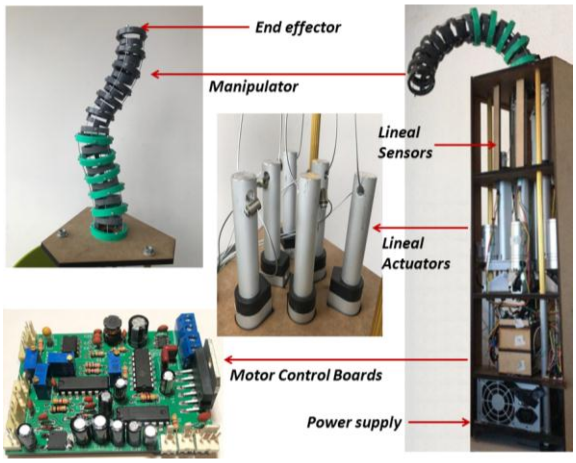

Figure 3: Continuous redundant manipulator prototype and its mechanical architecture

The main components are listed as follow:

- *Processing central* by a remote station computer with ROS software.
- *Motor Control Boards* using six own developed amplifiers cards mastered with an Arduino card.
- *Lineal Actuators and Transmission Mechanics* by six ECO-WORTHY: stroke length 150mm, rated at 5.7mm/s, 1500N pull and 1200N push force with magnetic encoder.
- *Cables* wire, stainless-steel (316), with 0.28m in length and 1 mm diameter.
- *Lineal sensors,* Contact transducer SoftPad sensor with internal variable resistance from 100ohm to 10k ohm, with 200mm length and 5 V.
- *Manipulator* 2 segments were designed: the first segment is composed by 7 Polypropylene tube sections with 0.20m in length and 0.14m in diameter, with seven sections, free joints. The second segment is composed by 7 PVC tube sections with 0.22m in length and 0.08m in diameter, with seven sections, free joints.
- *End effector* finally locating point of manipulator.

The kinematic model used to obtain the necessary cable lengths to move the manipulator to a certain position was simulated with MATLAB, using the equations of the further section.

3 ANALYSIS AND MATHEMATICAL MODEL

This section descripts the manipulator shape and end-effector position by analysing the robust kinematic model based on constant curvature, describing the movements of the structure and workspace.

The classic modelling of an articulated robot system consists in compute the position and orientation of the end effector based in world reference coordinates; this are achieved by defining a robot with link or rigid elements and lineal or rotated joints. However, this mathematical method is not suitable to a system that has more degrees of freedom than those needed to carry out; as a result, not useful to continuous robots.

The kinematical model developed for continuous redundant manipulator (Jones et al., 2006) and (Chirikjian and Burdick, 1995a), uses a series of substitutions on the Denavit-Hartenberg (D-H) transformation matrix, with the aim of obtain a model that defines a more accurate behaviour of translations and rotations with standard homogeneous transformation matrix *A(θ, d)*, equation 1.

$$A = \begin{bmatrix} \cos^2(\phi)[\cos(ks-1)]+1 & \sin(\phi)\cos(\phi)[\cos(ks-1)] & -\cos(\phi)\sin(ks) & \frac{\cos(\phi)[\cos(ks-1)]}{k} \\ \sin(\phi)\cos(\phi)[\cos(ks-1)] & \cos^2(\phi)[\cos(ks-1)]+\cos(ks) & -\sin(\phi)\sin(ks) & \frac{\sin(\phi)[\cos(ks-1)]}{k} \\ \cos(\phi)\sin(ks) & \sin(\phi)\sin(ks) & \cos(ks) & \frac{\sin(ks)}{k} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Further derivations is requires with different mathematical analysis, in which a series of substitutions are made on the D-H transformation matrix, in order to obtain a model that relates a more approximate behaviour. The conventional notation involving a homogeneous matrix is yielded by *A(θ, d)*, where: *θ* represents the independent rotations of the joints and d the translations. However, for continuous robots, performing this analysis involves a homogeneous matrix for each section that makes up a segment, so authors such as Ian D. Walker, which associates the shape of the robot with a curve in space by the middle of the Frenet Serret equations (DHB, 2013), one can establish an equivalent to rotations and translations.

