A Multi-Link Kinematics Model for Microrobots with Artificial Muscle Structure

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Abstract: In this paper, we described a new multi-link kinematics type model for multi-DOF manipulators with artificial muscle (IPMC) segments structure. We developed the kinematic modeling of multilink motions for the control of the manipulator using a transposed Jacobian and an inverse Jacobian. The IPMC film is used with dual purpose for the manipulator links: actuator and sensor. This is easily achieved by separating electrically the IPMC film with a groove and using a section as actuator and one section as sensor. In this way, the actuator and the sensor are unified into the same structure. The paper contains simulation results of this model.

Keywords: Electroactive Polymer Artificial Muscle (EPAM); Ionic Polymer-Metal Composite (IPMC); Degree-Of-Freedom (DOF), dual actuator-sensor film; microrobot manipulator; multi-link kinematics; transposed Jacobian control.

1 Introduction

A bimorph-type soft polymer gel actuator, which we call an electroactive artificial muscle, is an ionic polymer-metal composite (IPMC) consisting of a perfluorosulfonic acid membrane with chemically plated gold or platinum as electrodes on both sides [1, 2]. It has some excellent characteristics for robotic applications compared with other soft polymer actuators [3, 4, 5] as follows:

- Low power consumption;
- Driven with low voltage (< 3V);
- Fast response (> 10 Hz in water);
- Mechanically and chemically durable and stable;
- Soft and compliant;
- Works in water or in wet conditions.

Moreover, it has an advantage for miniaturization with its simple actuator structure. With these characteristics, we expect to apply it to micromanipulations in the bioengineering or medical fields. Our goal is to realize bioinspired soft robots, for example a multi-degree-of freedom (DOF) microrobot manipulator [6, 7].It is easy to miniaturize the actuator because of its simple structure.

In the future, is possible to make robots that can swim in thin tubes or in blood vessels, or various kinds of micromanipulators in the biomedical field.

In this paper, we show some results from simulations of the proposed manipulator control method of the multi-DOF bending motion and simulated results for the dual actuator–sensor segment structure IPMC film (see Figure 1b).

Because The IPMC artificial muscle is not stable when work in air, but has a good stability in aqueous medium [4, 5], hand-arm was sunken in water (see Figure 1a).

2 The Multi-DOF Manipulator Structure

Micromanipulations in bioengineering or in the medical field can be one of the applications of the artificial muscle. Our goal is to investigate the possibilities to realize a multi-DOF microrobot manipulator that is automatically controlled by a dual system actuator-sensor, as shown in Figure 1 [8]. IPMC films are separated electrically by cutting grooves and both the sensor and the actuator can be unified in the same structure. This arrangement is more effective to sense motion than the parallel arrangement because there is less interference with the actuation by the sensor part [9]. The size of the strip is 3 × 20 [mm]. The strip is separated into the two sections, the sensor part is 1 mm wide, and the actuator part is 2 mm wide. Two sets of electrodes were arranged for the actuator and the sensor [9]. The laser displacement sensor was used for IPMC sensor film calibration.

The block diagram of the control system for this model of multi-DOF composed by three segments IPMC actuator-sensor is shown in Figure 1a. The patterning of electrodes on an IPMC enables the multi-DOF bending motions of a manipulator with a simple structure.

The proposed feedback control system showed in Figure 1 includes a sensing system, a Jacobian and error estimation component, a control component, and a multi-DOF patterned artificial muscle (IPMC). The manipulator is hung in water below the electric connector.

