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Enhanced Position Control for Pneumatic System by Applying Constraints in MPC Algorithm

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ABSTRACT

This paper demonstrates the effectiveness of applying constraints in a controller algorithm as a strategy to enhance the pneumatic actuator system's positioning performance. The aim of the present study is to reduce the overshoot in the pneumatic actuator positioning system's response. An autoregressive with exogenous input (ARX) model structure has been used to model the pneumatic system, while a model predictive control (MPC) has been employed as a control strategy. The input constraint has been applied to the control signals (on/off valves signals) to ensure accurate position tracking. Results show that the strategy with constraint effectively reduced overshoot by more than 99.0837 % and 97.0596 % in simulation and real-time experiments, respectively. Moreover, the performance of the proposed strategy in controlling the pneumatic positioning system is considered good enough under various loads. The proposed strategy can be applied in any industry that used pneumatic actuator in their applications, especially in industries that involved with position control such as in manufacturing, automation and robotics. The strategy proved to be capable of controlling the pneumatic system better, especially in the real-time environment.

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1. INTRODUCTION

A pneumatic actuator system is a mechanical system that is often used in industries that are involved with object transportation and motion control applications. However, nonlinearity and uncertainty issues in the system make the usage of this actuator system limited to certain applications. These issues have caused the pneumatic actuator system to fail to control its positioning system, in order to get good accuracy. Many studies have been done to tackle these issues and have contributed towards the creation of intelligent actuators in 1992 [1]. The pneumatic actuator system used in this study is of this type; namely the intelligent pneumatic actuator (IPA) system. This actuator integrates actuator, microprocessor and sensors together in a system [2],[3]. Although the IPA is more sophisticated than any other conventional pneumatic actuator system, the complexity of the system has led to the control process of the system becoming more complicated.

Like other pneumatic systems, controlling the IPA is not easy, since it has several nonlinear characteristics to be considered, such as valve dead zone, air compressibility, air leakage, and friction in the system's parameters [4],[5]. The IPA positioning system was first controlled in 2010 using a proportional-integral (PI) controller [2],[3],[6]. Two years later, a pole-placement feedback controller was designed for the same purpose, and the performance was compared with previously developed PI controllers [7]. Simulation results showed that the latter controller strategy gave a more stable control performance than the PI controller in tracking the desired set-point. In 2013, [8] proposed a PI controller and bang-bang controller in order to access the position control performance of IPA system in real-time environment. The application of optical sensor and pressure sensor to develop a real-time model similar to the existing IPA system was the main concern in this work. Experimental results showed that both sensors were capable applied as a feedback sensors in real-time system and the developed model can also be used to develop a system identification model. During the last four years, researchers have shown a great interest in using a predictive controller to control the IPA positioning system [9]–[13]. Generalized predictive control (GPC) and predictive functional control (PFC) are types of controller that are often used for this system. Studies using both types of controller found that the predictive controller is suitable for providing accurate control of the IPA positioning system; in both simulation and real-time environments.

Based on this fact, this study proposes a model predictive control (MPC) as a new control strategy to control the IPA positioning system. MPC was considered in this study since it has the ability to predict the future position of the pneumatic actuator cylinder stroke; thus guaranteeing the accurate tracking of the system; especially when implementing within a real-time environment [14],[15]. Furthermore, one of the advantages of using MPC as a control strategy is that MPC can consider input and output constraints presented in the particular system [16]–[20]. The use of constrained MPC to control the IPA positioning system was published in 2015 [21]. In this work, the input constraint was applied to the on/off valve signals. Simulation results showed that the constrained MPC was more effective in giving a better transient response than the unconstrained MPC. These findings prove that giving constraints to the controller's algorithm can enhance the tracking accuracy of the IPA positioning system. However, the study was only done in simulation and the performance of the controller in a real-time environment is still unconfirmed. This study was therefore undertaken to verify the performance of the proposed strategy in a real-time environment. An observer is necessarily used in this case to estimate the real IPA system's states; so that the MPC can take control action accordingly. An overshoot in the system's response is expected to be high, when the controller is implemented in a real-time environment that normally contains nonlinearities and uncertainties in the system's parameters. Consequently, this paper proposes new control techniques using a constrained MPC with an observer system to enhance the IPA positioning system's performance in a real-time experiment. The major concern of this paper is to eliminate (or reduce) overshoot in the system's response, to ensure that accurate and precise positioning control of the IPA system can be achieved. In this study, giving constraints to on/off valves signals is very important as these signals were mainly used to control the inlet and outlet air of the cylinder, in order to perform the extension and retraction of the cylinder stroke. In other words, positioning performance of IPA system also depend highly on the signal to the on/off valves. Simulation and real-time experiments were carried out to verify the effectiveness of the strategy. Because the MPC is a model-based type controller, which is explicitly based on the plant model itself to predict the future plant behaviour, this study used a system identification technique, based on autoregressive with exogenous input (ARX) model structure, to model the IPA system.

