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Model Reference Adaptive Controller Without Integral (MRACWI) for Position Control of DC Motor

Abstract: Direct Current (DC) motor is an important actuator and has been used extensively in many industries such as for positioning machines and robotic system. Proper position regulation of DC motor is inherently important in industry due to several factors such as requirement for accurate positioning and safety. Therefore, this study focuses on the developments of Model Reference Adaptive Control without Integral (MRACWI) to achieve better positioning regulation of DC motor. Based on the results, it is shown that MRACWI capable to provide robust and precise performance in controlling position of DC motor and produce better performance in terms of settling time, percentage overshoot and mean square error (MSE) as compared with PID controller, standard MRAC and MRAC with sigma modification (MRACSM).

Keywords: DC motor, Position control, ARX model, Model reference adaptive control without Integral (MRACWI), PID controller

1. INTRODUCTION

A positioning system is an important part in industry and one of widely actuator used for positioning system is a Direct Current (DC) motor [1]. The popularity of DC motor comes from its features, such as posses excellent torque-speed characteristics [2], high reliabilities and low costs [3]. Up to now, there are abundance documented work related to the implementation of DC motor in positioning system such as in pick and place robotic arm [4], conveyor system[5, 6] and servo valve [7].

Over the last few decades, development of advanced control strategy for position control of DC motor has received tremendous study towards achieving precise position control intended to full fill industrial demands. This because, the controllers design of position control of DC motor is not straight forwards particularly in achieving fast speed response with minimum overshoot and later maintaining the position accurately. There are several factors that can contribute to the difficulties in providing precise regulation position of DC Motor such as time varying dynamic [8], uncertainties [9], model mismatch [10] and nonlinearities[8, 11]. Besides that, several study [12-15] shown that the implementation of conventional PID controller family in regulating position of DC motor will generated high percentages overshoot. With that, Mamani *et al.* [10] has proposed continuous sliding mode control (SMC) to compensate the effect of payload variations and model mismatch for providing excellent position trajectory of DC motor. On the other hand, Kumar *et al.* [16] apply quadratic controller for DC motor position control to solve the existence of nonlinearities dynamic while Wong *et al.* [17] proposed PI anti windup (SIPIC) for minimize overshoot produced by PI controller during regulating position of DC motor. Other advanced controller found used in improving position control of DC motor are as Model Predictive Controller (MPC) [11], Fuzzy Logic [13] and Artificial Neural Network (ANN) controller [14].

Apart from that, several scholars in [18-21] emphasized the implementation of Model reference adaptive control (MRAC) for improving position control of DC motor. The ability of MRAC to cope with time varying dynamic, unknown process parameter and gives desired response to the reference signal are among the factor that contribute on the implementation of MRAC in improving DC motor position control. However, the implementation of conventional MRAC such in [19, 20] does not guarantee robust tracking performance. The existence of nonlinearities or uncertainties will lead mismatch between the reference output and actual output and caused adaptation gain of MRAC drift away. This in turn can caused MRAC produce high overshoot or even unstable response. For that reason Humaidi *et al.* [9] implement $\mathbf{L_1}$-Adaptive for achieving precise position control of DC motor against uncertainties while Pathak *et al.* [22] replace standard Lyapunov adaptation law of

MRAC with ANFIS to prevent drift away MRAC adaptation gain to improving tracking performance of DC motor position control. In line with these, this study will focus on another robust MRAC design namely MRAC without Integral (MRACWI) towards achieving precise position regulation of DC motor. To evaluate the robustness of MRACWI in regulating position of DC motor, the common nonlinearities exist on the system namely input constraint is initiated on the system along the experiment. Besides that, the performance of MRACWI will be compared with conventional MRAC, MRAC with sigma modification (MRACSM) and PID controller. The comparison would highlight the extent of improvement given by MRACWI in regulating position of DC motor.

The remaining parts of this article are organized as follows. Section 2 will describe the characteristics of DC motor used in this study followed with the interfacing DC motor with Arduino and computer (Matlab). Section 3 will describe the modeling strategy used for modeling the DC motor in this study while Section 4 describe about controller design that are consider in this study. The simulation results and discussion of this study will be presented in Section 5 while Section 6 describes the conclusion of this study.

2. SYSTEM DESCRIPTION

This study is conducted based on DC Gear Motor JGB37 and the specifications of DC motor obtained from the manual are as shown in Table 1.