3 Modeling of Multi-Link Kinematics

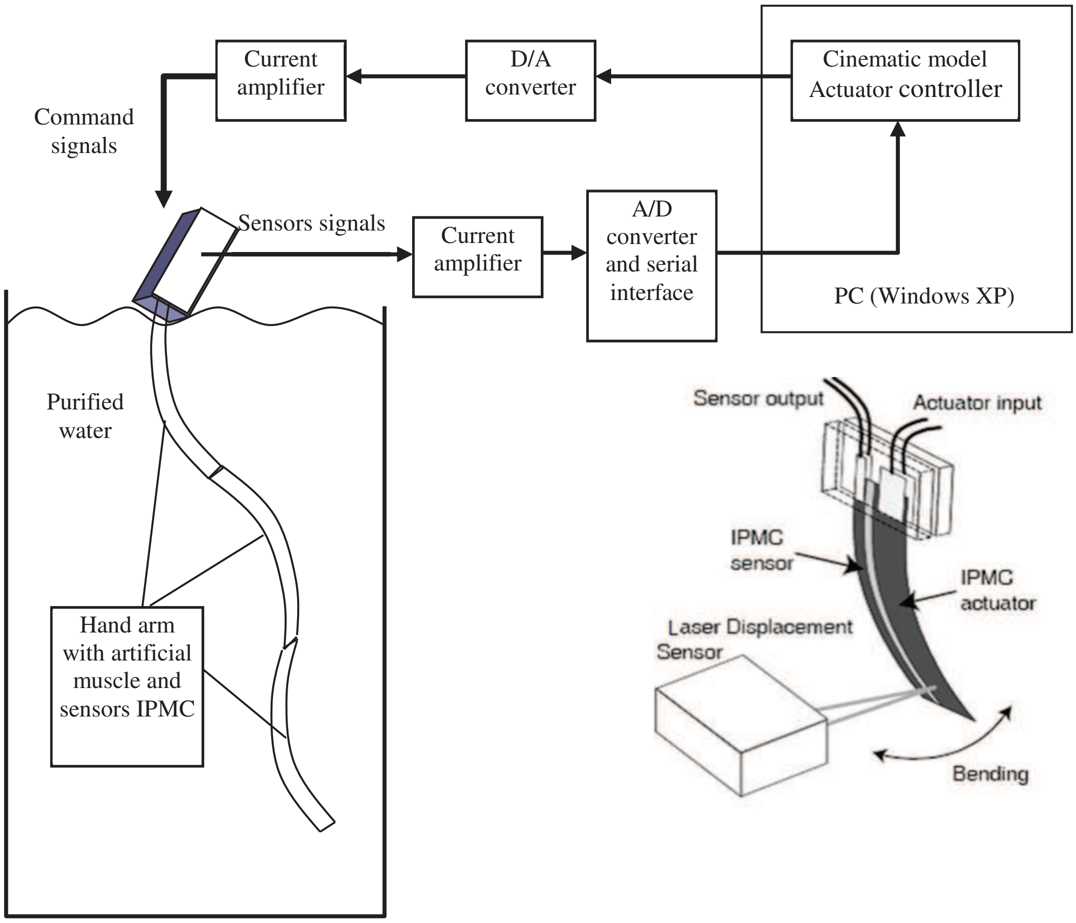
To realize the multi-DOF motion of a manipulator, we can connect several links in series in the same way as in conventional serial-link manipulators. In this study, as a first step in our research, we restrict the motion of the manipulator to a two dimensional space, in which two DOF for position and one DOF for the tangential direction of the end point are controlled. We can control all three DOF independently by controlling the three links of an IPMC.

We now define coordinate systems $\sum_{i}, (i = \{0,1,2,3\})$ one at the origin, one at each joint of the multi-link system, and one at the end point of an arm, as shown in Figure 2 and Figure 3.

A homogeneous transfer matrix ${}^{i}A_{i+1}$ from $\sum_{i+1}$ to $\sum_{i}$ is (1):

$$ {}^{i}A_{i+1} = \begin{pmatrix} \cos(\theta_i + \alpha_i) & -\sin(\theta_i + \alpha_i) & -\frac{l_i}{\theta_i}(1 - \cos\theta_i) \\ \sin(\theta_i + \alpha_i) & \cos(\theta_i + \alpha_i) & \frac{l_i}{\theta_i}\sin\theta_i \\ 0 & 0 & 1 \end{pmatrix} $$

where the certain length of a link is l_i, the curvature is $\theta_i (= r_i / l_i)$, and if the link has a certain bending angle at the joint, this angle is referred as α_i. We consider that l_i and α_i are known and $\alpha_i = 0$.