The rest of the paper is organized as follows. The process of collecting the input and output data through experiment and modelling the system using a system identification technique are described in Section 2. The procedures in designing a controller to perform the control task are also explained in Section 2. The simulation and experimental results using the proposed strategy are discussed in Section 3, and the overall findings of the study are concluded in Section 4.

2. RESEARCH METHOD

2.1. Experimental design and system modeling

Figure 1 shows a physical view of the intelligent pneumatic actuator (IPA) system used in this research. Five major components play major roles in ensuring that the IPA system works well; the optical sensor, laser stripe rod, pressure sensor, on/off valves, and the programmable system on chip (PSoC) control board. Each of these components has their own role, and is interconnected with each other. The system used in this study is called "intelligent" because it involves a microcontroller board (PSoC board) that serves as the brainto control the entire system operation. Mounted on the cylinder body, the PSoC board is also considered a major player; particularly when involving embedded operations within the system. In this study, the effectiveness of the proposed controller, for controlling the position of the cylinder stroke for the IPA system, will be presented and discussed. To perform this task, an optical sensor will be used. This sensor, which was mounted on top of the cylinder, will be used to detect the position of the cylinder stroke based on the position reading given by the laser stripe rod. The signal will then be sent to the PSoC board to be processed by the user. Other components, such as the pressure sensor and the on/off valves, also play important roles in controlling the system. These two components were mainly used to control the inlet and outlet air of the cylinder, in order to perform the extension and retraction of the cylinder stroke. The movement of the IPA system cylinder stroke is based on the operations of the on/off valves i.e., the stroke is extended when the on valve is activated and retracted when the off valve is activated.

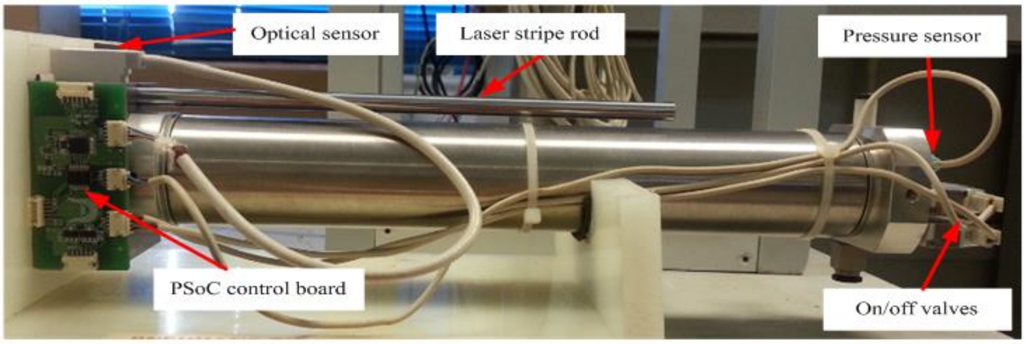

Figure 1. A physical view of the IPA system

Before the task, such as designing a controller, monitoring, predicting, etc., can be implemented in the system, it is very important to know about the dynamics and behaviour of the system under control. This process is known as “system modeling”. An experimental approach, known as “system identification”, is one of the methods that can be used for this purpose. The concept of system identification contrasts with another method (theoretical approach), because it is based on the analysis of observations (experiment), not fundamental laws of nature. The mathematical representation of the IPA system has a limitation to derive, because the system has several unknown parameters that need to be considered. As an alternative, the system identification method was chosen to model the system used in this study. This method is also very suitable in the complex system or process; especially in a practical environment [22]. Figure 2 illustrates the process used to obtain the input and output data based on an experimental approach. The input and output data contains 1500 data points of continuous step input signals applied to the valves $(u1)$ and 1500 data points of the position signal $(y1)$ sampling every 0.01 s. Figure 3 shows the plot of input and output data from the real-time experiment. For modeling using the system identification method, the first 750 samples were selected for training while the last 750 were used for validation purposes.