Table 1. The specification of the DC Gear Motor JGB37.

Parameters	Value
Voltage (V)	12
Current (A)	0.24
Torque (kg/cm)	4.5
Speed (rpm)	166

For collecting the input and output data for modeling purpose, the DC motor has been interfaced with computer via Arduino Uno and the configuration of the interfacing is as shown in Figure 1. Meanwhile Figure 2 shows the complete configuration between Arduino Uno board, IC motor driver (l293D), DC motor and potentiometer. For monitoring, controlling and collecting the input and output data, Matlab software is used. Along the experiment, the input and output data are captured with sampling time 0.01 s.

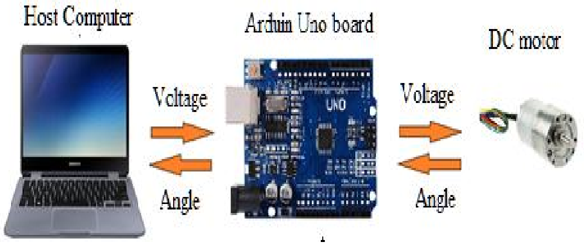


Figure 1. Configuration of system interfacing.

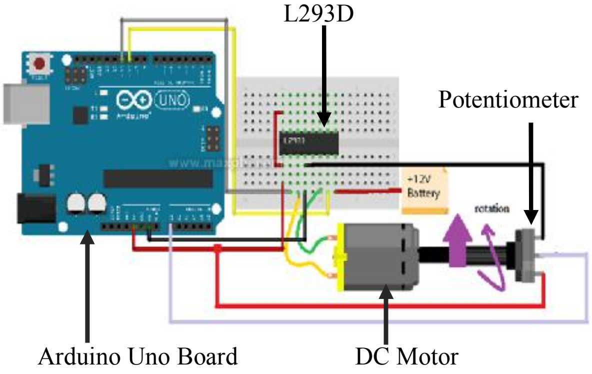


Figure.2. Hardware Setup.

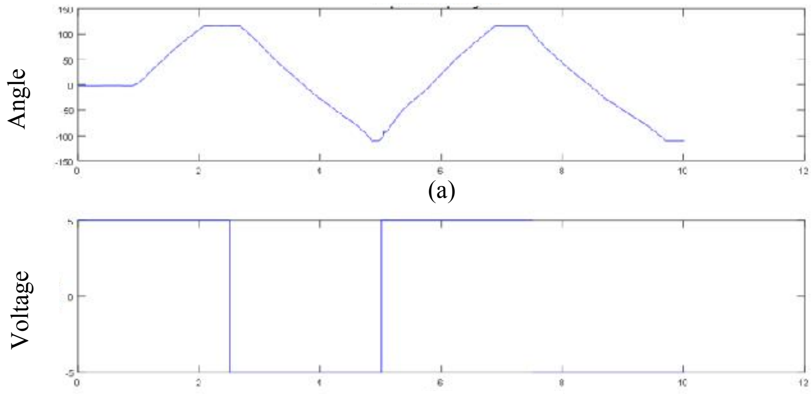
3. MODELING STRATEGY

The Auto-Regressive with Exogenous (ARX) model is chosen in this study for develop the transfer function that describe the relationship between the input voltage and position for the DC motor. To obtain open loop data, a square wave signal with magnitude 5V and -5V is injected to the DC motor via Matlab software and the experiment is carried out for 10 s. The collected open loop experimental data is as shown in Figure 3. Prior used the experimental data for modelling purposed, the data has been divided into two (2) using interlacing technique where even data is for training the model while odd data is for model validation. For developing the model, the following Matlab coding is used;

Model = arx ([Yk Uk],[na, nb, nk])

Where *Yk* and *Uk* represent output and input data respectively while *na, nb* and *nk* indicated for the denominator order, numerator order and time delay respectively for the transfer function. By considering the DC motor is sufficient to be describe with second order model the *na* is set into 2 while *nb* and *nk* is set equal to1.

Three (3) validation tests is considered in this study for validate the model which are best fits, Akaike's final prediction error (FPE) and mean square error (MSE). For best fit, the higher the percentages best fits which is closed to 100% indicated more accurate the developed model while for FPE and MSE, closer value to 0 indicate higher accuracy model replication of the real dynamic.



(a)

(b)

Figure.3. Open loop experimental data: (a) input (b) output data.

