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Kinematic Analysis of Electroactive Polymer Actuators as Soft and Smart Structures with more DoF than Inputs

Rahim Mutlu, Gursel Alici and Weihua Li

Abstract—Electroactive polymer (EAP) actuators have been attracting the attention of researchers due to their muscle-like behaviour and unusual properties. Several modelling methods have been proposed to understand their mechanical, chemical, electrical behaviours or ‘electro-chemo-mechanical’ behaviour. However, estimating the whole shape or configuration of the EAP actuators has always been challenging due to their highly non-linear bending behaviour. This paper reports on an effective method to estimate the whole shape deflection of the EAP actuators by employing a so-called backbone approach. Tri-layer configured polypyrrole (PPy) based EAP actuators were used as a soft and smart structure with more degrees of freedom than its input. After deriving the inverse kinematic model of the actuator, its complete shape is estimated by solving the inverse kinematic model with an angle optimization (AngleOPT) method. The experimental results and numerical results have demonstrated the effectiveness of the method in estimating the highly non-linear bending behaviour of the PPy actuators and applicability of this modelling approach to other EAP actuators.

I. INTRODUCTION

ELECTROACTIVE polymers are not only promising materials, but also pose challenging research questions to researchers. They are commonly researched for their sensing and actuating behaviours [1]. The EAPs as actuators have many advantages over conventional actuators due to their favourable properties such as small energy consumption, compliant structure, light mass ratio, biocompatibility, insensitivity to magnetic field, ability to operate in air and aqueous environments, and suitability for miniaturisation. Though there are a few configurations of the electroactive polymers to be used as actuators, composite (laminated) type is the most common one in which the electroactive polymer actuator has a passive layer and active polymer layers grown on both sides of the passive layer. When an electrical potential or current applied to this composite type EAP actuator, the polymer layers change their volume—while one polymer layer expands, the other

polymer layer shrinks. This volume change results in a mechanical bending when the EAP actuator is fixed at one end (with electrical contacts) and the other end is free that this cantilevered composite structure can be used as an actuator. Also, the electroactive polymer can be used as a sensing device when a displacement or a force is applied as the mechanical input and the electrical potential change is measured as the output.

Several studies have been conducted on soft and hyper-redundant manipulators. While a soft robotic manipulator is a continuum system, a hyper-redundant manipulator is modelled as a discrete system consisting of serially connected rigid links. When the number of links in the manipulator is high enough, the manipulator can be treated as a soft robotic manipulator. There are some studies on such robotic systems inspired from nature in which the working mechanisms of an octopus arm, an eel [2, 3], an elephant trunk [4-6] and a snake [7] are mimicked. These devices are built by conventional actuation means such as tendons, pneumatic actuators etc. In the literature, kinematic models are established for such soft and hyper-redundant robotic systems [8-10] using the *backbone* approach. The backbone approach assumes that a curve, so-called *backbone* represents posture of the manipulator and parts (links) of the whole manipulator oriented along this curve. These models demonstrate promising features of soft robotic manipulators whether they are modelled as continuum or discrete (hyper-redundant) systems. These models can also be utilized for micro/nano manipulation systems. However, with conventional materials, this would be impractical.

With miniaturisation in mind, the EAPs can be more suitable materials to be employed in the soft robotic devices mimicking micro/nano biological creatures with their muscle-like features. For instance, a swimming robot might be built in which a bacterium’s flagellum curling is imitated by an EAP actuator. Many potential applications have been proposed for the electroactive polymer actuators [17-21]. However, prior to employing the EAPs in such bio-mimetic devices, a good understanding of the EAPs’ working principles must be promoted. In other words, for more advanced applications, a complete model is required to predict their whole shape behaviour dynamically under some voltage input or displacement/force input if the electroactive polymer to be utilized as a sensing device. There are some significant studies conducted in modelling electroactive polymer actuators [11-16]. However, majority of them focuses on modelling the electroactive polymer actuator as a

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whole system which predicts the actuators tip displacement rather than the actuator's whole shape behaviour.

This paper presents a numerical method to model and analyse the inverse kinematics of a bending type conducting polymer actuator with more degrees of freedom (DoF) than inputs. The conducting polymer actuator is kinematically modelled as a hyper-redundant soft robotic arm. We employ a method based on the optimisation of joint angles (AngleOPT) in order to solve the inverse kinematic model of the conducting polymer actuator. We have also employed an image processing technique to measure the tip position of the polymer actuator as a function of time and used these data as the input in order to estimate the angular position of each segment forming the hyper-redundant soft robotic arm.