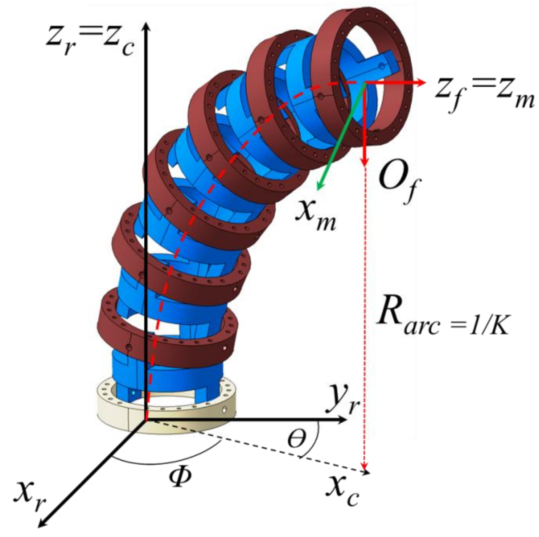

Figure 4: Parameters for continuous redundant Robot Manipulator with free joint sections.

The figure 4 shows the variables for the first step process to obtaining a reliable mathematic model, is to establish a relationship between the D-H parameters θ, and the trunk parameters s, k, φ, and from this, obtaining a more approximate approach to the continuum robot movements in terms of the cable length (Jones and Walker, 2006), (Webster and Jones, 2010). The space transformations between the D-H parameters and s, k, φ and actuators length is shown in Figure.5.

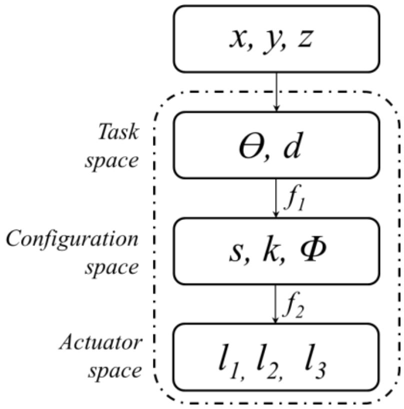

Figure 5: The space transformations between the D-H parameters to actuations spaces s, k, φ, l_1, l_2, l_3.

According to the coordinate system and the geometric relationship with the *arc* parameters, the homogeneous matrix of the *n* segment can be calculated as Equation 1, where the matrix of transformation *A*, allows us to know the position and orientation to perform an analysis of the bending of the continuum robot of the end effector and its 3D workspace. Figure 6 is showing the computer simulation.

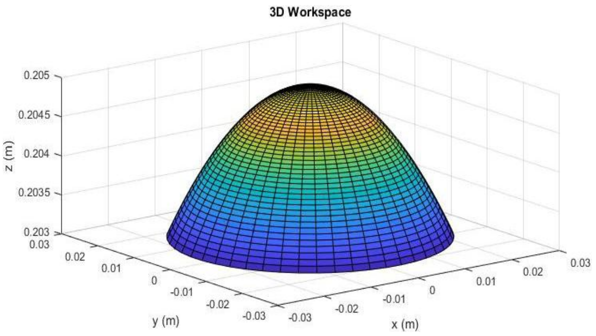

Figure 6: Workspace of Continuum Robot Manipulator with 0.22m length.

