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Kinematic Modeling of a Spatial Soft Robot by an Improved Analytical Method Based on Serial Robots

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ABSTRACT: In this paper, kinematic modeling of a soft pneumatic robot, including a combination of 3 soft actuators, with the capability of spatial positioning is presented. The proposed kinematic model in this research, unlike former methods, corresponds to the physics of robot and the main idea is modeling its configuration and movement by serial rigid robots which generate the same configuration and movement. The given kinematic model consists of forward and inverse problems and uses accurate geometrical solutions. In addition, the velocity Jacobian of soft robot has been determined by two different approaches based on rigid serial robot principles. Furthermore, the robot workspace and its configurations have been determined by considering the kinematic constraints. Modeling accuracy has been evaluated by finite element simulation and also experiments. Simulation results show the maximum error of 1.6% for the inverse kinematic model and the maximum error of forward kinematic model has been 13% in experiments due to manufacturing errors and gravity effects. These results demonstrate that the proposed model has proper accuracy for motion modeling and its control in future works.

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1. INTRODUCTION

Soft robotic systems have received major attention in recent years. These robots consist of soft materials and a continuously deformable structure with muscle-like actuators that emulate biological systems and have a relatively large number of degrees of freedom as compared to hard robots [1].

For modeling the forward kinematics of the soft robot, it should be considered that the deformation of soft robot is inherently continuous, complex, and compatible with the environment. Also, it is permanently under actuation and has inactive degrees of freedom in it, so designers typically model the kinematics of the soft robot by using simplified assumptions like piecewise Constant Curvature (CC) assumption [2]. The most famous method for solving forward kinematics was proposed by Webster and Jones [3]. They solved the forward kinematic problem of several types of continuous robots assuming that most parts of the robot bend at a constant curvature, completely and in five different ways. However, their paper lacks laboratory results and analysis. Godage used a numerical and computational method to solve the kinematics of a soft robot based on the shape function of the actuator [4]. This approach has been the most stable numerical model presented so far and simulates movement and configuration of the robot in space accurately. Walker and Frazelle presented an approximate and geometric model and compared it to the models of Godage, Allen and Jones for the OctArm robot [5]. The average error of the model of Jones and Allen for this robot was less than that of the Frazelle and Godage model.

The aforementioned researches on kinematic modeling of soft robots usually use mathematical, innovative, and sometimes complex methods independent of the physics of the system with excessive degrees of freedom to express the kinematics of the robot, regardless of the degree of accuracy. The purpose of this study is to present an improved analytical kinematic modeling method based on kinematic models of rigid robots. To this end, we propose models based on serial robots by inspiration from the behavior of soft actuators, which can simulate the kinematic behavior of soft actuators. Consequently, the principles of serial robots can be used to analyze the kinematic behavior of soft robots by applying some modifications.

2. METHODOLOGY

Most modelings in the field of soft robots have based their assumptions on constant curvature assumption and no twisting. In this study, this assumption is the basis of the modeling too, so the bending of the soft spatial robot has been simplified as shown in Fig. 1.

Mapping from the configuration space to the Cartesian space is obtained by using a proposed analog model. This model finds the position of the end-effector by matching shape and motion of the robot with shape and motion created by a rigid serial robot.

The model shown in Fig. 2 has four degrees of freedom but using the constant curvature assumption causes the two

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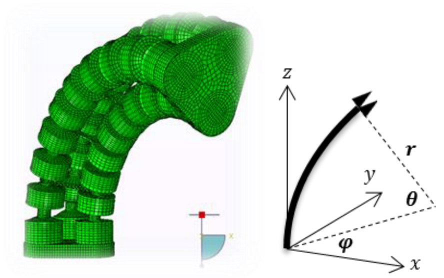

Fig. 1. Simplification of bending and determination of shape parameters of the robot in space

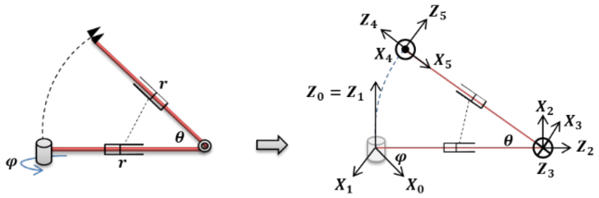

Fig. 2. D-H Frames for the 4-DOF model of the soft arm

prismatic joints to be coupled together. The transformation matrix in this model is achieved similar to the previous two models as in Eq. (1). The advantage of this model is the application of the serial robot rules and simplification of the movement of a soft robot with the familiar motion of a rigid robot. Physical compatibility with the original robot and the ability to use it for finding velocity Jacobins also make it superior to other models.

$$T = \begin{bmatrix} \cos\varphi\cos\theta & -\sin\varphi & \cos\varphi\sin\theta & r\cos\varphi(1-\cos\theta) \\ \sin\varphi\cos\theta & \cos\varphi & \sin\varphi\sin\theta & r\sin\varphi\left(1-\cos\theta\right) \\ -\sin\theta & 0 & \cos\theta & r\sin\theta \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{(1)}$$

3. VELOCITY JACOBIANS

According to the presented analytical models, it is possible to calculate the Jacobians of the robot by the conventional methods of serial robots, however, by applying the changes caused by constraints of the motions of the soft robots. According to the velocity propagation method in the conventional serial robots, the Jacobian matrix of the soft robot was obtained as in Eq. (2).

