PREDICTIVE FUNCTIONAL CONTROL OF TWO CHAMBERS PNEUMATIC SOFT ACTUATOR

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ABSTRACT: *Researches in Soft Actuators are now growing rapidly because of their adequacy to be applied in sectors like medical, agriculture, biological and welfare. This paper presents System Identification (SI) and control of the force generated by a two chambers Pneumatic Soft Actuator (PSA). A force mathematical model for the actuator was identified experimentally using data acquisition card and MATLAB SI toolbox. Two control techniques; a Predictive Functional Control (PFC) and conventional Proportional Integral and Derivative (PID) schemes are proposed and compared based on the identified model for the soft actuator flexible mechanism. Results of this study showed that both of the proposed controllers ensure accurate tracking when the closed loop system was tested with the step, sinusoidal and multi-step reference input through MATLAB Simulation although the PFC provides a better response than the PID.*

Keywords: Predictive Fuctional Control (PFC), Proportional Integral and Derivative (PID), System Identification, Soft Actuator

1. INTRODUCTION

The use of pneumatic system is rapidly increasing in the world of automation and robotics. Nowadays a lot of pneumatic actuation tools are being developed, studied and used in order to convert compressed gas energy to mechanical energy [1]. Pneumatic actuators can be classified into hard and soft actuators. The hard actuator is a metal structure type of the actuators which is heavy, rigid, difficult, expensive to develop and not suitable for human interaction but has high response time and its rugged. On the other hand soft actuator has high compliance, inexpensive to develop, can be applied in structure and unstructured environment, light weight, high power-to-weight ratio and safer when it comes to interaction but has slow response and it is difficult to control than its counterpart [2-3]. The properties of soft actuator mentioned above makes it suitable for application in areas like medical, agriculture, biological and welfare which requires a biologically inspired robots that are less rigid and safer. However, the potential soft actuators have not been fully exploited due to their inherent properties like high nonlinear hysteresis and time dependent behaviour [4].

The study in this paper includes modelling of a two-chambers Pneumatic Soft Actuator (PSA) using System Identification (SI) method. Many methods which are categorized as analytical modeling; numerical modeling and artificial intelligence based modeling have been used to build dynamic equations that best represent the soft actuator [5]. Tondu *et. al.* used the principle of virtual study to drive the equation of a Pnuematic Artificial Muscle (PAM) based on the inner braided angle of the actuator [6]. S. W. Chan, *et. al.* modeled the PAM by 3-element mechanics consisting of contractile element, dashpot and spring with all elements have pressure dependent coefficients [7]. In [8], the use of conservation energy equation to model, i.e. the input work should be equal to the output work and Mooney-Rivlin was also used for the pneumatic muscle actuator's strain energy expression [8-9]. D. Schindele *et. al*. used finite element method to design a PSA taking into account the non-linearity of the rubber tube, and of the mechanism for transferring load to the braided cords surrounding the tube [9]. Authors of [4] approximate the PSA model as the ratio of pressure in the actuator to the control signal on the valve. A more precise and simpler expression that describes the static behaviour of the PAM with a transfer function showing the correlation between the force, contraction and the required pressure was presented in [10]. In [11-14], the modeling of soft actuator was based on Artificial Intelligence (AI) technique such as Fuzzy Inference System (FIS) and Neural network.

Actuators based on PSA have their specific attributes that make their control different than control of common pneumatic drives. Selection of right method of control for specific device is important for further successful design of control system [11]. In previous researches, many types of controllers like AI and adaptive based have been employed but most of them were on the expansion and contraction force model of pneumatic muscle actuator but study on bending force is rarely being considered. The bending force is considered in this study. Ján Pite, *et. al*. used model reference adaptive controller which was designed from simulation results of the geometric model [12]. An innovative force-based control was employed in [13]. It exploits both a neural network and a PID to obtain a fast and oscillations-free response. Development of an offline self organizing fuzzy controller was discussed in [4]. In [14], the authors proposed Predictive Functional Control (PFC) with observer design to control the force and displacement of a pneumatic system. Three control strategies of position, force and compliance control were proposed. Transfer function of the system is also obtained from SI method. In this paper, PFC design as the control strategy for the pneumatic system is presented. PFC is one of the Model Predictive Control (MPC), which is based on the same approach of prediction of the future outputs using an internal model, specification of a reference trajectory and determination of the control law [15]. Performance assessment of the proposed controller is performed in MATLAB simulation software. The PFC was also been compared with a PID controller.