a) b)

Figure 1. a) Application of multi-DOF artificial muscles IPMC;
b) Structure of IPMC actuator-sensor film

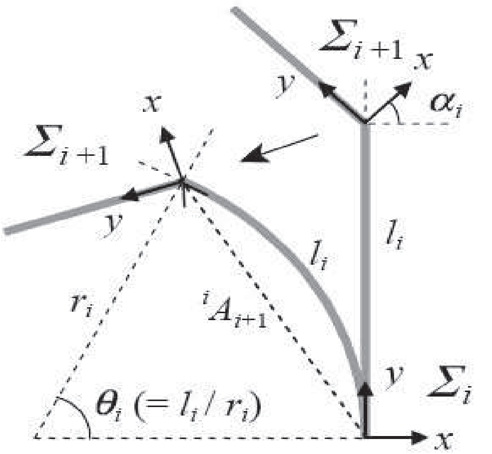


Figure 2. One-link kinematic modeling (note that usually $\alpha_i = 0$, as in this study)

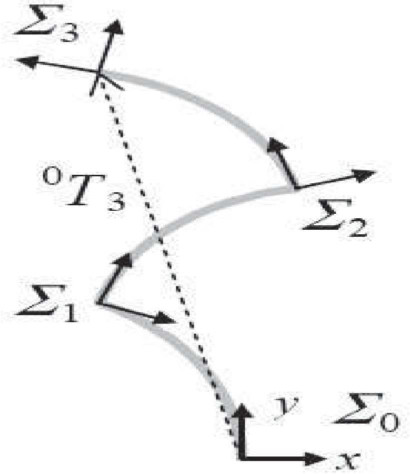


Figure 3. Multi-link coordinate system (joints are usually not bent, as in this study)

A transfer matrix from the base to the end point is calculated by multiplying each matrix of the link from the first to the last using

$$ {}^{0}T_3 = {}^{0}A_1 \, {}^{1}A_2 \, {}^{2}A_3 \qquad (2)$$

which is shown in Figure 3. From this equation, we can obtain the position vector ${}^{0}\mathrm{P}_e$ and rotation angle ${}^{0}\theta_e$ of the end point in the base coordinate system $\sum_0$ as follows expressions (3),

(where $\mathrm{P}_e = ({}^{0}\mathrm{P}_e, {}^{0}\theta_e)^t = (\mathrm{P}_{ex}, \mathrm{P}_{eY}, \mathrm{P}_{e\theta})^t$:

$$\mathrm{P}_{ex} = \frac{\mathrm{I}_2}{\theta_2}\cos(\theta_0 + \theta_1 + \theta_2 + \alpha_0 + \alpha_1) - $$
$$- \frac{\mathrm{I}_2}{\theta_2}\cos(\theta_0 + \theta_1 + \alpha_0 + \alpha_1) + \frac{\mathrm{I}_1}{\theta_1}\cos(\theta_0 + \theta_1 + \alpha_0)$$
$$- \frac{\mathrm{I}_1}{\theta_1}\cos(\theta_0 + \alpha_0) + \frac{\mathrm{I}_0}{\theta_0}(\cos\theta_0 - 1)$$
$$\mathrm{P}_{e\theta} = \theta_0 + \theta_1 + \theta_2 + \alpha_0 + \alpha_1 + \alpha_2$$

$$\mathrm{P}_{eY} = \frac{\mathrm{I}_2}{\theta_2}\sin(\theta_0 + \theta_1 + \theta_2 + \alpha_0 + \alpha_1) - $$
$$- \frac{\mathrm{I}_2}{\theta_2}\sin(\theta_0 + \theta_1 + \alpha_0 + \alpha_1) + \frac{\mathrm{I}_1}{\theta_1}\sin(\theta_0 + \theta_1 + \alpha_0)$$
$$- \frac{\mathrm{I}_1}{\theta_1}\sin(\theta_0 + \alpha_0) + \frac{\mathrm{I}_0}{\theta_0}\sin\theta_0$$

To control the position and orientation of the hand of the manipulator, we have to solve an inverse kinematic problem. More specifically, we have to solve $\hat{\mathrm{P}}_e = \mathrm{P}_e(\theta)$ by $\theta = (\theta_0, \theta_1, \theta_2)^t$ from Eq. (3), where $\hat{\mathrm{P}}_e$ denotes both the objective position and orientation. However, it is quite difficult to solve Eq. (3); thus we use Jacobian methods for controlling and define control variables to converge to objective values.