In Equation 2, specify the space position of the end effector as follow:

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \begin{bmatrix} \frac{\cos(\phi)[\cos(ks-1)]}{k} \\ \frac{\sin(\phi)[\cos(ks-1)]}{k} \\ \frac{\sin(ks)}{k} \end{bmatrix} \tag{2}$$

Through equations 3, 4 and 5 can be computed to find the position of the end effector based on the *arc* parameters, these parameters can be controlled by adjusting the length of the tensor cables, as a result, it is necessary to derive the mapping from the linear actuators length to the *arc* parameters.

$$\phi = \tan^{-1}\left(\frac{\sqrt{3}}{3}\cdot\frac{l_3+l_2-2l_1}{l_2-l_3}\right) \tag{3}$$

$$k = 2\frac{\sqrt{l_1^2+l_2^2+l_3^2-l_1l_2-l_2l_3-l_1l_3}}{d(l_1+l_2+l_3)} \tag{4}$$

$$s = \frac{l_1+l_2+l_3}{3} \tag{5}$$

Finally to obtain the position of the end effector in relation to the cable lengths is necessarily to know the following parameters from a section of the manipulator; the length of one of its segments, the curvature of the section *(k)*, the angle at which the curvature *(φ)* is found, the distance from the center of the manipulator to the location of the cables *(s)*, and the number of segments in the manipulator section *(n)*; with a combinations of all of these variables finally its obtain the Equation 6.

$$\begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix} = \begin{bmatrix} s\left[1-kd\sin(\phi)\right] \\ s\left[1+kd\sin\left(\frac{\pi}{3}+\phi\right)\right] \\ s\left[1-kd\cos\left(\frac{\pi}{6}+\phi\right)\right] \end{bmatrix} \tag{6}$$

4 CONTROL SYSTEM AND INTERFACE

User interface

The figure 7 shows the graphic user interface (GUI) that allows direct interaction with electronic devices to be controlled through graphic icons and visual indicators, avoiding modifications of code in situations in which the changes implemented are punctual and frequent. In order to work with GUI in ROS environment, we had work with the "RQT" package; this is a framework based on the QT design software.

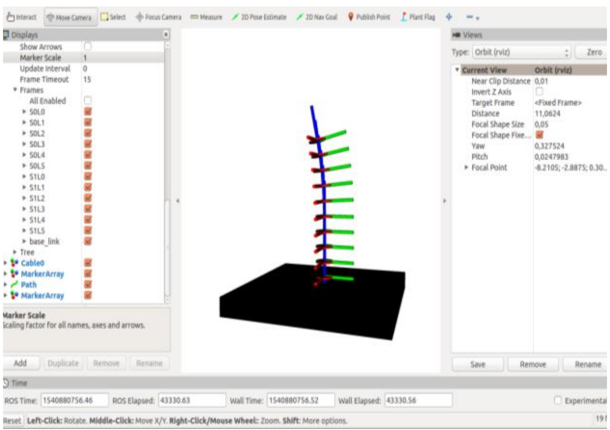

Figure 7: Graphic user interface in ROS of the continuous redundant manipulator

Control algorithm

The system used a PID control algorithm in which the position signal delivered by a subsystem that is continuously monitoring to be able to move the actuator from an initial position to a desired position with less possible error. When the control algorithm is working with the control pack, the system takes one input position from virtual world, and then, reviews the status data from feedback sensors resulting of try to reach the target position. It uses a generic loopback feedback mechanism, usually a PID controller, to control the output, that is, the information sent to the actuators. To adapt the control to the robotic system, the control parameters must be calculated based on the electromechanical characteristics of the actuators. See figure 8.

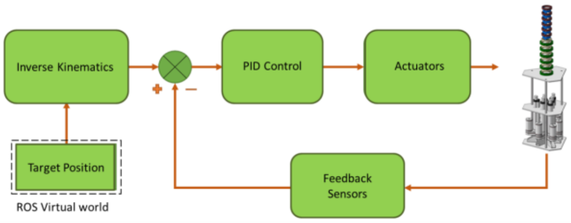

Figure 8: Internal software architecture for the continuous redundant manipulator

The calculation algorithm is responsible for establishing the linearization and performs the conversion of the obtained variables by the feedback sensors of the robotic system; these numerical variables is interpreted by the control algorithm as distances, in order to obtain the actuator position as close as possible to the target position.