2. ACTUATOR DESIGN

A two- chamber pneumatic soft actuator with two degrees of freedom of motion which are bending and stretching is considered in this paper. The actuator thickness consists of three layers; inner rubber layer, central spiral fiber reinforcement, and outer rubber layer. The rubber is reinforced with spiral fiber around its wall in the circular direction to resist deformation in the radial direction [18]. The basic structure of the two chamber rubber actuator is shown in Fig. 1. The actuator has two internal chambers, in which pressure is passed through the pneumatic tubes independently. When the pressure is increased in one of its chamber, the actuator bends in the opposite direction to the pressure-increased chamber and extends in the axial direction when pressure is equally increased in both its two chambers. Suzumori *et al.* [18]. This type of soft actuator has its own advantages and disadvantages over the hard type. Table 1 shows some of the qualifications.

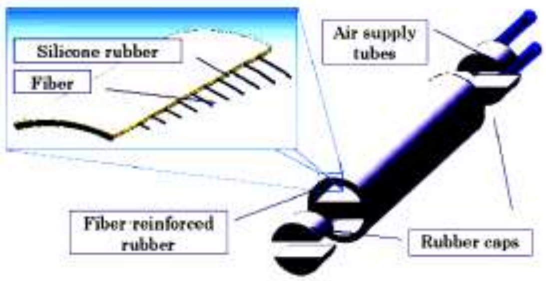

Fig (1) A two chamber pneumatic soft actuator [18].

Table 1: Characteristics of Soft and Hard actuators

PROPERTIES	SOFT ACTUATOR	HARD ACTUATOR
Safety	Safe	Dangerous
Working Environment	Structured and unstructured	Structure only
Degree of freedom/compliance	Infinite	Few
Cost	Low	High
Robotic actuation	Under Actuated	Fully actuated
Controllability	Difficult	Easy
Position Sensing	Difficult	Easy
Materials	Rubber,electractive polymer	Metals, Plastics
Inspiration	Muscular hydrostats	Mammalian Limbs
Load Capacity	Low	High
Accuracy	Low	High
Dexterity	High	Low
Material strain	Large	None

The design of the actuator begins with simulation modelling using non-linear finite elements analysis to design suitable actuator and fabrication of the actuator begins with using CAD software to design the inner and outer cylinder mold (POM material). The design of the mold is then imported into CNC machine for engraving. The rubber actuator is physically produced using the mold block. Detail information on the materials used for developing the soft actuator and the dimension of the considered PSA is given in Table 2

Table 2.
Dimension and materials for developing the soft actuator

Property	Dimension / Material
Actuator Thickness, T_a (mm)	1
Separating Wall Thickness, T_s (mm)	2.5
Ratio, T_s/T_a	2.5
Fiber location from outer actuator diameter (mm)	0.5
Fiber material	Nylon
Rubber material	Dow Coming® Silastic PI
Max Bending Angle, (^{0})	124.4
Actuator Length, L_a (mm)	150

3. MODEL DESCRIPTION

Many strategies have been used to model PSA. One of the most popular and effective way is to choose a given model structure based on the prior knowledge of the system and identify the system parameters by estimation method using experimentally acquired data. This method is known as System ID method.

A two-chamber pneumatic actuator as in [18], an actuator that takes in pressure as an input and produces a force is considered. The force mathematical model was identified experimentally using Data Acquisition Card (DAQ), sensors and MATLAB System Identification toolbox. The schematic diagram for the experiment configuration is shown in Fig. 2 while the flow for system identification process is shown in Fig 3.