The Jacobian of P_e with θ is defined by following expressions:

$$\mathrm{J} = \left[\mathrm{J}_0 \mathrm{J}_1 \mathrm{J}_2\right]$$
$$\mathrm{J}_i = \frac{\partial}{\partial \theta_i}\mathrm{P}_e, \quad (i = \{0,1,2\}) \qquad (4)$$

Using the Jacobian, the following control, which is an inverse Jacobian method, will induce the control variable to converge to an objective value $\hat{P}_e$ exponentially:

$$\dot{\theta} = \lambda' J^{-1}(\hat{P}_e - P_e) = \lambda' J^{-1}\varepsilon \qquad (5)$$

where λ, in this expression, is a given constant.

Using the transposed Jacobian method will also induce convergence to an objective:

$$\dot{\theta} = \lambda' J^{t}(\hat{P}_e - P_e) = \lambda' J^{t}\varepsilon \qquad (6)$$

This is possible if an appropriate value of a constant λ' is chosen. **J** can be calculated explicitly, but we omit such calculations.

4 Simulations

We performed some simulations to verify our control methods. A block diagram of a control system simulation is shown in Figure 4.

Is possible to obtain results by the inverse Jacobian or by the transposed Jacobian method but we present in this paper only the transposed method. The results obtained by this method are shown in Figure 5.

All results show that each segment of an IPMC membrane is properly bent to realize the given trajectories of positions and orientations of the end points. By the inverse Jacobian method, trajectories in Cartesian coordinates are straightforward and exponentially converged to the objective, where they are not by the transposed Jacobian. However, an inverse Jacobian is not stable near a singular position, in this case, at the upright position, whereas a transposed Jacobian is defined and stable at any point. From these results, it is confirmed that is possible to control all three DOF of a 2-D manipulator by these methods.

5 Conclusions

In this study, we described a new type of multi-DOF manipulator using a structure with three artificial muscle (IPMC) segments, and proposed the kinematic modeling of multilink motions for the control of the manipulator using a transposed Jacobian or an inverse Jacobian. The sensors elements of motions was realized by IPMC film too, because was used the special actuator-sensor segments presented in Figure 1a. By experiments we have checked that the segments actuator-sensor in given circumstances is working. Simulations verify our approach.

By using the inverse Jacobian and transposed Jacobian methods, trajectories in Cartesian coordinates are converged, but the inverse Jacobian is not stable near a singular position while the transposed Jacobian is defined and stable at any point.

From the simulated results, it is confirmed that is possible to control all three DOF of a 2-D manipulator by these methods.

We consider that is very important to address the problem of the low conductivity of segment interconnections. It is possible to increase the width of the interconnections and/or increase the amount of gold plating, so that their conductive layers become thicker. Although bending velocity generally follows a given voltage signal, nonlinear characteristics, such as swing back motion, also contribute to a dynamic response.