5 RESULTS

The implementation of ROS as the main system resulted in a structured project in a modular manner, which allowed the implementation of some scripts that can model any type of continuous robot regardless of its size or number of sections or disks. Figure 7 showing the simulation of the continuous robot model in the RVIZ environment, in which the dynamics of an internal or vertebrate cable is responsible for carrying out the movement according to the trajectory that was established. In Addition, when it was implemented the constant curvature model was necessary to generate a different transformation to each virtual model discs to make-up the segments; as a result, when a variation was made in the angle curvature, it is reflected at each time in the virtual model and reproduced by the prototype showing in figure 9.

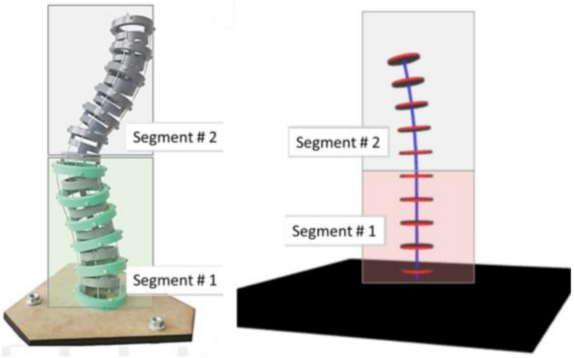

Figure 9: Reproduced position and comparison between physical prototype (left) and simulation (right)

Figure 10 (top) is showing the data results generated by feedback sensors on a real tests. The contact sensor or SoftPot was necessary to calibrate with previous acquisition data; and the following results were obtained: when an end-to-end displacement was executed, this is obviously considered to the maximum values *k* for each tendon trajectory. The figure 10 (bottom) also is showing the values behavior of configurations space parameters *s, k, φ*, performed by the prototype in one desired target positions.

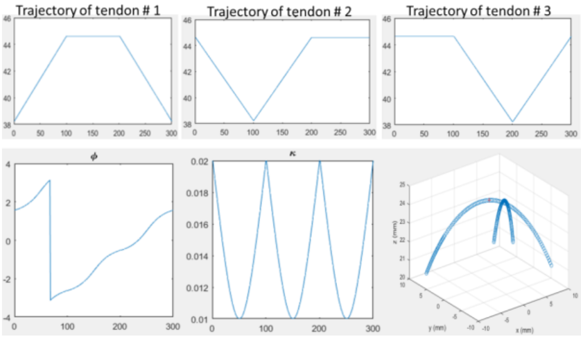

Figure 10 (top) Tendon´s trajectory actuated in segment #2; (bottom) graphic results of configurations space parameters s, k, φ, executed in segment #1.

6 CONCLUSIONS

This paper was focused in the design and functionality of the proposed prototype of continuous redundant manipulator. It started from the selection of components, the mathematical model analysis to end in the implementation, simulation and control of it from ROS system. It has significant advances in all areas from mathematical analysis and simulation to real world test prototype.

This paper also presents a further test manipulator experiments for two segments based in the mathematical model presented by (S. Mosqueda et al, 2018) where the mathematical model in the space transformations between the D-H parameters and *s*, *k*, *φ*, l_1, l_2 and l_3 was implemented and tested for one segment. Its model is the constant curvature kinematic currently used in most continuous robot manipulators.

Figure 11 showing the video sequences of the modular continuous redundant manipulator proposed with 2 set of segments, whose length can be extended even further by adding sections to the segments (links) and, in turn with a new define configuration by extending the length of the manipulator. Some difficulties where observed in the executed prototype. The top segment manipulator requires one specific central chamber to go through the wire cables in order to minimize its error. When the prototype was set with only one segment it has very small positioning error of 1.6 mm presented in the published paper (S. Mosqueda et al, 2018). Nevertheless, this functionality would allow the continuous robot manipulator to track trajectories in the combination of a convex and concave radius of curvature that could be used to perform spatial shifts and obstacle avoidance. The experimental setup allowed validating the mathematical model and identifying the proposed modular link design.