$$\mathrm{v} = \begin{bmatrix} -r\,s\varphi\left(1-c\theta\right) & r\,c\varphi\,s\theta & c\varphi\left(1-c\theta\right) \\ r\,c\varphi\left(1-c\theta\right) & r\,s\varphi\,s\theta & s\varphi\left(1-c\theta\right) \\ 0 & r\,c\theta & s\theta \\ 0 & -s\varphi & 0 \\ 0 & c\varphi & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{r} \end{bmatrix} \quad \textbf{(2)}$$

In the alternative method, for the proposed four-degree-of-freedom model, because of the virtual constraints between two and four degrees of freedom for harmonious and uniform movement, the conventional method of modified serial robots must be rewritten and the effect of these two degrees of freedom must be applied simultaneously on the end-effector velocity at the Jacobian matrix as in Eq. (3) and the Jacobian matrix is equal to the Jacobian obtained in Eq. (2).

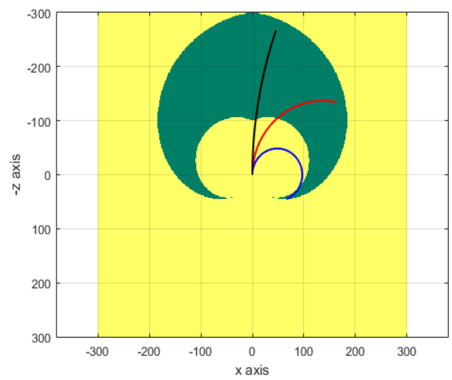

Fig. 3. Actuator workspace and robot configuration in it

$$J^0 = \begin{bmatrix} z_1 \times \left(o_5 - o_1\right) & z_3 \times \left(o_5 - o_3\right) & z_2 + z_4 \\ z_1 & z_3 & 0 \end{bmatrix} \quad \textbf{(3)}$$

4. WORKSPACE

Each soft robot can only increase or decrease to a certain extent depending on its material and physical structure. To obtain the workspace in this study, the initial length of the robot is assumed to be 200 mm, and this maximum value is assumed to be equal to half of the initial length of the robot in expansion or contraction. So, the allowed range for the length of the actuators is:

$$l_{allowable} \in \left(l_0 - \frac{l_0}{2}, l_0 + \frac{l_0}{2}\right) = \left(\frac{l_0}{2}, \frac{3l_0}{2}\right) \quad (4)$$

Drawing the workspace of this robot using Eq. (4) must be with attention to satisfaction of geometrical constraints between actuators with the help of inverse kinematic relations. Fig. **3** shows the result of the possible workspace.

5. VERIFICATION BY SOFTWARE SIMULATION AND EXPERIMENTAL RESULTS

In Fig. 1, a simulated soft robot is shown in the Abaqus software. The robot is actuated by various pressures inside it to move through space. The only loading on the robot is the pressure inside the actuators, meaning that there is no gravity. Despite the error centers in the software drawing and calculation of the parameters, the highest error in the simulation was 1.6%, which involved the actuation of only one actuator with a pressure of 1 bar, and in calculating the length of the three actuators which is insignificant.

Experimental tests for verifying the kinematic models were performed using a soft robot depicted in Fig. **4**. Errors of the kinematic model compared with the experimental tests include the inaccuracy of the size of the robot actuators due to manufacturing errors, the perturbation, and inaccuracy of

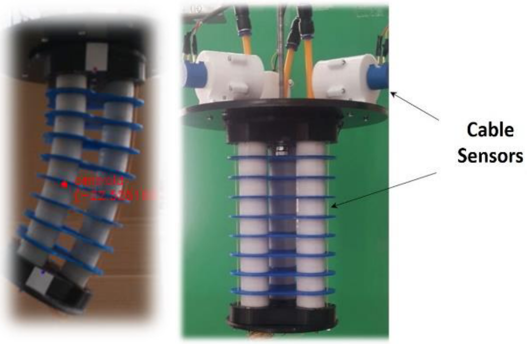

Fig. 4. The robot used in experiments

Table 1. The results of experimenting the second condition (actuation of only two actuators)

Pressure (bar)	$y_{Meas.}$ (mm)	$z_{Meas.}$ (mm)	yCC (mm)	zCC (mm)	%error$y$	%error$z$
0.4	20.9	178.2	23.2	179.4	9	0.6
0.6	33.6	179.9	37.2	182.2	9.6	1.2
0.8	47	184	53.9	183	12.8	0.5

actuator length changes, the error of zeroing initial locations due to the limitations of the camera installation, and so on. Of course, the main reason for the error in the empirical test is to exclude the effect of gravity in the CC model, and this error exists in all constant curvature methods which did not consider gravity.

Table 1 presents the results of the experiments and compares them with the CC kinematic model for actuation of only two actuators.

6. CONCLUSIONS

In this paper, to simplify the problem of moving of soft robots, a three-degree-of-freedom spatial soft robot was replaced by a serial rigid robot whose shape and end-effector position were the same as the final shape of the actuated soft robot. The advantage of this method is the simplicity and application of serial robot rules and their compliance with the physics of the robot, which has not been noticed in most previous models. The results show 1.6% error for the inverse kinematic model compared with the simulation results. Also, the evaluation of model accuracy against the results of a laboratory robot motion in a spatial actuation indicates an error of at most 13% for the kinematic model in detecting the position of end-effector in the y-direction. Therefore, considering the sources of errors in simulation and empirical test measurements, the proposed model has good accuracy.

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