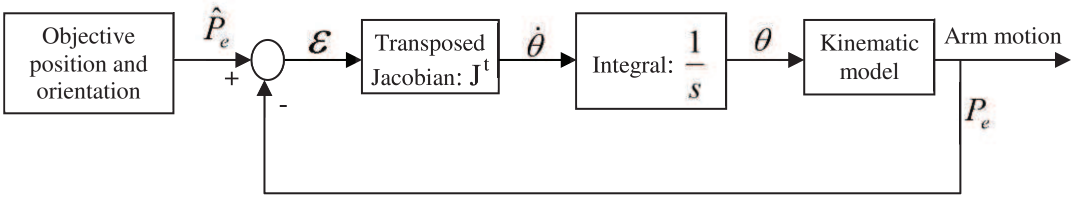


Figure 4. Block diagram of simulation system

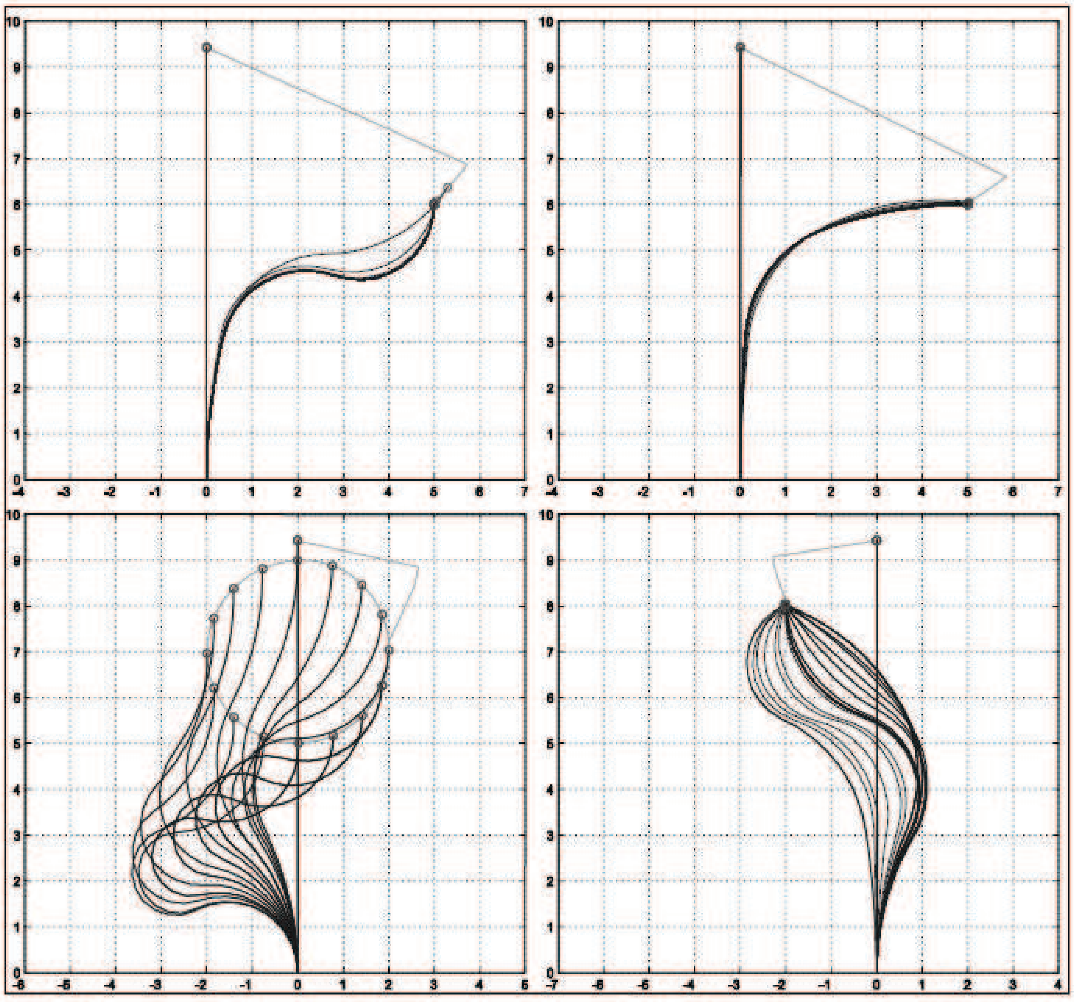


Figure 5. Results obtained by transposed Jacobian control (upper left: hand is kept in upper direction, upper right: its direction is changed to right, bottom left: tracking a round trajectory, bottom right: move and swing)

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