II. THE LAMINATED CONDUCTING POLYMER ACTUATORS

The electroactive polymers are smart materials derived from monomers; commonly pyrrole, thiophene and aniline. They have been used to establish different types of devices such as sensors, membranes and materials for energy storage and actuators [17-21].

In this paper, laminated configuration of the conducting polymer actuators is used as the soft robotic arm whose kinematic behaviour is modelled and analysed. Pyrrole monomer is used to fabricate the conducting polymer actuator by following a number of steps. Firstly, both sides of a non-conductive porous layer (i.e. polyvinylidene fluoride, PVDF) were sputter coated with a thin gold layer till resistance of the PVDF layer was less than 20Ω . The PVDF layer acts as an electrochemical cell separator layer and also reserves electrolytic ions (e.g., Li.TFSI). The PVDF layer used in this study is $110\ \mu\text{m}$ in thickness as received. Meanwhile, a polymer growth solution containing pyrrole monomer (0.1 M), lithium trifluoromethanesulfonimide (Li^+TFSI^- , 0.1 M) and 1 % water in propylene carbonate (PC) was prepared for polymerisation process. Then the gold coated PVDF was submerged in this solution using supports to prevent any short circuit between a working electrode (the gold coated PVDF) and a counter electrode. The polypyrrole (PPy) layers were galvanostatically grown from the growth solution at a current density of $0.1\ \text{mAcm}^{-2}$ for 12 hours on the gold coated PVDF. This polymerisation process provides $\sim 30\ \mu\text{m}$ thickness of PPy layer on both sides of the gold coated PVDF. The total thickness of the laminated PPy based conducting polymer actuator was therefore approximately $170\ \mu\text{m}$ and is called PPy polymer actuator throughout the paper unless otherwise stated. The PPy polymer actuator's tri-layer configuration and operation principle are depicted in Fig.1.

The PPy polymer actuator's special operation principle is based on the energy conversion from an electrochemical process to a mechanical output. An electrical input applied to the polymer layers stimulates counter-ions to move in and out of the PPy layers. While the positively charged polymer layer is oxidised, the negatively charged layer is reduced.

The TFSI⁻ anions move from electrolyte into the positively charged PPy layer and an opposite reaction happens in the other PPy layer in order to neutralize the charge in the PPy layers. This ion movement causes a volume expansion in the positively charged PPy layer and a volume contraction in the other PPy layer. These electro-chemo-mechanical processes thus generates a bending behaviour, as illustrated in Fig.1.

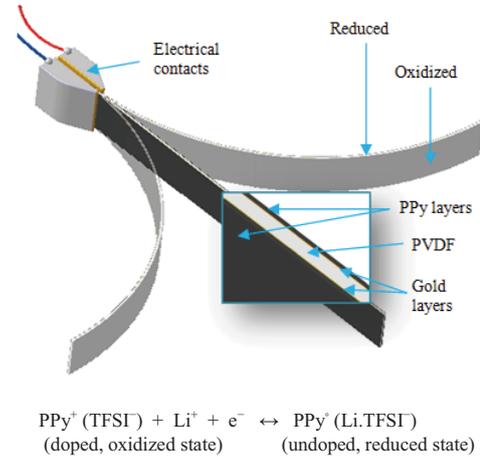


Fig. 1. Structure and the operation principle of the laminated polypyrrole polymer actuator.

III. KINEMATIC ANALYSIS OF THE PPy POLYMER ACTUATOR AS A HYPER-REDUNDANT SOFT ROBOTIC ARM

Classical beam theories such as Euler-Benoulli and Timoshenko beam theories are applied to materials with *condition-independent* properties under linear deflection assumptions throughout the beam [15]. Since electroactive polymer actuators are soft materials in their nature and have condition-dependent properties (e.g. Elasticity modulus of the EAP actuator changes as a function of the electrical stimulus applied to the EAP actuator), the classical beam approach fails for estimating the highly non-linear deflection of the electroactive polymer actuators. Alternatively, a soft robotic manipulator approach which assumes that there is a backbone in the PPy polymer actuator passing through the centre of the cross sections of the actuator can be utilized to model the PPy polymer actuator kinematically [22]. The kinematic model of the PPy polymer actuator based on soft robotic manipulator approach can be comprised of two parts;

1. Obtaining a mathematical model for the PPy polymer actuator's backbone
2. Generating and orientating the cross sections of the PPy polymer actuator using Frenet formulations and Denavit-Hartenberg transformations.