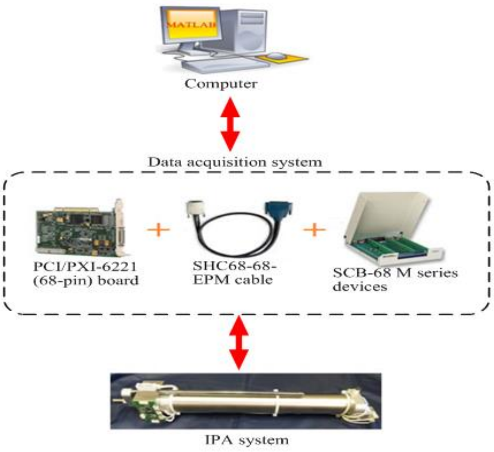

Figure 2. Process of collecting input and output data

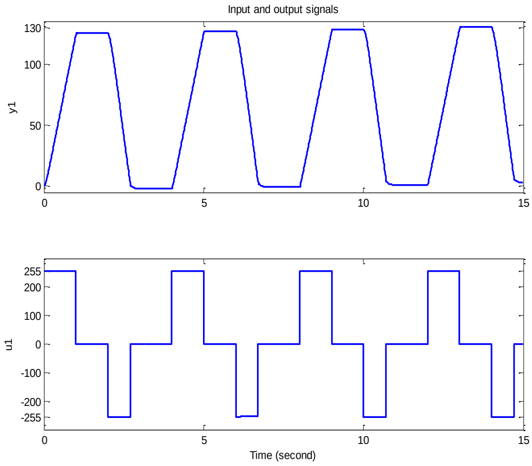

Figure 3.The plot of input and output data

In system identification, there are several parametric model structures that can be utilized to represent the system, such as auto-regressive with exogenous input (ARX), auto-regressive moving average with exogenous input (ARMAX), output error (OE), and box Jenkins (BJ) [23]. In this study, only ARX will be considered as a model structure to represent the mathematical model of IPA system. The input and output data that was collected during the real-time experiment will be used for this purpose. Equation (1) is the identified discrete ARX transfer function, while Equation (2) is the discrete state-space IPA system model used in this study.

$$\frac{B(z^{-1})}{A(z^{-1})} = \frac{0.0016z^{-1}}{1-1.8690z^{-1}+0.9976z^{-2}-0.1284z^{-3}} \tag{1}$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0.1284 & -0.9976 & 1.8690 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},$$

$$C = [0.0016 \quad 0 \quad 0],\ D = [0]. \tag{2}$$

The plant model identified using the ARX model structure, sufficiently represents the IPA system; since it gives a 91.09 % fit with the actual plant and a lower error value. Acceptance of this model is also confirmed, as the model is also stable.

2.2. Controller design

A model predictive control (MPC) is the type of controller that will be used to control the IPA positioning system considered in this study. MPC is a model-based controller that predicts the future outputs and takes control action accordingly by solving the optimal future control actions (cost function and constraint). In this study, MPC will be used to determine the future adjustments of the signal to the valves to ensure that the stroke of the cylinder is at the assigned positions. Equations (3) and (4) describe the cost function and optimal control signal of the MPC algorithm.

$$J = (R_s - y(k))^T(R_s - y(k)) + \Delta U^T(k)\bar{R}\Delta U(k) \tag{3}$$

Where

$$R^T{}_s = \overbrace{[1 \quad 1 \quad \cdots \quad 1]}^{n_p}\ r(k);$$

$$y(k) = Fx(k) + \Phi\Delta U(k);$$

$$F = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ \vdots \\ CA^{n_p} \end{bmatrix}; \quad \Phi = \begin{bmatrix} CB & 0 & 0 & \cdots & 0 \\ CAB & CB & 0 & \cdots & 0 \\ CA^2B & CAB & CB & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & 0 \\ CA^{n_p-1}B & CA^{n_p-2}B & CA^{n_p-3}B & & CA^{n_p-n_c}B \end{bmatrix}$$

$$\Delta U(k) = (\Phi^T\Phi + \bar{R})^{-1}\big(R_s - Fx(k)\big) \tag{4}$$

The optimal control signal in Equation (4) can also be represented as in Equation (5).

$$\Delta U(k) = u(k) - u(k-1) \tag{5}$$

where J is the cost function, R_s the set-point, y the predicted output, ΔU is the optimal control signal, $\bar{R}$ is the diagonal matrix $(= r_w I_{n_c \times n_c}(r_w \geq 0))$, $x(k)$ is the state variable at time k, $r(k)$is the set-point signal at time k, n_p is the prediction horizon, and n_c is the control horizon. In this study, the value of n_p used is 20, while the value of n_c is 3.

