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Stability analysis and snap-through evaluation of the cable-driven continuum robots

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ABSTRACT: Most of the continuum robots have flexible backbones that are deformed under the internal and external loads and a considerable amount of potential energy may be stored in the backbone. Hence, the continuum robots are exposed to instability issues such as snap-through. The snap-through instability occurs when, with changes in the applied forces, the robot reaches the boundary of its stable region and then moves toward a stable configuration in an uncontrolled manner. Snap-through instability is harmful to the continuum robots and its prediction is important for the design and control of the robot. However, most of the studies focused on design, kinematics, and dynamics of the continuum robots and there are limited studies worked on stability analysis of these robots. In this paper, the stability analysis of the cable-driven continuum robots is investigated. For this, the static equilibrium configurations of the robot are firstly determined under the internal and external loadings. Then, the stiffness matrix of the robot is obtained and the robot stability and snap-through condition are evaluated. The accuracy of the static equations of the robot is verified using the experimental results and the possibility of snap-through occurrence is modeled through simulations. Besides, the effects of the external loads, robot configuration in space, and cross-section of the backbone on the workspace and snap-through occurrence are studied.

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1- Introduction

Continuum robots have infinite degrees of freedom due to their flexible structure. Therefore, the kinematic and dynamic analysis of the continuum robots is more complex than conventional robots. So far, various methods have been proposed for the kinematic modeling of continuum robots. Among them, the constant curvature [1-3] and the variable curvature [4, 5] kinematic models are the most famous models. For dynamic modeling of the continuum robots, various models based on Euler-Lagrange [6] formulation, Kane's formulation [7], and Cosserat rod theory [5] have been proposed.

In addition to the kinematic and dynamic modeling of the continuum robots, it is important to investigate the stability of these robots and the occurrence of the snap-through phenomena in these robots. Continuum robots are under-actuated robots. Therefore, to control their movement they should be in their stable equilibrium region. Continuum robots may deviate from their stable region under certain loading conditions and the snap-through may occur for them. The purpose of this paper is to provide a method for analyzing the stability of the cable-driven continuum robots in three-dimensional space. For this purpose, a three-dimensional static model of the robot is obtained. Then, a stiffness matrix is created for the continuum robot and the stability of the robot is evaluated based on the Eigen-values of the stiffness matrix. Next, the snap-through condition of the continuum robot is described. Finally, the stable workspace of the robot is obtained under different load conditions

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2- Kinematics of cable-driven Continuum Robots

A representative model of a cable-driven continuum robot is shown in Fig. 1. The kinematic model of the robot is based on the reference [6], where for each section of the robot three DOFs are considered.

3- Static Equations

To obtain the static equations of the robot, the virtual power method introduced in the reference [7] is used. The virtual power equation of a robot with n moving parts is calculated as follows:

$$P = \sum_{i=1}^{n} \left(M_{i,ex} \,.\, \omega_i + F_{i,ex} \,.\, v_i \right) \tag{1}$$

where, $F_{i,ex}$ and $M_{i,ex}$ are the resultant external forces and torques exerted to the center of mass of the part i. Also v_i and ω_i are the linear and angular velocities of part i, respectively.

4- Validation of Static Model

Fig. 2 shows the experimental setup for validation of the static model.

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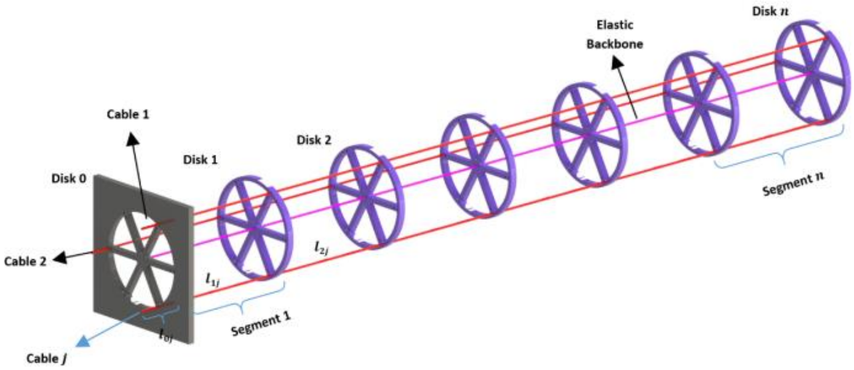