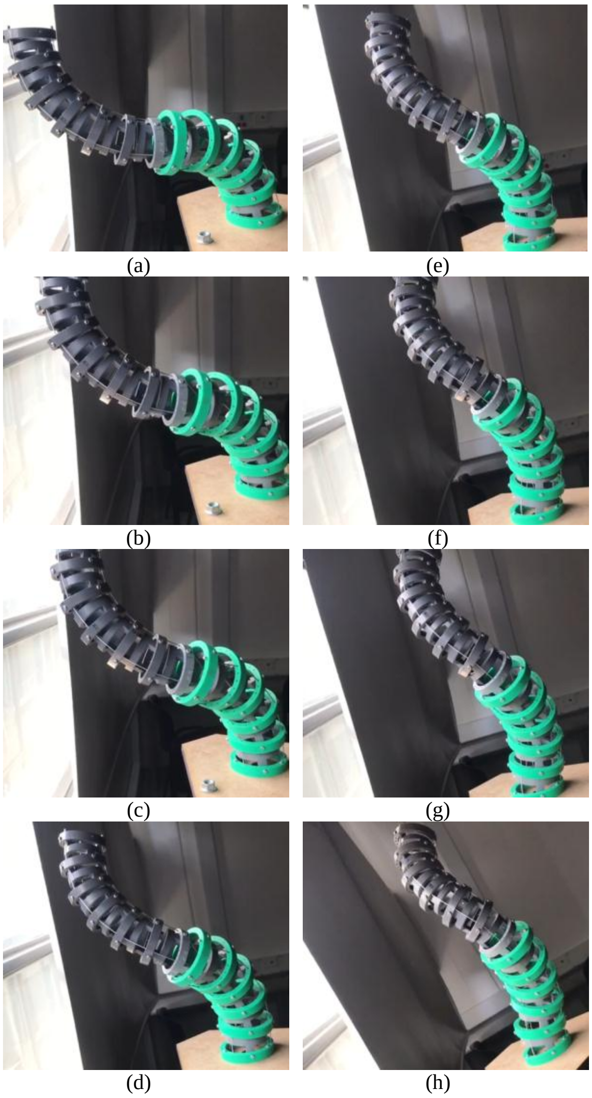

Figure 11: Video sequences of continuous redundant manipulator.

7 ACKNOWLEDGEMENTS

This work is supported by a grant from the El Bosque University and the Research Vice-rectory with the project number PCI-2017-8832. The authors also wish to thank the Electronic Engineering and Bioengineering departments of the faculty of Engineering of El Bosque University for all the support received.

REFERENCES

Burgner, J., Rucker, D. C., Gilbert, H. B., Swaney, P. J., Russell, P. T., Weaver, K. D., and Webster, R. J. (2014). A telerobotic system for transnasal surgery. *IEEE/ASME Transactions on Mechatronics*, 19(3):996–1006.

Burgner-Kahrs, J., Rucker, D. C., and Choset, H. (2015). Continuum Robots for Medical Applications: A Survey. *IEEE Transactions on Robotics*, 31(6):1261–1280.

Chirikjian, G. S. and Burdick, J. W. (1995a). Kinematically Optimal Hyper-Redundant Manipulator Configurations. *IEEE Transactions on Robotics and Automation*, 11(6):794–806.

Chirikjian, G. S. and Burdick, J. W. (1995b). The Kinematics of Hyper-Redundant Robot Locomotion. *IEEE Transactions on Robotics and Automation*, 11(6):781–793.

Crespi, A., Badertscher, A., Guignard, A., and Ijspeert, A. J. (2005). AmphiBot I: An amphibious snake-like robot. *Robotics and Autonomous Systems*, 50(4):163–175.