One of the advantages of using MPC is that it has the possibility to easily account for constraints. In this study, two cases of control signal are investigated. For the unconstrained case, no limitation has been given to the signal that came out of the controller. Meanwhile, for the constrained case, the signal will be constrained/limited between the maximum allowable values (±255 or ±5 V). This is because the unconstrained signal to the valves normally contributes to the larger value of overshoot and lower accuracy; especially when implemented in real-time environment.

In this study, an observer system is required for use in the MPC algorithm, in order to estimate the internal states of the IPA system; especially in the real-time environment experiments. The Luenberger observer is used in this study and can be represented as follows.

$$\begin{aligned}\dot{\hat{x}}(k) &= A\hat{x}(k) + Bu(k) + L\big(y(k) - \hat{y}(k)\big) \\ y(k) &= Cx(k)\end{aligned} \tag{6}$$

where x is the system states, $\hat{x}$ is the estimated states, u is the input variable, y is the actual output, $\hat{y}$ is the estimated output, and L is the observer gain.

The observer system is beneficial, as it estimates the internal states of the IPA system, from measured input and output, to provide system corrections based on error reading. $L(y - \hat{y})$(as shown in Equation 6) is the term used to provide the correction to enhance the IPA system's positioning performance. The observer system used in this study is asymptotically stable, as the matric $A - LC$ has all the eigenvalues inside the unit circle. The identified plant model is also controllable and observable as it complies with the controllability and observability tests (has full row rank and full column rank).

3. RESULTS AND ANALYSIS

This paper proposed a model predictive control (MPC) with observer system, as a strategy to control the intelligent pneumatic actuator (IPA) positioning system. The aim is to control and maintain the IPA's cylinder stroke at a desired position, so that an accurate positioning control of the IPA system can be achieved. Two cases of control strategy were validated (unconstrained and constrained MPC) and both strategies were implemented in simulation and real-time experiments.

3.1. Unconstrained case

Figure 4 shows the performance of the controllerto control and maintain the cylinder stroke position of the IPA system at 100 mm in simulation and real-time experiment. At this time, no load is attached at the end of the cylinder stroke for the purpose of transporting the object. The simulation result indicates that at simulation time 0.3900 s, the stroke strayed about 1.3314 mm from its original position (100 mm). This simulation result was later confirmed in real-time experiment. Result from the experiment show that the cylinder stroke overshoots by more than 70 % from its original position at the beginning of the experiment. It has been demonstrated that overshoot in the system's response is the main factor that restricts accurate positioning control of the pneumatic system from being achieved. This may be due to issues in the system itself, such as air compressibility and leakage, friction, valve dead zone, and uncertainties in the system's parameters. To test the robustness of the controller in real-time experiment, several value of loads (1 kg, 3 kg, 5 kg, and 9 kg) were attached at the end of the cylinder stroke. The performance of the controller to transport the object (load) when the position to be achieved by the stroke is fixed at 100 mm is shown in Figure 5. Meanwhile, Figure 6 shows the performance of the controller when the position to be achieved by the stroke is unfixed and constantly changing. Analyses for both simulation and experiment are summarized in Table 1.

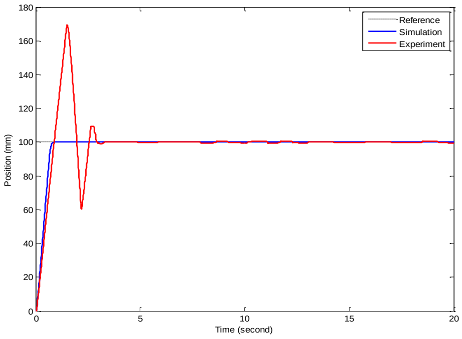

Figure 4. Simulation vs. real-time experiment performances for the unconstrained case (no load attached)

