PREDICTIVE CONTROLLER WITH KALMAN FILTER FOR INTELLIGENCE PNEUMATIC ACTUATOR (IPA)

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ABSTRACT: This paper discusses and analyzes the performances of an Intelligence Pneumatic Actuator (IPA) positioning system using Predictive Functional Controller (PFC) with Kalman filter Design. The uncertainties in the pneumatic system are undesirable. Kalman filter is useful in vast areas due to the prediction assets. The system models are designed based on previous research on the predictive controller and focused on position tracking. The transfer function for the pneumatic actuator is obtained by using system identification (SI) techniques. The initial covariance values of the Kalman filter system are determined according to the plant system. The performances of the proposed system are performed in MATLAB, Simulink and validated with IPA plant. The validation process of the IPA plant is run through real-time experiments using National Instrument (NI) devices. The Result showed the system is stable with Kalman filter is new implementation on both simulations and experiment process.

KEYWORDS: *Pneumatic Actuator; Predictive Functional Controller; Kalman Filter; Positioning Control; System Identification*

1.0 INTRODUCTION

Actuator is a device that converts physical energy into motion. These actuators have been developed into the various fields of applications including medical, food manufacturing and others. One of the famous actuators is pneumatic actuators. Advanced technology keeps ensuing with different techniques and methods. Pneumatic has shown great advantages in its usage. The advancement of the pneumatic actuator is to improve the weaknesses by overcoming with another factor such as improve the power to weight ratio performance, efficiency and construction rationalization so-called as introducing or invention of new devices. Intelligence pneumatic actuator (IPA) has been developed in a new generation of the actuator for Research and Development (R&D). IPA system is the next generation actuator developed with new features which are an all-in-one mechanism for compact systems.it has been developed in a few applications such as Pneumatic Actuator Seating System (PASS) and Ankle-Foot Rehabilitation Exerciser (AFRE) [1-3].

The controller is developed with the aim to improve the steady-state accuracy, stability of the system, maximum overshoot as well as reducing noise signals produced in the system [4-5]. A Model-based predictive control takes what is predictable in the future into account and controls the closed-loop component to achieve the desired response [6]. It is clear that isolating what may be controlled from the natural, open-loop behavior of the process simplifies the whole control procedure and, as a consequence, improves the results. They are interconnected by what is referred to as the structure, which is assumed to be invariant and may be represented by a mathematical model. A model is always inaccurate and predictive control endeavors to find the local compromise between the two strategies which is an open loop and closed loop.

Kalman filter was first introduced in 1960 as a solution to discrete-data linear filtering. Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of the process by minimizes the mean of the squared error [7]. The properties of the Kalman filter is included several aspects; the estimations of the past, the present and support the futures states. It also can act well when the precise nature of the modeled system is unknown. Kalman filtering comprehends in many fields of application with two purpose reasons; estimation and performance analysis of estimators [8-9]. The Kalman filtering allows estimating random behavior by using statistical information. In the Kalman Filter, it does not require to store all previous and processed every time a new measurement is taken. It concept refers to the recursive in the Kalman filter concept. This will be very important for the practical implementation of the filter. "Filters" are actually algorithmic processing data. Regardless of the typical meaning of a filter as a "black box" containing electrical networks, the fact is that in most practical applications, the "filter" is just a computer program in a central processor. As such, it inherently incorporates discrete-time measurement samples rather than continuous time inputs [10]. The main idea of this project is to implement the predictive controller with Kalman filter to intelligence pneumatic actuator (IPA) plant base system as the development on the predictive controller is still new and in a small scope [5]. The Predictive Functional Controller (PFC) are selected based on the previous research and cascaded with Kalman filter [11-13]. The linear based predictive functional controller is model using MATLAB system identifications toolbox for a third-order transfer function which is calibration data acquired from IPA plant model. By using system identifications techniques, time-consuming in modeling is shorter than deriving using mathematical calculations. The Kalman filter applied and presented as a feedback system to the controller. In this regard, Kalman filter is used to estimating unknown (or unmeasured) states of the proposed control system. The designated model in both simulations and real-time applications show acceptable performances. Several parameters have been considered in measuring the PFC-Kalman filter performance. The simulation results were compared and the performances of each controller in terms of positions tracking of IPA plant.