In this paper, we focus on the first part of the soft robotics approach for kinematic modelling of the PPy polymer actuator. In order to estimate the PPy polymer actuator's whole shape behaviour, inverse kinematic model is solved

by the AngleOPT method. Since the PPy polymer actuator employed in this study has a composite cantilevered beam structure, bending of the PPy polymer actuator occurs in one plane. The kinematic modelling is, therefore, carried out for planar conditions. In addition, the PPy polymer actuator has a continuum structure which is modelled as a hyper-redundant robotic manipulator with rigid links and revolute joints. A 3-link and a 16-link models are depicted in comparison with the PPy polymer actuator (continuum) in Fig.2.

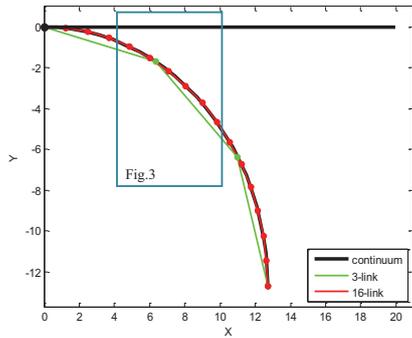


Fig. 2. The PPy polymer actuator representations with 3 and 16 link robotic manipulators.

Obviously, the higher is the number of the links in the model, the better is the shape correspondence between the PPy polymer actuator and the kinematic model. Though any number of links can be chosen for kinematic modelling, the 16-link hyper-redundant structure is chosen to be utilized for the kinematic modelling of the PPy polymer actuator in order to obtain a shape correspondence between the real PPy polymer actuator and its kinematic model using a numerical solution method, what we call the AngleOPT method. Beauty of this approach is that it is flexible for selecting DoF of the hyper-redundant structure. Though it is not in the scope of this paper, choosing the right DoF is a subject of another optimization problem between the computational cost (higher DoF system takes longer time to solve) and better shape correspondence.

A. Inverse Kinematics Based on an Optimization Approach

Inverse kinematic analysis is a difficult problem for robotic manipulators due to the existence of multiple solutions for a given configuration of the manipulators. It is virtually impossible to obtain the exact inverse kinematic solution of the 16-link kinematic model. With this in mind, numerical methods can be utilized to obtain inverse kinematic variables; joint angles, velocities and accelerations. Methods such as Jacobian matrix and least square estimations are possible methods of calculating inverse kinematic variables. However, an optimization approach, which we call AngleOPT, simplifies the complexity of the inverse kinematic problem. It does not require mathematical manipulations prior to computing the inverse kinematic variables, provided that appropriate joint constraints are imposed on the inverse kinematic solutions.

In other words, the 16-link inverse kinematic problem can be treated as a constrained optimization problem. To this aim, the AngleOPT problem can be solved utilizing recognized constrained optimization methods. The AngleOPT problem demonstrated in this paper was solved by employing *fmincon* function of MATLAB which uses the Sequential Quadratic Programming (SQP) algorithm. Although the SQP is relatively easy to implement, this algorithm does not find necessarily global minimum(s) that initial guesses of the variables searched and constraints for these variables must be selected reasonably well. If we call the function of the hyper-redundant kinematic model f , joint variables searched can be found by minimizing the function with local constraints, as presented below;

$$\min_{\theta} f(L, \theta, X, Y, Z) \quad (1)$$

i. lower and upper boundaries $lb \leq \theta_i \leq ub$
ii. constraints between joint angles $A \cdot \theta \leq b$

where L is the length of the individual links, θ is the joint angle, X , Y and XZ are the tip coordinates of the PPy polymer actuator relative to a fixed (base) point of the PPy polymer actuator, lb and ub are the lower and upper boundaries for the joint angles, respectively. $A \cdot \theta \leq b$ are the assigned relations between the joint angles. It must be noted that a joint angle closer to the far end of the PPy polymer actuator should be taken larger than that of the previous joint angle. This follows that the constraints should reflect the physical conditions of the actuator.