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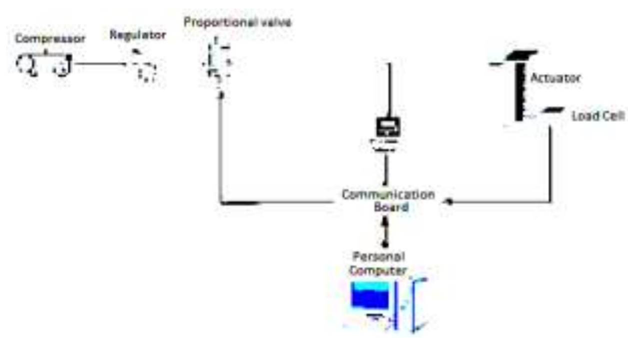
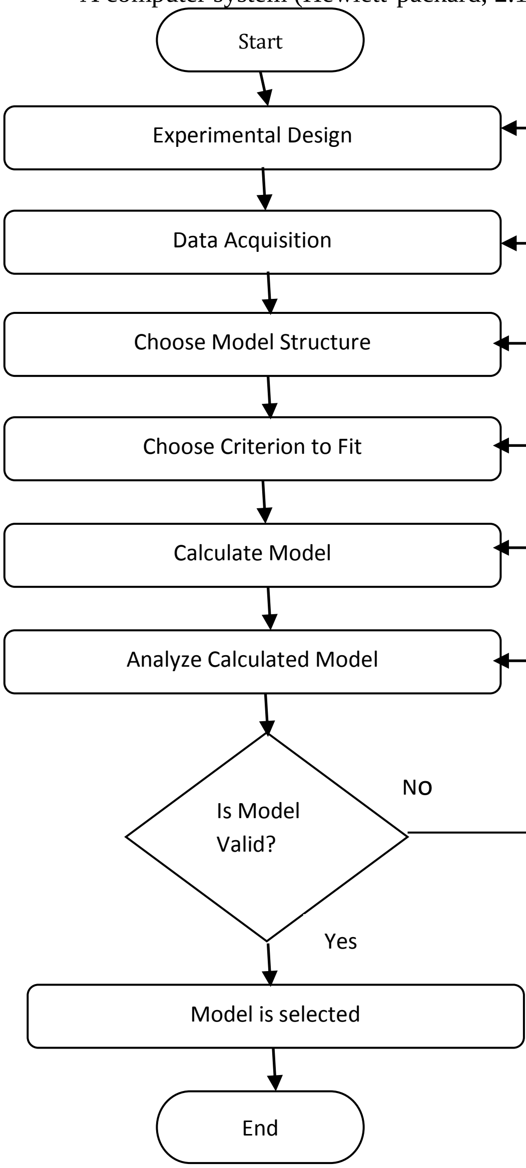


Fig (2) Hardware schematic diagram for the System Identification process

So All data collection was conducted on an experimental set-up that is capable of measuring the pressure and the bending force generated by the soft actuator simultaneously. The force measurement is depicted in Fig. 4. Main components of the set-up are the followings:

- A pressure sensor (Motorola MPX5999D).
- A force sensor (Futek Load cell).
- Proportional pneumatic control valve (Koganei KFPV050).
- Data acquisition card (Lab PCI 1226 National Instrument).

- A computer system (Hewlett-packard, 2.13GHz CPU).



Fig(3) System Identification process Flow Chart

Sine wave input signal was used to excite the plant in open loop in order to perform the identification process at sampling time of t_s=0.02s. A stable Transfer Function (TF) model structure with one zero and three poles is chosen for the Force model. The model validation is performed by comparing the measured and simulated model and percentage best fit is more than 85%. The Force model is as in equation (1).

$$TF = (800.8S + 1.09e04)/(S^3 + 2.14S^2 + 98.98S + 110.6) \quad (1)$$

4. CONTROLLER DESIGN

In this section, PFC will be studied, designed and simulated using MATLAB/Simulink. PFC is proposed because it provides high quality control performance with improved rise time, precise tracking, fast response and robust stabilization. It also has low online computational burden, low constrain handling capability, low line optimization and has simpler yet more intuitive design guideline over other MPC algorithms [14,16]. Thereafter, PID control will be conducted with the pneumatic system for performance testing and comparison.