This paper is organized as follows. The experimental setup for this research is explained in Section 2. The development and performance analysis of the controllers were discussed in Section 3. Conclusion remarks of the study is stated in Section 4.

2.0 METHODOLOGY

The simulation process experimented in the MATLAB Simulink toolbox. The platform was used as the graphical user interface (GUI) in the form of a block diagram. The system is a single input single output (SISO) where the output is the position tracking at y. The input is the step as the reference value in plotting the graph. Figure 1 shown a simplified block for the operation of the overall process.

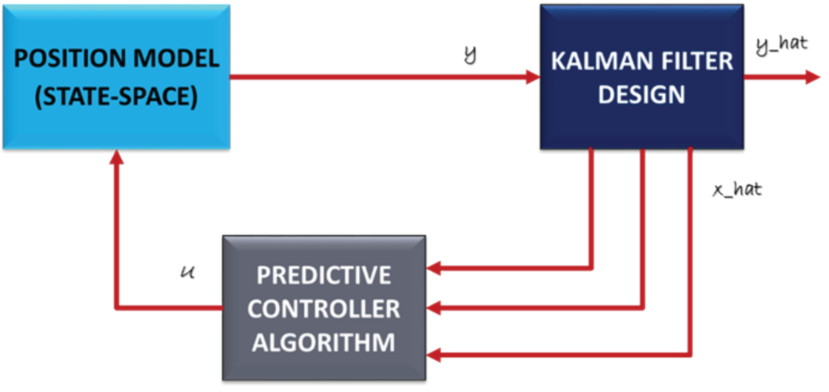

Figure 1: Simplified proposed block diagram

The preferred a pneumatic actuator in this model is the Intelligence Pneumatic Actuator (IPA). IPA was designed with a sensor, embedded function or microcontroller board that consist of Programmable System on a Chip (PSoC), valves and laser stripe pitch. The sensors that equipped at the actuator is optical sensor and pressure sensor. The PSoC board act as the brain for this IPA system and its place on the top of the actuator in a single device. The main criteria that have been declared as the intelligence part of this IPA where it can decide the output target based on the feedback inputs with a real-time communication capability. The actuator has a 200mm stroke and can give force up to 100N. The 0.16mm laser stripe pitch has very high accuracy and can give a high accuracy for the position tracking and control. On the bottom part of the PSoC circuit board, an optical reflective surface mount encoder is placed. The encoder chip consists of three main part; an LED light source, a photo detector IC and optical lenses. The lenses focus LED light onto the code strips on the guide rod and reflected light on the photo detector IC. Figure 2 shows overall parts of the intelligent actuator [3].

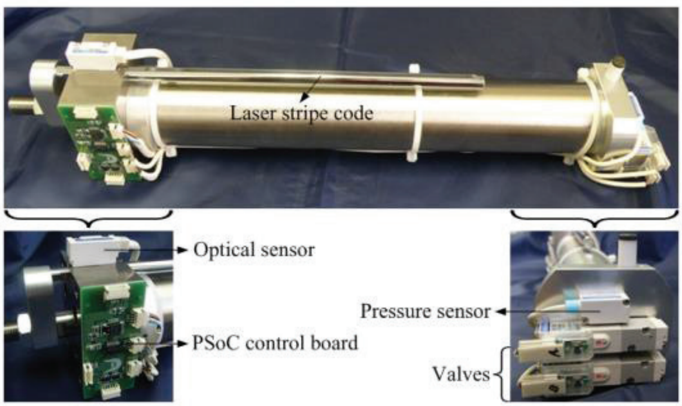

Figure 2: IPA parts [11]

The experimental setup for this research is shown in Figure 3. The pneumatic actuator system and the Personal Computer (PC) (equipped with MATLAB software as the platform) communicates using the National Instrument (NI) Data Acquisition (DAQ) card PCI/PXI-6221 (68-Pin) board, SHC68-68-EPM cable, and SCB-68-M series devices. There are three (3) signals from the board which is analog output signals for valves, an analog signals input for pressure and a signal counter for the encoder. The signals will be transferred and exchanged between plant and personal computer through DAQ card.

