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Dynamic characterization and simulation of two-link soft robot arm with pneumatic muscles

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ABSTRACT

Pneumatic artificial muscles (PAMs) belong to the group of nonconventional actuators with remarkable force/weight ratio that can be used for the construction of soft mechanisms safe in contact with humans. In order to be able to design an effective control of 2-link soft robot arm actuated with PAMs, a dynamic model of this system needs to be derived. We use a PAM dynamic model derived using first principles modeling (for contraction, pressure, and air flow dynamics) and ANFIS-based approximation based on the experimental data for the muscle force function. To derive the dynamics of the robot arm, we use Lagrangian mechanics approach for planar arm with the inertial and mass data based on the 3D CAD model. To validate the complete dynamic model of the soft robot arm, we used a gravity test (without PAM actuation) and pulse excitation for PAM control. The results confirm good validity of the dynamic model for all relevant variables (joint angles, muscle contractions, and pressures) as well as the dynamic coupling between the joints.

1. Introduction

Industrial robots are commonly actuated with some kind of electric motors, which bestow them with highly dynamic performance as well as good precision for carrying out their tasks. In order to be only minimally affected by the effect of various disturbances, these robots rely on extremely high stiffness to maintain their performance. This, however, does not come without its downsides—high costs associated with their production as well as operation and potential hazard to humans are possibly two most notable within the industrial area. Due to this fact, one could observe increasing interest in the research of soft actuators used for actuation of robot mechanisms. These kind of actuators include series elastic actuators (SEA), variable impedance actuators (VIA), electroactive polymer actuators (EAPA), or shape memory alloys-based actuators (SMAA), the application of which can be found in works [1–7]. Use of soft actuators in robotics can then be considered for machines, which position within the industry should not be viewed as replacing (for the current robots) but rather complementary with the possibility of implementation of low-cost and safe solutions for simpler applications without high demands for precision and dynamic performance. In addition to the abovementioned types of soft actuators, another type – pneumatic artificial muscle – has come a relatively long way to become a fully commercialized actuator (e.g. by Festo). Its simple construction consisting of elastomer cylinder with embedded aramid fibers, extraordinary power/weight ratio, and clean operation has made pneumatic artificial muscle attractive for various applications in biomedical or industrial areas [8–13]. As yet, several approaches to modeling of pneumatic artificial

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muscles have been developed and used in research works. According to [14], these approaches can be basically divided into three different groups based on the mathematical/physical nature of the model: geometric model, empirical model, and phenomenological model. The first one represents a classical approach to modeling of PAM, which is based on geometric parameters of given muscle (e.g. thread length, thread angle, number of thread turns, muscle diameter etc.). The second approach is based on the fact that the behavior of PAM can be likened to the behavior of (nonlinear) mass-spring-damper system and is well-suited for describing the dynamics of pneumatic muscle [15,16]. The last approach can be used for predicting steady-state values of important variables (like force and muscle length) of muscles with different lengths and diameters [17].

While in some works the modeling and control of a single muscle is presented, in most of the works, the model of PAM is developed in order to obtain a complete model of mechanism driven by pneumatic muscles. The type of a joint that is naturally suitable to be driven by pneumatic muscles is a rotational joint, in which case a pair of muscles in antagonistic connection is needed. In [18], the three-element phenomenological model of PAM was used together with the one-link robot arm dynamics model to design the adaptive control of joint angle. Similarly, the one-link arm driven by a pair of braided pneumatic artificial muscles was used in [19], where the researchers proposed simultaneous torque and stiffness control using the classical geometric model of PAM. In [20], the geometric model of PAM was again used with some of the parameters identified using experimentally obtained data. In contrast to the abovementioned works, researchers in [21] used horizontally placed muscles to drive a load on linear guide-rail. The muscles were controlled using only one 5/3 servovalve and the control design was based on empirical model of PAM. A full state model of PAM in standard canonical form based on the standard geometric model was derived in [22] and used for the sliding mode control design.

The phenomenological model approach was applied to modeling of one-degree-of-freedom arm system driven by PAMs in [9]. In comparison to geometric and empirical model, this type of modeling has the main advantage in its direct representation of the muscle's dynamics expressed in the form of nonlinear differential equation. The system actuated by PAMs and described using such phenomenological model is thus directly amenable to conventional methods of dynamic analysis and simulation of robotic mechanisms.

From kinematic point of view, structures used in the abovementioned works were of the simplest type possible, i.e. with one degree of freedom which are useful for extracting the salient points of dynamics of PAM-driven mechanisms. On the other hand, moving from the one-DOF structure to more complicated kinematic configurations entails the presence of dynamic coupling effects between the joints [23–25], which makes the analysis of PAM-driven mechanism more challenging. The results of research of two-link PAM-driven robot arm were presented in [26], where feedforward neural network was used for construction of nonlinear MIMO NARX model of the system. Two-DOF planar arm driven by PAMs was also used in [27], where the actuator dynamics description was based on the classical geometric model of pneumatic artificial muscle. Mechanical structures with higher number of degrees of freedom and actuation provided by PAMs were researched in [28,29], where again a geometric model of PAMs was used to derive the complete dynamic model of biped and robotic arm, respectively. As a part of our previous research, we derived a dynamic model of one-DOF kinematic structure ([9]) which was used for the controller design. In order to obtain a more accurate model of the same structure for optimization purposes, a recurrent neural network was used for the identification of un-modeled dynamics [30]. In the presented publications, the geometric or empiric models were applied for two-arm controlled system. The main disadvantages of these approaches were either their absence of physical interpretation of the model or significant complexity of the resulting model, which was also harder to analyze from the control point of view.

Using the approach developed for one-DOF system with phenomenological model of PAM, the two-DOF arm system is considered in this paper. Pneumatic artificial muscle is represented by two-element nonlinear mass-spring-damper system implemented through fuzzy approximator and pressure-dependent damper. The dynamics of the soft arm is derived using Lagrangian formalism, based on the kinetic and potential energy of the whole system. The model was implemented in Matlab/Simulink environment with additional modeling done in SimMechanics toolbox to allow for better evaluation of the robot arm behavior through its visualization.

The main objective is to offer a systematic derivation of full dynamic model of two-DOF planar arm driven by pneumatic artificial muscles within the industrial robotics framework. We combine the well-established dynamic model of planar robotic arm with dynamic model of a PAM as new type of actuator based on our measurements. We have used very accurate ANFIS-based muscle force function to obtain good accuracy of the PAM description with subsequent validation of the full dynamic model using combined Simulink/SimMechanics planar arm model. This allowed us to derive a model relatively comfortably transferrable to more complex (multi-DOF) systems.

The paper is organized into five sections. After the Introduction, in Section 2, the dynamic characterization of planar arm driven by PAMs is presented. Hardware description and modeling of the system is given. All functional elements of the planar arm needed for model validation and control are described. After short general description of the system, in Section 3, its dynamics (for one axis), complete dynamic model of both manipulator, and PAM (as manipulator actuator) are derived. In Section 4, simulation of the dynamic model is presented. The obtained results are shown and discussed after which conclusion of the paper follows.

2. Physical model of the system

The main elements of the examined system were two pairs of pneumatic artificial muscles (FESTO MAS-20) with diameter of 20 mm and length of 250 mm. Each of them was equipped with force compensator limiting the maximum muscle force to 1200 N. The process of inflation and deflation of each of the muscles was provided by a pair of 2/2 on/off valves (Matrix 821).