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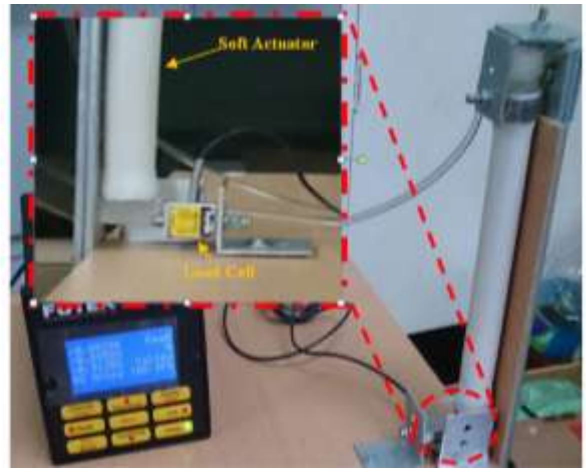

Fig(4) Bending Force measurement

4.1. PREDICTIVE FUNCTIONAL CONTROLLER (PFC)

Since we are dealing with a single input single output system, we have the advantage of using PFC. Moreover when PFC is interfaced with a state-space model description, the design method and the constraint handling are far simpler than with typical MPC, the online computational demand is significantly reduced, gives easy analysis of the closed-loop properties and handles nonlinear processes and fast applications well [16] [17].

PFC prediction algorithm can be derived as a linear feedback control law as in [16]. The model predictive controller is designed based on the linear state-space system description, reference trajectory equation, a set of coincidence points and prediction equation depicted in Equations (2), (3), (5) and (6) respectively. The desired closed-loop dynamic is place into the reference trajectory as shown in equation (3). The control law is obtained by forcing the equality of equation (4) to hold using the d. o. f.

$$\underline{x}_{k+1} = A\,\underline{x}_k + B\,\underline{u}_k \;\; ; \;\; y_k = C\,\underline{x}_k + D\,\underline{u}_k \quad (2)$$
$$w_{k+i/k} = r_k - (r_k - y_k)\,\Psi^1 \quad (3)$$
$$y_{k+n} = w_{k+n}\,,\; n = n_1, n_2, \ldots. \quad (4)$$
$$y_{k+n} = w_{k+n} = r_k - (r_k - y_k)\,\Psi \quad (5)$$

where $n = n_1, n_2, \ldots.$

w is the loop set point, r is the actual set point, y_k is the recent output, Ψ is the tuning parameter to set the desired closed-loop pole. [2,1].

The state input and output prediction equation can be written as follows:

$$\underline{x}_k = P_{xx}\,\underline{x}_k + H_x\,\underline{u}_{k-1} \quad (6)$$
$$y_k = P\,\underline{x}_k + H\,\underline{u}_{k-1} \quad (7)$$

where $\underline{x}_k$ is the state vector, $\underline{u}_k$ is the input vector, $\underline{y}_k$ is the measured output vector. P_{xx}, H_{xx}, P and H are matrices obtained from parameter of Equation (2) by substituting equation (6) and (7) with (5);

$$y_{k+n} = P\,\underline{x}_k + H\,\underline{u}_{k-1} = r_k - (r_k - y_k)\,\boldsymbol{\Psi}^i \quad (8)$$

The control law can be formulated by rewriting equation (4);

$$\underline{u}_k = -H^{-1}\left[\,P\,\underline{x}_k + (\,r_k - (r_k - y_k)\,\boldsymbol{\Psi}^i\,)\,\right] \quad (9)$$
$$\underline{u}_k = -K\,\underline{x}_k + \beta\,r_k \quad (10)$$

where; $K = -H^{-1}(P - \Psi^i y_k)$ and $\beta = -H^{-1}(1 - \Psi^i)$.

In this work, one coincident point is chosen and the PFC tuning parameters selected with n = 6, desired time constant Ψ.= 0.900 to obtain desired closed loop response.

4.1. PID CONTROLLER DESIGN

A PID controller using the Particle Swarm Optimization (PSO) algorithm was developed to improve the transient response of the two chambers pneumatic soft actuator. The in depth controller design analysis and procedure is as described in [19]. Optimal PID controller parameters K_p, K_i and K_d, were determined by utilizing the PSO algorithm. The number of particle in each swarm is set to 20 and the maximum number of iteration is set to 100. As default values of velocity constants, $c1$ and $c2$ are set as 2. The initial value of ω is 0.9. The PID controller was formed based upon the parameters chosen, and the global best solution was selected for the set of parameters, which had the minimum error. Based on PSO, the PID tuning parameters for the model as shown in Table I were adopted.