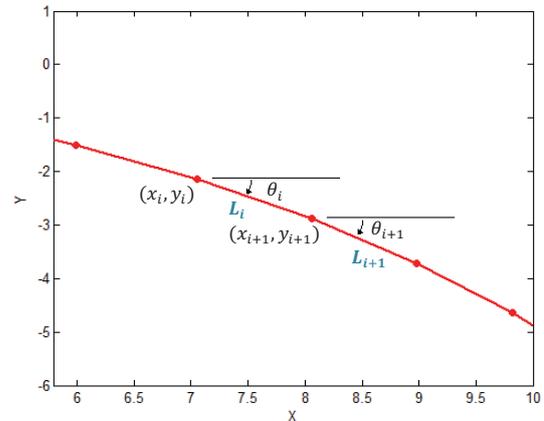


Fig. 3. Position vectors of the PPy polymer actuator model's joints.

B. Kinematic Model and Its Analysis

Using the actuator configuration depicted in Figures 2 and 3, the position vector of each joint may be calculated with an angle respect to the base frame. The position vector of a joint respect to the previous joint can be expressed as

$$\vec{r} = (x_i, y_i) \quad (2)$$

where

$$(x_i, y_i) = (x_{i-1} + L_i \cos \theta_i, y_{i-1} + L_i \sin \theta_i) \quad (3)$$

Applying Eq.3 to express the position vector of each joint through the PPy polymer actuator's model, the tip coordinates can be calculated as

$$(X, Y) = \left(\sum_1^{NoL} L_i \cos \theta_i, \sum_1^{NoL} L_i \sin \theta_i \right) \quad (4)$$

where (X, Y) indicates the tip coordinates, NoL number of links or the degree of freedom (considering revolute joints with 1-DoF), x_i and y_i are the position vectors of the joints along the PPy actuator's kinematic model. After deriving f function (Eq.1) of the PPy polymer actuator, X and Y coordinates are obtained by analysing a recorded video of the actuators' bending motion utilizing an image processing algorithm in MATLAB. The image processing algorithm is depicted in Fig.4.

The inverse kinematic algorithm including the image processing steps is presented in Fig.4. As it is indicated in the algorithm, an adaptive boundary conditions and constraints method is employed to determine the joint variables effectively using the proposed optimisation method. After obtaining a satisfactory shape correspondence between the kinematic model with estimated joint angles and the PPy polymer actuator, the joint velocities and accelerations are also calculated utilizing the AngleOPT method and Jacobian method in order to demonstrate effectiveness of the AngleOPT method.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Angle Estimation for the PPy Polymer Actuator

The PPy polymer actuators used in the experiments have the same dimensions, 20x3x0.17mm, length, width and thickness, respectively. Experiments were conducted utilizing the actuation and measurement system depicted in Fig.4. The electrical input signals were generated using SIMULINK and passed through a USB-type NI-DAQ card (NI USB-6251) to a potentiostat. The electrical input is applied to the PPy polymer actuator using a gold coated toothless clamp. The motion of the PPy polymer actuators is recorded using a camera (Nikon D5100). The videos were recorded in 30fps which is quite sufficient to record the bending motion of the PPy polymer actuators.

Tip coordinates of the PPy polymer actuator were extracted from the videos recorded, utilizing an image processing algorithm. Images were extracted in every second or half a second in the videos depending on duration of the bending motion of the PPy polymer actuator and frequency of the electrical input. Then, these tip coordinates were used as the inputs in the kinematic model to predict the configuration of the PPy polymer actuator from a no-input state to a fully charged state. As the AngleOPT method uses provided tip coordinates to estimate overall shape of the PPy polymer actuator, it is important to mention that a dimension change of the actuator will result in different displacements (tip coordinates and of course overall shape). In this study, we keep dimensions, 20x3x0.17mm, of the PPy polymer actuator constant. The experiments were carried out by

applying the electrical inputs ranging from 0.25 to 1.0V. Although the model verification was carried out for different experiments, the results for 1.0V only are presented due to a space limit. The model estimation and the real PPy polymer actuator's final configuration under 1.0V step input for 40 seconds (the PPy polymer actuator reaches its steady state) are shown in Fig. 5. The model estimation corresponds with the real PPy polymer actuator quite well considering the highest deflection generated among the electrical inputs—0.25-1.0V applied to the actuator.