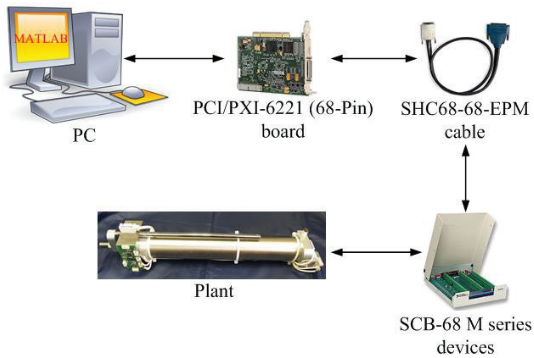

Figure 3: National Instrument (NI) devices connection [7]

As MATLAB were the main part of the overall system, the proposed design was designed in the Simulink toolbox and generate the result for a reference when comparing with IPA system performance. The proposed system is including PFC and Kalman filter system as shown in Figure 4.

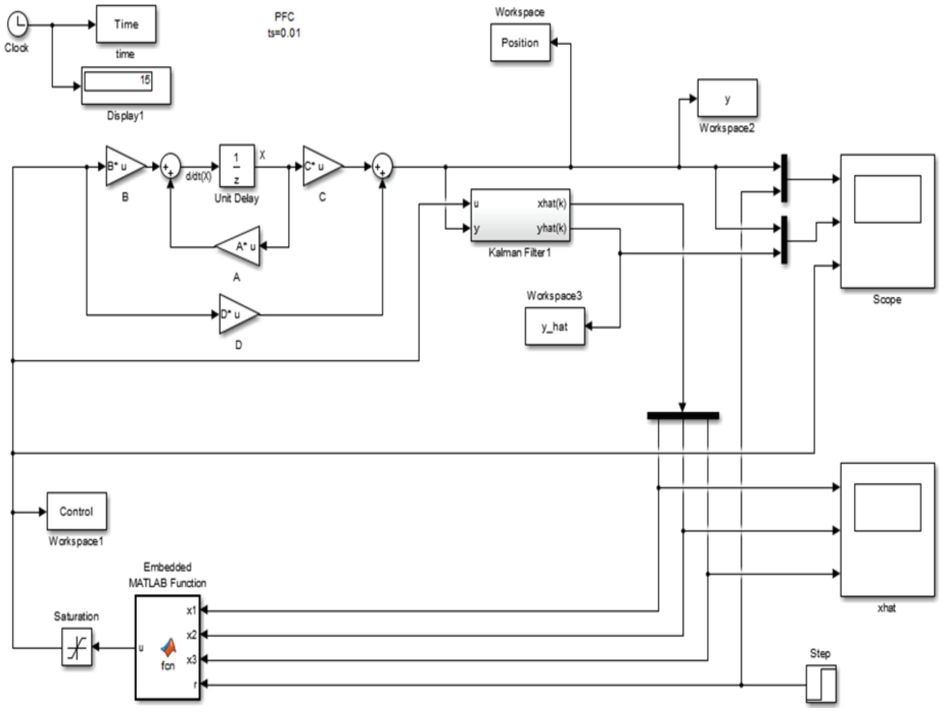

Figure 4: Proposed system

3.0 RESULTS AND DISCUSSION

The system is constructed based on the Kalman properties. According to the equation of the Kalman filter, the graphical form is shown in Figure 5.