Table 3: PID controller parameters

Parameter	Optimum Tuned Value
K_p	0.00204
K_i	-0.00267
K_d	0.00489

5. RESULTS AND DISCUSSION

After The control techniques proposed were designed and implemented using the block diagram environment for multi domain simulation and model based design (SIMULINK), we implemented the discussed controllers system on the pneumatic actuator according to the configuration that is shown by Fig. 5 (a) and (b).

The control signal for the step input tracking is shown in Fig. 6. This is to evaluate the force tracking performance of the close loop for a class of continuous and discontinuous functions. As can be seen clearly, three input signals including a sine wave, multistep function and step function has been formed. Two manual switches allow the change of reference input signal condition. Fig. 7, Fig. 8 and Fig. 9 show the compared closed loop system responses of the two controllers.

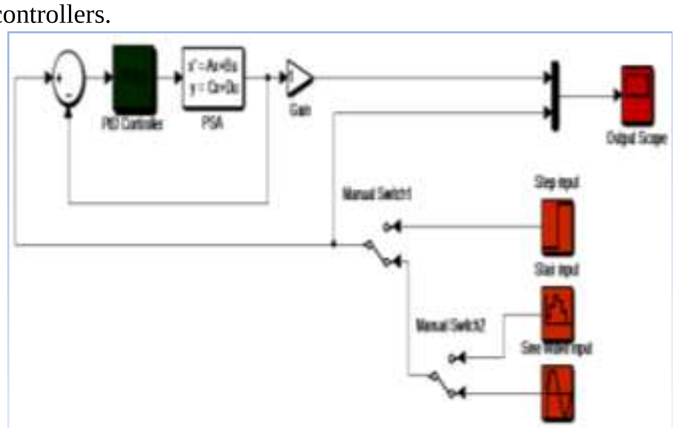

Fig (5a) Simulink Block Diagram of Model interfaced with PFC Controller

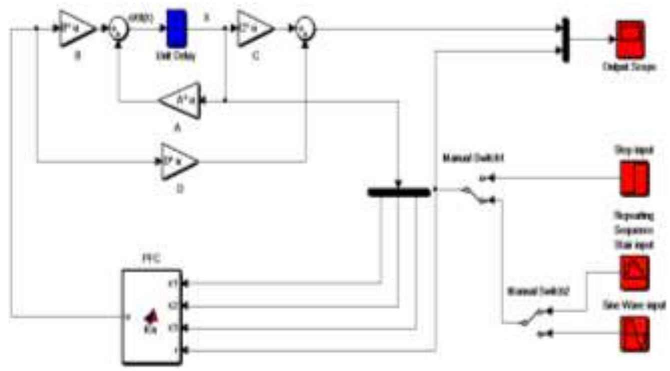

Fig (5b) Simulink Block Diagram of Model interfaced with PFC Controller

The control signal for the step input tracking is shown in Fig. 6. This is to evaluate the force tracking performance of the close loop for a class of continuous and discontinuous functions. As can be seen clearly, three input signals including a sine wave, multistep function and step function has been formed. Two manual switches allow the change of reference input signal condition. Fig. 7, Fig. 8 and Fig. 9 show the compared closed loop system responses of the two controllers.

With the implementation of PFC and PID as in Fig. 6 below, with a step input it can be noticed that the PFC has a lower rise time and settling time than the PID controller while both are having no overshoot and steady state error. For sinusoidal input signal, the PFC controller adequately makes the actuator track the input for the entire time period than the PID though it is within acceptable bandwidth. In the case of multistep input signal, it was observed that the conventional PID controller has a setback in terms of tracking the input. The PFC tracks the reference with a more reasonable rate of efficiency than the PID controller.