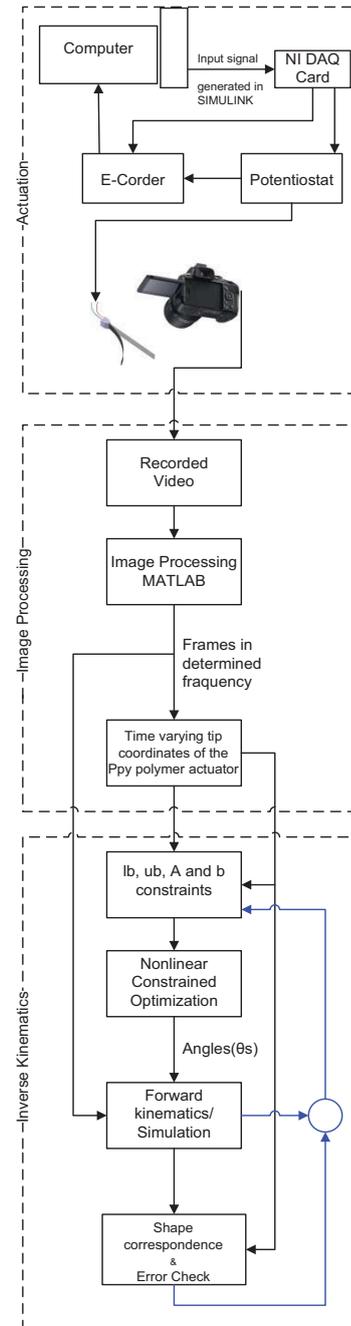


Fig.4. Shape variation prediction algorithm for the PPy polymer actuator.

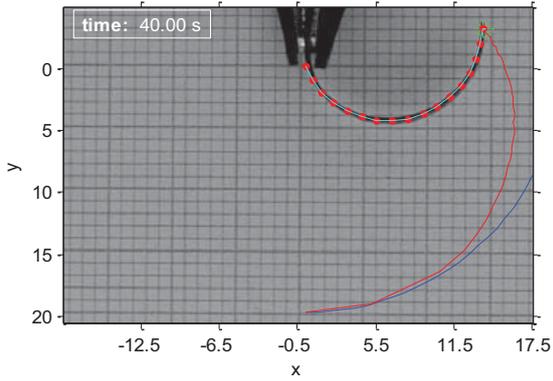


Fig.5. Shape correspondence between the kinematic model (white and red dotted line) and the PPy polymer actuator (black as it is background of the figure) in their final position (Color print).

Also, a sequential motion of the kinematic model is demonstrated in Fig.6 starting from the neutral state of the actuator.

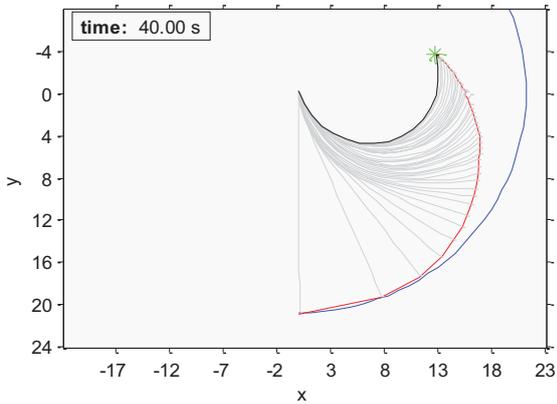


Fig.6. Sequential motion of the kinematic model.

The accuracy of the model is evaluated by employing the root means square (RMS) error method. In this case, RMS is applied between the experimental tip coordinate data extracted from the images and the tip data re-generated by the estimated angles by the AngleOPT method. The RMS error for the tip data is calculated from

$$RMS_x = \sqrt{\frac{1}{n} \sum_{j=1}^n (x_r - x_e)_i^2} \quad (5)$$

$$RMS_y = \sqrt{\frac{1}{n} \sum_{j=1}^n (y_r - y_e)_i^2} \quad (6)$$

The RMS errors between re-generated and experimentally obtained tip coordinates errors are given for various electrical inputs in Table I. The close correspondence between the experimental and numerical results

demonstrates the efficacy of the AngleOPT method, and the constraints and conditions applied while solving the inverse kinematic model. The RMS errors between the experimental and estimated tip coordinates are possibly due to numerical truncations and experimental measurement errors.

TABLE I. RMS errors between experimentally obtained and re-generated tip data under electrical inputs 0.25-1.0V.