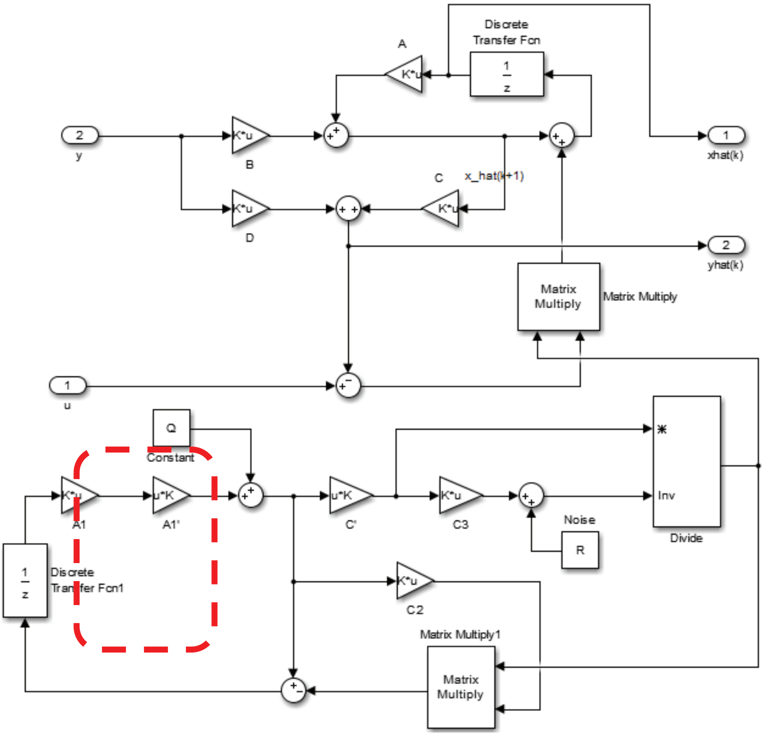

Figure 5: Kalman algorithm

The equations of the Kalman filter are as follows [14]:

Model:

$$\hat{x}_{k+1} = A\hat{x}_k + Bu_k + w_k;\ w_k \approx N(0, Q) \tag{1}$$

$$\hat{y}_k = Cx_k + Du_k + v_k;\ v_k \approx N(0, R) \tag{2}$$

Gain:

$$K_{k+1} = \bar{P}_{k+1}C^T[R + C\bar{P}_{k+1}C^T]^{-1} \tag{3}$$

Measurement update:

$$\hat{x}_{k+1} = \hat{x}_{k+1} + K_{k+1}[\hat{y}_{k+1} - C\hat{x}_{k+1}] \tag{4}$$

$$P_{k+1} = \bar{P}_{k+1} - K_{k+1}C\bar{P}_{k+1} \tag{5}$$

Time update:

$$\hat{x}_{k+1} = A\bar{x}_k + B\hat{u}_k \tag{6}$$

$$\bar{P}_{k+1} = AP_{k+1}A^T + Q \tag{7}$$

As mention in the model equations, w_k and v_k is the covariance added to the system. After the derivation, w_k or Q is represent the initial covariance for the plant or system while v_k or R is the measurement covariance for the system. The measurement is taken as the instrumentation error of the plant. In the red box in Figure 5, the initial value is set as the initial covariance, P0 of the system. From the setting, the initial covariance Q must be smaller than R. This is due the covariance properties in the Kalman Filter. Hence, the simulations result in the MATLAB shown in Figure 6, a constant stability with small overshoot values. The control performance is categorized and compared with IPA plant model. The results are tabulated in Table 1.

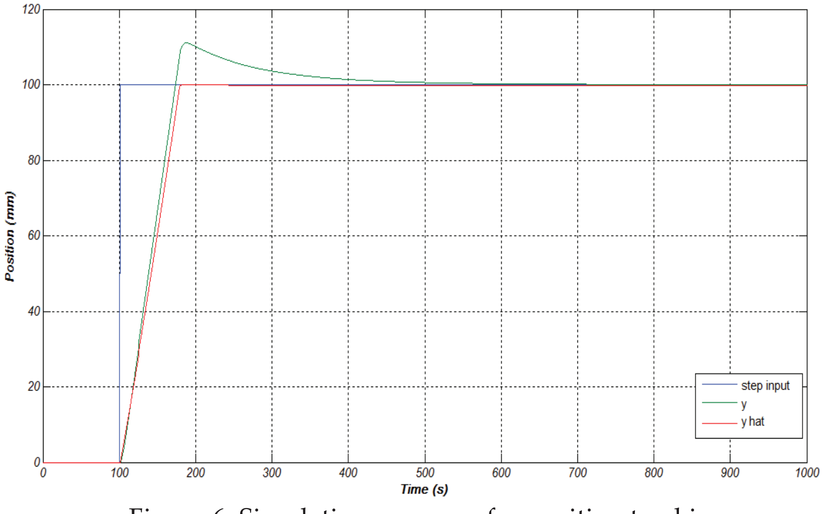

Figure 6: Simulation response for position tracking

Table 1: Simulation performance characteristics

Performances Index	Output	
	y	y_hat
Rising Time, Tr (s)	0.5622	0.6245
Settling Time, Ts (s)	3.5995	1.7698
Overshoot OS (%)	11.0505	0.2305
Steady-State Error, (%)	0.0001	0.0001