Fig. 1. A cable-driven continuum robot

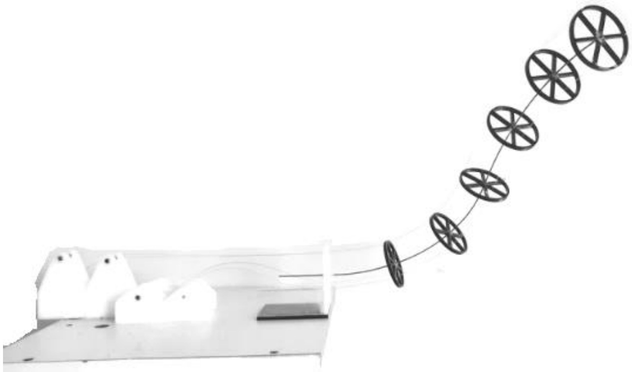

Fig. 2. The continuum robot used for experimental validation

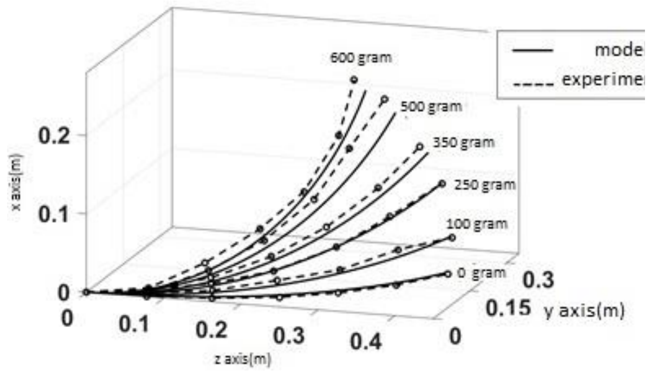

Fig. 3. Comparison of the results obtained from the static model and experiments

The continuum robot was tested in several out-of-plane loadings. For the actuation of the robot, the actuation cables were pulled by different mass loads. Fig. 3 demonstrates that the static model accurately predicts the deformation of the robot.

5- Stability Analysis of Continuum Robot

The stiffness matrix is obtained through partial differentiation of the total potential energy of the robot, Π, with respect to its generalized coordinates $q_i(i=1:n)$ as the following equation:

$$s=\begin{bmatrix} \frac{\partial^2\Pi}{\partial q_1\partial q_1} & \cdots & \frac{\partial^2\Pi}{\partial q_1\partial q_j} & \cdots & \frac{\partial^2\Pi}{\partial q_1\partial q_n} \\ \vdots & \ddots & \vdots & & \vdots \\ \frac{\partial^2\Pi}{\partial q_i\partial q_1} & & \frac{\partial^2\Pi}{\partial q_i\partial q_j} & & \frac{\partial^2\Pi}{\partial q_i\partial q_n} \\ \vdots & & \vdots & \ddots & \vdots \\ \frac{\partial^2\Pi}{\partial q_n\partial q_1} & \cdots & \frac{\partial^2\Pi}{\partial q_n\partial q_j} & \cdots & \frac{\partial^2\Pi}{\partial q_n\partial q_n} \end{bmatrix} \tag{2}$$

For the stability of the robot all Eigen values of the stiffness matrix must be positive. Because the total potential of the robot varies through the load conditions, therefore the Eigen values of the stiffness matrix may change. If the smallest Eigen value of the stiffness matrix becomes negative, the robot becomes unstable on that equilibrium condition. It is worth mentioning that if a robot reaches to an unstable static equilibrium condition, it quickly moves to another static equilibrium with stable condition. This phenomenon is known as snap-through. Fig. 4 shows a snap-through condition for the continuum robot, when a mass load is attached to the robot's tip and simultaneously the robot is actuated by a cable's force.