RMS axis	0.25V	0.5V	0.75V	1.0V
x	0.4511	0.7115	0.8456	0.4319
y	0.6115	0.7829	0.4749	0.3846

B. Velocity and Acceleration Estimation for the PPy Polymer Actuator

The velocity and acceleration of the PPy polymer actuator can be estimated by computing angular velocity and angular accelerations for each joint. Three methods are used to predict the velocity and acceleration parameters of the PPy polymer actuator; i) An approximation method which uses the variation of the angular displacement of the joints by time ($\Delta\theta_i/\Delta t_i$), ii) AngleOPT method and iii) Jacobian method. All three methods are employed to calculate the velocity and accelerations of the joints. However, due to size limitation, only joint velocities are estimated and presented in Fig.7.

The AngleOPT method is as effective as the Jacobian method in estimating the angular velocities of the hyper-redundant robotic arm, as seen in Fig.7. While the Jacobian method predicts angular velocities efficiently for small changes in joint angles, it calculates some higher angular velocities inaccurately that the Jacobian is a relationship between small changes of both end effector and joint angles. However, the kinematic model generates large angle changes in this case since discrete motion with 1fps is used to analyse tip data from recorded videos. On the other hand, the AngleOPT method estimates angular velocities quite well. A scenario is prepared using the inverse kinematic model and the Jacobian method in order to examine the efficacy of the Jacobian method with smaller angle changes that the Jacobian method estimates the angular velocities in the scenario designated to generate smaller angle changes in the joints with an acceptable accuracy. The same methods can be utilized in order to estimate the joint angular accelerations. Although the accelerations have been computed and a scenario has been designated to solve the inverse kinematic model of the PPy polymer actuator by the Jacobian method, they cannot be presented here for the sake of brevity.

V. CONCLUSIONS AND FUTURE WORK

We have presented an effective method to estimate the kinematic behaviour of an electroactive polymer actuator, which is treated as a hyper-redundant soft robotic arm. The results presented show that the AngleOPT method can estimate highly non-linear shape variations of the PPy polymer actuators. The AngleOPT shows a better

performance when estimating the larger angular positions, the higher angular velocities and angular accelerations from a kinematic model derived for a hyper-redundant system, which has more degrees of freedom than the inputs required. Also, the AngleOPT has a power of control on shape correspondence between the real PPy polymer actuator and its hyper-redundant model.

The future work includes extending the AngleOPT method to estimate tip coordinates of the PPy polymer actuator in order eliminate prior experimental measurements and investigating on effect of dimensions of the actuator on displacement rates.

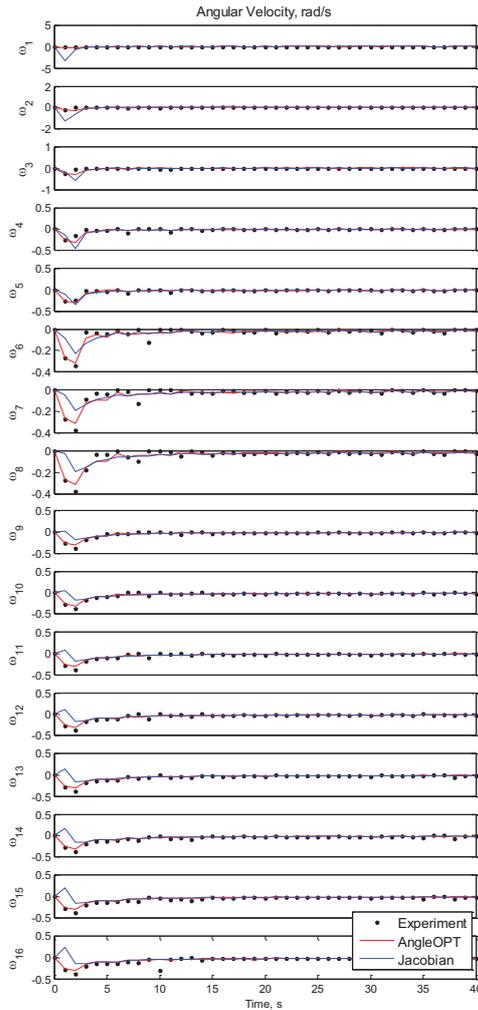


Fig.7. Angular velocity comparison for the joints along the 16-DoF model of the PPy polymer actuator by three methods.

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