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Modeling of pneumatic artificial muscle using a hybrid artificial neural network approach

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ABSTRACT

Pneumatic Artificial Muscle (PAM) actuator has been widely used in medical and rehabilitation robots, owing to its high power-to-weight ratio and inherent safety characteristics. However, the PAM exhibits highly non-linear and time variant behavior, due to compressibility of air, use of elastic-viscous material as core tube and pantographic motion of the PAM outer sheath. It is difficult to obtain a precise model using analytical modeling methods. This paper proposes a new Artificial Neural Network (ANN) based modeling approach for modeling PAM actuator. To obtain higher precision ANN model, three different approaches, namely, Back Propagation (BP) algorithm, Genetic Algorithm (GA) approach and hybrid approach combing BP algorithm with Modified Genetic Algorithm (MGA) are developed to optimize ANN parameters. Results show that the ANN model using the GA approach outperforms the BP algorithm, and the hybrid approach shows the best performance among the three approaches.

1. Introduction

Pneumatic Artificial Muscle (PAM) is a biomimetic device that mimics the behavior of skeletal muscles. It exhibits force–length characteristics similar to that of a human muscle. PAM has simple construction and consists of a rubber tube connected to pneumatic valves at one end. The rubber tube is housed in a sheath made-up of non-elastic and high-strength fibers. The fibers are arranged in a rhomboidal fashion, which allows a defined contraction motion in a longitudinal direction when the inner tube is inflated which results in shortening of the PAM. Consequently, force is exerted by the PAM on the environment, attached at the other end, in the axial direction. Compared to conventional actuators such as electric and hydraulic actuators, PAM draws certain advantages such as high power-to-weight and high power-to-volume ratios, low maintenance, low price, cleanliness, compliance, pliability, inherent safety, and applicability in rough environments. Air compressibility and elasticity of inner tube also plays cushioning role against unpredictable impacts. Owing to these advantages, PAM is considered an attractive and safe actuator to use in devices operating in human proximity compared to electric or hydraulic actuators.

Recently, PAM has been regarded as a suitable alternative to hydraulic and electric actuators in medical and rehabilitation robot applications. A few examples of the successful use of PAMs in mechatronic devices for rehabilitation purposes can be found in the literature. Applications in the form of an exoskeleton exist for upper limbs [1,2] lower limbs [3], hand [4], elbow [5], and the ankle joint [6].

Unfortunately, PAM exhibits highly nonlinear pressure–length characteristics and time-variant properties due to compressibility of air, elastic-viscous properties of the inner tube and geometrically complex behaviors of the PAM shell. Rubber like behavior of the inner tube also lead to hysteresis and hence the PAM shows different characteristics during inflating and deflating. Thus, it is not easy to control them and obtain the required performance features. In view of this, previous studies have focused on methods for modeling of pneumatic muscles and controller design to improve control performance in recent years, including [7,8].

Considering that the precise modeling of PAMs can be the first step in improving the control performance of system, this paper presents the dynamic modeling of PAM. In order to identify behavior of a PAM, many models to estimate behavior of PAMs have been proposed in the past. The pioneering work in the field of PAM modeling can be classified into two aspects, analytical modeling and artificial intelligence-based modeling identification.

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Analytical modeling method is a common method and an early adopter. Initially, to reduce the model complexity, elastic energy contained in the inner tube was ignored and the relations between axial force, length and pressure were formulated based on the principle of virtual work [9]. Later, nonlinear characteristics of PAM were addressed which included, irregular geometric shape of the rubber tube [10,11], elastic energy of the inner tube [12], and hysteresis behaviors of PAMs. A friction model was also developed for the thread-on-thread friction in the braided shell [9,10,13]. Until recently, most researches have been focused on the static characteristics of PAMs assuming no pressure variance inside the tube during very slow motions. Chou and Hannafordpresented a simple lumped-parameter model of pneumatic circuits to estimate dynamic response of pneumatic circuits [14]. Kang and Kothera proposed a dynamic modeling of PAM [15]. The quasi-static characteristics of the PAM are modeled followed by the dynamic characteristics through spectral analysis [16]. A new approach to model the hysteresis of a basic antagonistic manipulator joint constructed by a pair of Festo fluidic muscles is present [17].