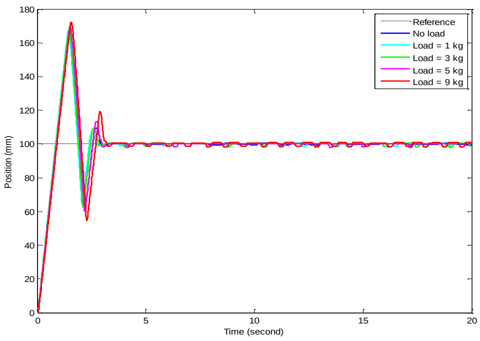

Figure 5. Real-time experiment performances for the unconstrained case (fixed position)

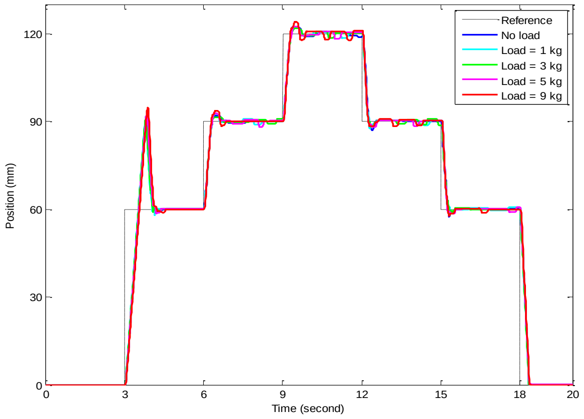

Figure 6. Real-time experiment performances for the unconstrained case (unfixed position)

Table 1. Comparison betweenSimulation and Real-Time Experiments for the Unconstrained Case (Fixed at 100 mm)

	Simulation	Real-time experiment				
Load	No load	No load	1 kg	3 kg	5 kg	9 kg
Rise time ($\boldsymbol{t_r}$)	0.1722 s	0.6658 s	0.6513 s	0.6474 s	0.6727 s	0.6880 s
Settling time ($\boldsymbol{t_s}$)	0.2970 s	2.8827 s	2.7073 s	19.8637 s	17.2385 s	19.6583 s
Overshoot ($\boldsymbol{OS}$)	1.3314 mm	70.1798 mm	66.5967 mm	70.1168 mm	68.6882 mm	70.3715 mm
Steady-state error ($\boldsymbol{e_{ss}}$)	0 mm	0.47 mm	0.11 mm	1.55 mm	0.09 mm	0.95 mm

3.2. Constrained case

As previously described, the constrained case is different to the unconstrained case. In this case, the signal to the valves has been limited to a maximum value that can be accepted by the valves (± 255); compared to the unconstrained case, in which no limitation has been given to the valves. Figure 7 shows the performance of the controller for the constrained case to control and maintain the position of cylinder stroke of the IPA system at 100 mm. Similar to the unconstrained case; no loads are attached at the end of the cylinder stroke when the simulation is performed. From Figure 7, the simulation result indicate that the stroke strayed about 0.0122 mm at the beginning of the simulation, while verification through real-time experiment shows that the resulting overshoot for this case was just 2.0636 mm, compared to 70.1798 mm in the unconstrained case. This proves that the application of constraints in the control strategy successfully reduced the overshoot in the system's response. The performance of the controller when the position to be achieved by the stroke is fixed at 100 mm is shown in Figure 8. Meanwhile, Figure 9 shows the performance of the controller when the position to be achieved by the stroke is unfixed and constantly changing. Both Figure 8 and Figure 9 considered loads in their responses. All findings, for both simulation and experiment, are summarized in Table 2. The addition of constraints in the controller algorithm undeniably caused the controller to be less aggressive; however, the findings (as shown in Table 2) demonstrate that the proposed strategy is still relevant to be used and the response is considered fast enough for a pneumatic system.