Based on the obtained data, a simulations results showed a great performance for the proposed system. The PFC show a constant stability with a 0.0001% steady state error between reference step inputs. It required 3.5995 s to achieve the steady state and 0.5622 s for rising time. Hence the simulation is compared with IPA plant verification results. Figure 7 and Table 2 shows a positions tracking of IPA plant with the reference input at 100. Unlike simulations results, it does not achieve the reference input but with a stable system performance. IPA plant show higher readings than simulations results. It looks 5s+ to reach the settling time with percentage of error at 17.99%.

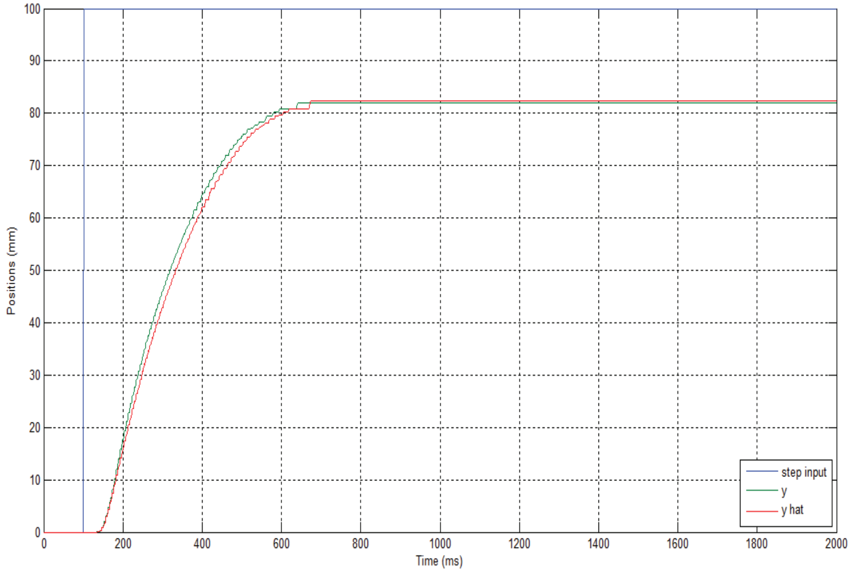

Figure 7: Real-time experiment response for position tracking

Table 2: Real-time experiment performance characteristics

Performances Index	Output	
	y	y_hat
Rising Time, Tr (s)	3.0462	3.2531
Settling Time, Ts (s)	5.9186	6.1739
Overshoot OS (%)	0	0
Steady-State Error, (%)	17.99	17.69

At the end of this experiment, the proposed controller (PFC) with Kalman filter design is applied to the IPA system is detailed out. The simulations result is proved by validations through real time experiment with IPA plant system in terms of positions tracking. From the results obtained, the simulations and real time experiment showed that the stability of the controller is maintained. Since the transfer functions of the controller is linear, the real time experiment showed slightly different from the simulations. Despite that, the pneumatic actuator is a nonlinear actuator which is the result still acceptable. Several parameters are considered in comparison the controller performance between simulations and real time data.

4.0 CONCLUSION

Along with the process development, result shown that the simulations of Kalman filter with Predictive Functional Controller (PFC) for the pneumatic actuator is closely matched to the input response. Meanwhile, due to the nonlinear characteristic of IPA and unsuitable initial covariance value of Kalman Filter, the performance of IPA is differing from simulations results. But the system stability of the IPA control system is desirable has been proposed. This research will provide greater opportunities for future work such as the development of graphic user interface (GUI) to enhance online communication with more than one actuator and improvement of Kalman filter initial covariance value for the nonlinearity and uncertainties of the pneumatic actuator.

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