DHB (2013). Differential Geometry. *Reading*, 1(4):0.

Hannan, M. W. and Walker, I. D. (2003). Kinematics and the implementation of an elephant's trunk manipulator and other continuum style robots. *Journal of Robotic Systems*, 20(2):45–63.

Hirose, S. (1995). Biologically Inspired Robots: Snake-Like Locomotors and Manipulators. *Applied Mechanics Reviews*, 48(3):B27–B27.

Jones, B. A., McMahan, W., and Walker, I. D. (2006). Practical Kinematics for Real-Time Implimentation of Continuum Robots. *IEEE International Conference on Robotics and Automation*, pages 1840–1847.

Jones, B. A. and Walker, I. D. (2006). Kinematics for multisection continuum robots. *IEEE Transactions on Robotics*, 22(1):43–55.

Laschi, C., Cianchetti, M., Mazzolai, B., Margheri, L., Follador, M., and Dario, P. (2012). Soft robot arm inspired by the octopus. *Advanced Robotics*, 26(7):709–727.

Li, C. and Rahn, C. D. (2002). Design of continuous back- bone, cable-driven robots. *Journal of Mechanical De- sign*, 124(2):265–271.

Li, Z., Ren, H., Chiu, P. W. Y., Du, R., and Yu, H. (2016). A novel constrained wire-driven flexible mechanism and its kinematic analysis. *Mechanism and Machine Theory*, 95:59–75.

Li, Z., Wu, L., Ren, H., and Yu, H. (2017). Kinematic com- parison of surgical tendon-driven manipulators and concentric tube manipulators. *Mechanism and Ma- chine Theory*, 107(September 2016):148–165.

Liu, S., Yang, Z., Zhu, Z., Han, L., Zhu, X., and Xu, K. (2016). Development of a dexterous continuum ma- nipulator for exploration and inspection in confined spaces. *Industrial Robot: An International Journal*, 43(3):284–295.

Ma, S., Hirose, S., and Yoshinada, H. (1994). Develop- ment of a hyper-redundant multijoint manipulator for maintenance of nuclear reactors. *Advanced Robotics*, 9(3):281–300.

Mahl, T., Hildebrandt, A., and Sawodny, O. (2014). A Variable Curvature Continuum Kinematics for Kine- matic Control of the Bionic Handling Assistant. *IEEE Transactions on Robotics*, 30(4):1–15.

Meng, G. Z., Yuan, G. M., Liu, Z., and Zhang, J. (2013). Forward and Inverse Kinematic of Continuum Robot for Search and Rescue. *Advanced Materials Research*, 712-715:2290–2295.

Pires, N. (2007). Robot Manipulators and Control Sys- tems. *Industrial Robots Programming. Building Ap- plications for the Factories of the Future*.

Robotics OC (2016). LaserPipe Remote in-bore laser weld- ing of industrial pipelines.

S. Mosqueda, Y. Moncada, Cecilia Murrugarra, H. León-Rodriguez; Constant Curvature Kinematic Model Analysis and Experimental Validation for Tendon Driven Continuum Manipulators; In Proceedings of the 15th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2018) - Volume 2, pages 211-218, ISBN: 978-989-758-321-6; 28th – 31th July 2018; Oporto, Portugal.

Tiefeng, S., Libin, Z., Mingyu, D., Guanjun, B., and Qinghua, Y. (2015). Fruit harvesting continuum ma- nipulator inspired by elephant trunk. *International Journal of Agricultural and Biological Engineering*, 8(1):57–63.

Walker, I. D. (2013). Continuous Backbone Continuum obot Manipulators. *ISRN Robotics*, 2013:1–19.

Webster, R. J. and Jones, B. A. (2010). Design and kinematic modeling of constant curvature continuum robots: A review. *International Journal of Robotics Research*, 29(13):1661–1683.