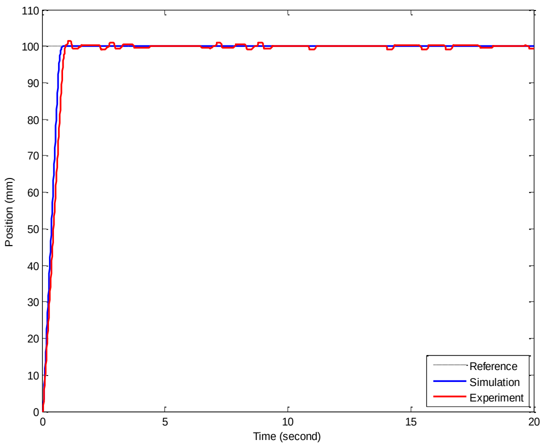

Figure 7. Simulation vs. real-time experiment performances for the constrained case (no load attached)

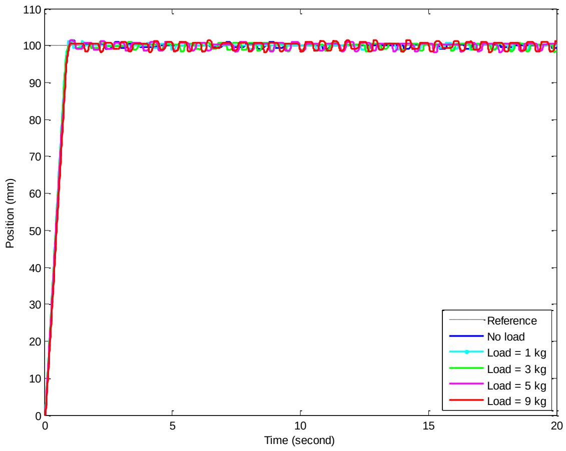

Figure 8. Real-time experiment performances for the constrained case (fixed position)

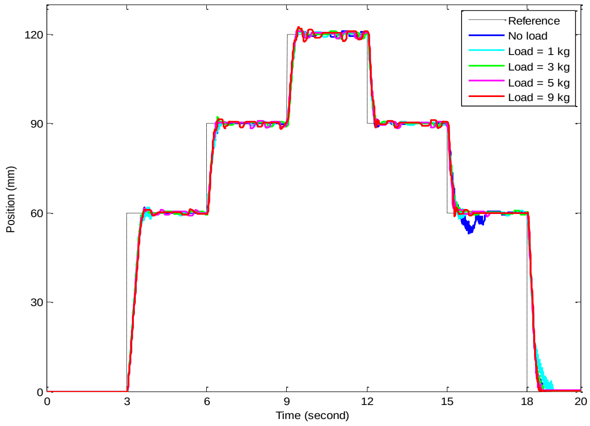

Figure 9. Real-time experiment performances for the constrained case (unfixed position)

Table 2. Comparison between Simulation and Real-Time Experiments for the Constrained Case (Fixed at 100 mm)

	Simulation	Real-time experiment				
Load	No load	No load	1 kg	3 kg	5 kg	9 kg
Rise time (t_r)	0.5330 s	0.6633 s	0.6498 s	0.6457 s	0.6961 s	0.6864 s
Settling time (t_s)	0.7331 s	1.1666 s	0.8496 s	18.7601 s	18.6658 s	19.8968 s
Overshoot (OS)	0.0122 mm	2.0636 mm	1.1383 mm	2.9869 mm	0.8959 mm	0.2667 mm
Steady-state error (e_{ss})	0 mm	0.66 mm	0.15 mm	1.57 mm	0.46 mm	1.23 mm

4. CONCLUSION

This paper presents the modeling and positioning control of an intelligent pneumatic actuator (IPA) system. A system identification technique, using an auto-regressive with exogenous input (ARX) model structure, was used to represent the pneumatic system's behaviour. Meanwhile, model predictive control (MPC) was used as a controller to ensure accurate positioning control of the system. The aim of this paper was to demonstrate the effectiveness of applying constraints on the input signal of the controller algorithm to reduce overshoot in the system response. Simulations and real-time experiments show that constraints on the input signal are very effective at reducing overshoot; especially in a real-time environment. Verification through real-time experiments showed that applying constraints can reduce overshoot by approximately 97.0596 %, 98.2908 %, 95.7401 %, 98.6957 %, and 86.669 % for load = 0 kg, 1 kg, 3 kg, 5 kg, and 9 kg, respectively. Including constraints in the controller algorithm has caused the controller to be less aggressive as it requires more computational effort to optimize the cost function, compared to the unconstrained case.

However, the proposed strategy is still relevant to be used and the response is considered fast enough for a pneumatic system. The steady-state error (e_{ss}) for both cases also within the limit allowed (±2 mm), which is acceptable for control system engineering. Future work investigating the technique to improve the transient response of the proposed control strategy will be considered for the next stage of this study.

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