It is clear that PFC produces more robust and stable results than the PID controller. Thus, the simulation results affirm that PFC can be a reliable and stable controller that can be employed to handle the nonlinearity and hysteresis in the characteristics of the actuator

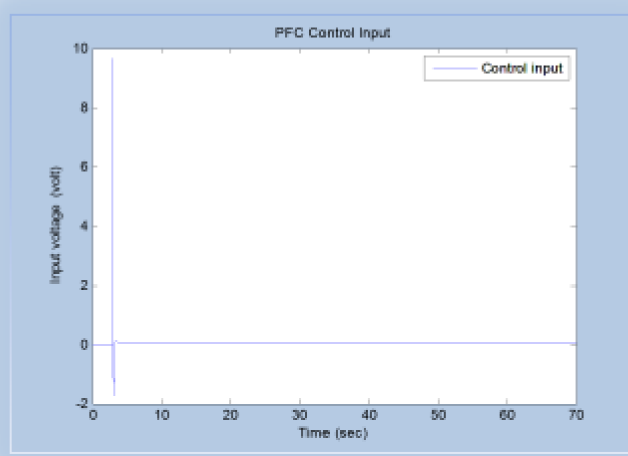

Fig (6) PFC step tracking control signal l

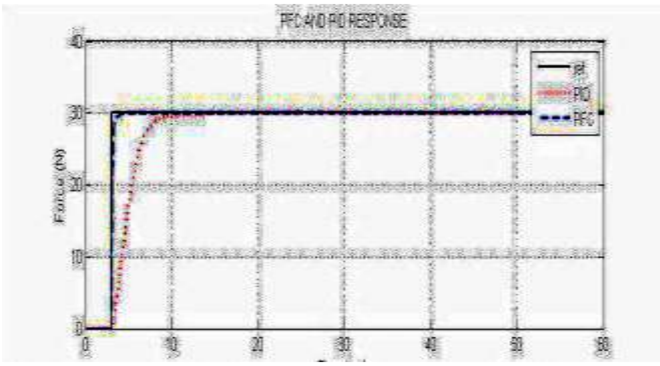

Fig (7) Performance comparison of PFC with PID for Step input signal

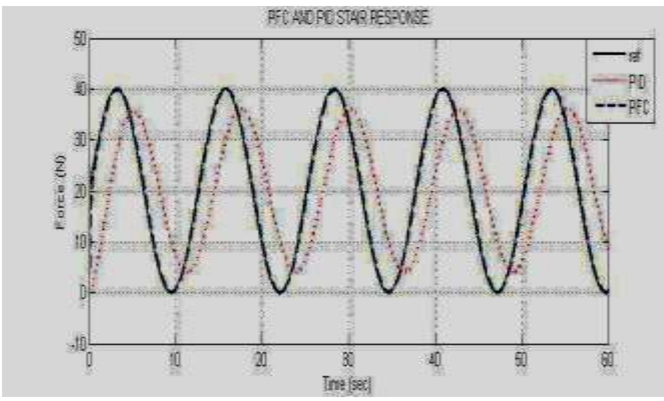

Fig (8) Performance comparison of PFC with PID for Sinusoidal input signal

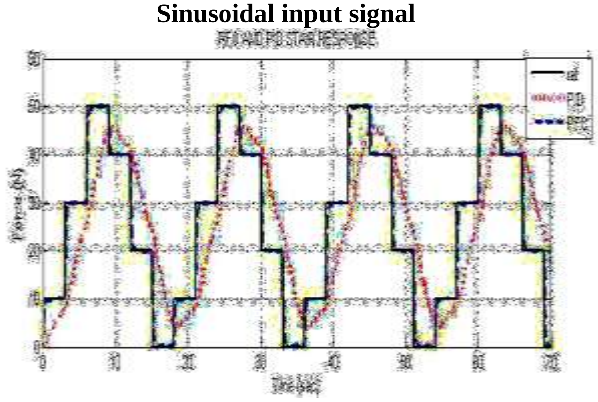

Fig (9) Performance comparison of PFC with PID for Multi Step input signal

6. CONCLUSIONS

An adequate force mathematical model that represents a two chamber pneumatic soft actuator was obtained using experiment data via MATLAB system identification Toolbox. Two controllers; Predictive Functional Controller and conventional PID tuned using PSO were designed and simulated based on the identified model. A performance comparison of the proposed controllers was done. From the results, it can be concluded that both PFC and PID control strategies implemented are capable to produce good response even though the PFC controller shows a better response than the PID controller.

We are working to implement the control algorithm on the test rig that was used for the system identification. We will report on our findings in due course.

7. ACKNOLEDGEMENT

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