While lot of work has been done to analytically model the pneumatic muscles, the accurate prediction of their dynamic behavior could not be achieved. These analytical models still have limitations in predicting on behavior of the PAM [18]. This is due to lake of knowledge of PAM behavior in the light of its conical ends, friction between the inner tube and outer sheath, valves and fluid flow characteristics and large hysteresis. It is evident from the discussion in the preceding section that the conventional tools cannot fully comprehend the non-linear and time dependent muscle characteristics. Therefore, the artificial intelligence-based modeling identification methods are introduced and quantifiable work has been done in this direction. Ahn and Anh applied a Modified Genetic Algorithm (MGA) for optimizing parameters of a linear auto-regressive with exogenous (ARX) model of the PAM manipulator, which can be modified online with an adaptive self-tuning control algorithm. Through experimental investigation, the proposed MGA-based identification algorithm achieves excellent performance in comparison with conventional SGA and LMS methods [19]. However, the work has been done for constant loading it cannot be used for force control applications of PMA. A neural network ARX (NNARX) model has been applied to non-linear modeling and identification of the PAM manipulator using a new INCBP algorithm [19–21]. The parametric values of the ARX model have been optimized using modified GA (MGA). The MSE of this model has been reported as 0.02616 rad. Incremental back propagation algorithm used to train the NN to further reduce MSE of the model as 0.0035 radians. Prashant proposed a PAM modeling method using modified fuzzy inference mechanism. To tune the parameters of fuzzy model three approaches namely, Gradient Descent (GD) method, Genetic Algorithm (GA) and Modified Genetic Algorithm (MGA) are used. MGA based fuzzy model was found to be more accurate [22]. A novel implementation of a SOFC is proposed for the control of a single PAM. In order to assess the advantage of the intelligent adaptive control system, a comparison of the performance of three types of nonparametric control algorithms (PD, FFC and SOFC) is also presented [23].

Summarizing the above discussion, most of the research on PAM modeling has been done in no-load load or constant conditions, neglecting loads, especially the change in loads. However, in this paper, the PAM will be used for ankle rehabilitation robot application, the loads cannot be taken as constant, moreover the load may change rapidly sometimes. And also, to obtain more accuracy control performance in rehabilitation robot field, the prediction accuracy from the previous models also needs to be improved.

Artificial neural networks can effectively model systems, which possess non-linearity and uncertainties [24]. In order to address above problems of PAM modeling, this paper proposes a multilayer artificial neural network to solve the PAMs' dynamic modeling problems. To get greater modeling accuracy, the parameters of the ANN model are optimized by three different approaches, namely, Back Propagation (BP) algorithm, Genetic Algorithm (GA) approach and hybrid approach combing with BP algorithm and Modified Genetic Algorithm (MGA). The results obtained from the three approaches are analyzed and compared in terms of mean square error (MSE) and maximum deviation of prediction pressure errors.

2. The basic characteristics of pneumatic artificial muscle

PAMs converts pneumatic energy into mechanical form by transferring the pressure applied on the inner surface of its tube into the shortening action. The relationship between pressure (P), length (L) and force (F) can be written as shown below based on the principle of virtual work [14]:

$$F = P \cdot dV/dL = P \cdot D_o^2 \pi/4 \sin^2\theta \cdot [3\cos^2\theta\lambda - 1] \tag{1}$$

where $\lambda = L/L_0$, and L_0, D_0 are the initial length and the diameter of the tube respectively, θ is the initial pitch angle of the braid. However, since the tube shape is not perfectly cylindrical when pressurized and large hysteresis is present in PAM, above models cannot be used in their present form, instead improved model has been built to compensate these variations. However, the model parameters are difficult to obtain because of the influence of uncertain factors, such as time-variety, nonlinearity and environment.

In order to construct a neural network based model of PAM, training data is required to be obtained. The experimental set up used for this purpose shown in Fig. 1.

Tests are conducted on a single PAM which is placed in a rigid hanger as shown in Fig. 1(a). Linear position sensor is positioned parallel to the PAM to record instantaneous length of PAM. A FUTEK load cell is connected to the PAM and used to measure the force dynamically.

Pneumatic muscle is inflated by connecting it to the pressure supply from a compressor. The supply pressure was fixed at 2 bar and two *Isonic* pressure regulating valves are used to control pressure inside the PAM. These valves are capable to provide a switching frequency of 10 ms and are used to fill, leave inflated and empty the PAM actuator.

As shown in Fig. 1(b), a dSPACE (DS1104) data processing system is used to provide interface to a PC allowing MATLAB and Simulink programs to be used. The dSPACE has a number of Input/Output (I/O) capabilities including serial, analogue, and digital, which are used to read data from various sensors and generator control signals. The PAM is controlled by compiling a Simulink model and downloading it to the DS1104 through the I/O interface. The dSPACE is connected to PC through RS-232 serial port.

Under different loads and different pressures, the experimental data are received through serial port from various sensors. The actual behaviors of the PAM obtained from the experiment setup is shown in Figs. 2 and 3. Results from the experiments (Fig. 2) show that the characteristic between length and pressure of PMA is non-linear. The variable external loading on the PAM also affects the characteristic considerably. Moreover, from Fig. 3, the plot is some of different while inflating or deflating the PAM and a lager hysteresis exists.

ANN is usually used to model complex relationships between inputs and outputs or to find patterns in data. Therefore, in this paper, a multilayered feed forward ANN is being proposed to model PAM.