To predict the occurrence of the snap-through in the continuum robot, the Eigen values of the stiffness matrix are used. Fig. 5 shows when the actuation force of the robot increases, the smallest Eigen value of the continuum robot decreases to zero. Because the negative Eigen value is equivalent to unstable static equilibrium, the robot suddenly jumps to a stable configuration and snap-through occurs.

6- Investigating Stable Workspace for Continuum Robot

Simulations and experiments have shown that various factors, such as the tip mass of the robot, the robot's orientation in space, and the cross-sectional area of the robot's backbone may affect the stable workspace of the robot. For example, Fig. 6 shows that the snap-through of the robot that was shown in Fig. 4 was eliminated in the vertical orientation of the robot.

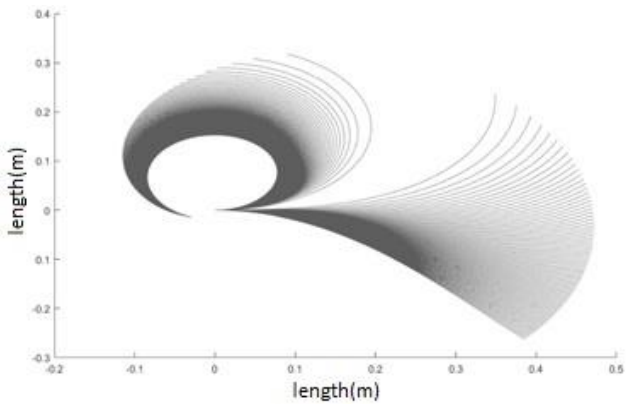

Fig. 4. The static configurations of the continuum robot when a 50gr mass load is attached to the robot's tip and the actuation force increases gradually.

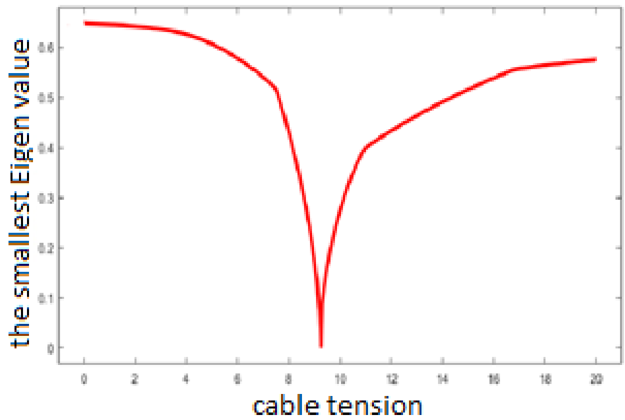

Fig. 5. The smallest Eigen value of the stiffness matrix vs. the actuation cable's force

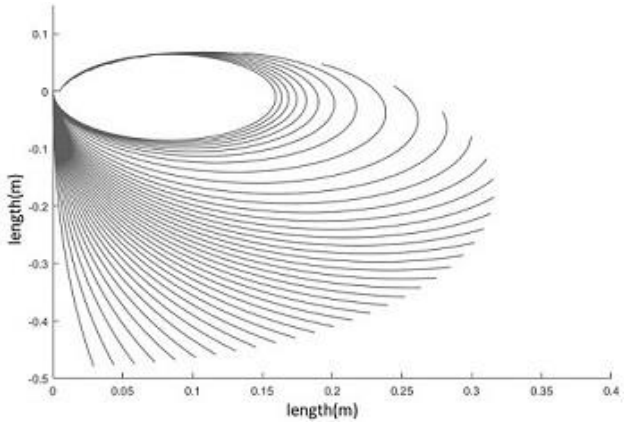

Fig. 6. The static configurations of the continuum robot in a vertical orientation when a 50gr mass load is attached to the robot's tip and the actuation force increases gradually.

7- Conclusions

In this study, the stability analysis of the cable-driven continuum robots was performed and it was shown the snap-through instability may be predicted by the Eigen values of the stiffness matrix.

Also, it was shown that the robot's orientation, tip mass load and cross-section affect the workspace of the robot. Therefore, the following suggestions may be useful to increase the workspace of the robot:

a) To decrease the mass attached to the robot's tip.

b) To Increase the robot's cross-sectional area.

c) To use the robot in an appropriate orientation when the robot's tip mass is considerable.

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