4. CONTROLLER DESIGN

This section will describe the entire controller used in this study and it's divided into 5 sub topics. The first subtopic will describe about the PID controller followed with standard MRAC based on Lyapunov theorem. Then it continues with description of MRAC with sigma modification followed with MRAC without integral. Meanwhile, final subtopic will describe about reference model design used in this study.

4.1 PID Controller

In this work parallel PID structure is used and the formula of the controller is as shown below;

$$G_{pid}(s) = \frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

where K_P, T_i and T_d is referred as proportional gain, integral time constant, and derivative time constant T_d respectively. To determine the K_P, T_i and T_d parameter, Ziegler Nichols (ZN) tuning formula is used while the value of process gain K, time delay Θ and time constant τ is estimated based on process reaction curve second methods as described in [23]. From experimental data shown in Figure 2, following PID controller parameter setup is obtained.

Table 2. PID controller parameter.

Controller	Kp	T_i	T_d
PID	0.5373	0.124	0.031

4.2 Model Reference Adaptive Controller (MRAC)

This study focus on Model Reference Adaptive Control (MRAC) based on Lyapunov approach and the design of MRAC is based on following controller output equation;

$$Uc = \theta_1 r - \theta_2 y_p \tag{2}$$

Where θ_1 and θ_2 is referred as adaptation laws for updating the controller and the equation of adaptation law can be obtain through derivation based on Lyapunov theorem while *r* and y_p indicated for desired output and actual output respectively. In this work, adaptation law described in [24] is used for developing MRAC for the DC motor and the equations is as described as follow;

$$\theta_1 = -\gamma_1 \frac{re}{s} \tag{3}$$

$$\theta_2 = \gamma_2 \frac{y_p e}{s} \tag{4}$$

where γ is referred as adaptation gain and the value of $\gamma > 0$ and can be select via try and error approach..

4.3 Model Reference Adaptive Controller with Sigma Modification (MRACSM)

Model reference adaptive control (MRAC) with sigma modification is a popular modifications of MRAC intended to provide robust MRAC design due to existence of nonlinearities or others factor that lead mismatch between actual output and reference model output thus caused the adaptation gain drift away resulted poor or unstable response characteristics. This modification involves additional extra term $-\sigma\theta$ in Equation (3) and Equation (4) and can be written as follow;

$$\theta_1 = -\gamma_1 \frac{re}{s} - \sigma_1 \frac{\theta}{s} \tag{5}$$

$$\theta_2 = \gamma_2 \frac{y_p e}{s} - \sigma_2 \frac{\theta}{s} \tag{6}$$

where γ and σ is referred as adaptation gain and sigma gain and the value of γ and $\sigma > 0$. Similarly with MRAC, an appropriate value of γ and σ can be achieved through try and error approach.

4.4 Model Reference Adaptive Controller without Integral (MRACWI)

This MRAC modifications has been proposed in[25] towards preventing the MRAC from windup phenomenon due to mismatch between reference model and actual model due to existence of input constraint during regulating temperature of glycerin bleaching process. With this modification, the integral term inside the adaptation law is totally removed. For adapting MRAC without integral on position control of DC motor, the adaptation law described in[25, 26] is used and the equations is as described as follow;

$$\theta_1 = -\gamma_1 re \tag{7}$$

$$\theta_2 = \gamma_2 y_p e \tag{8}$$

where γ is referred as adaptation gain and the value of $\gamma > 0$ and can be choose via try and error approach.

4.5 Reference Model

Reference model is an important part in MRAC design since it presents the desired system performance. The design of reference model can be done by selecting desired system performance such as desired settling time or desired system overshoot than followed with selection of desired damping ratio ζ for the system. Based on the selected information, the transfer function of reference model can be obtained through formula described in Equation (9) and Equation (10). In this work, the desired settling time is set at 0.915 s with damping ratio $\zeta = 0.9$. Based on the chosen parameter and by adapting Equation (9) and Equation (10), the resulted reference model transfer function used in this case study is as described in Equation (10)

$$Ts = \frac{4}{\zeta \omega_n} \tag{9}$$

$$G_m(s) = \frac{{\omega_n}^2}{s^2 + 2\zeta\omega_n + {\omega_n}^2} \tag{10}$$

$$G_m(s) = \frac{23.59}{s^2 + 8.74s + 23.59} \tag{11}$$

5. RESULTS AND DISCUSSION

This section is divided into 2 parts. The first part will describe the modeling results of DC motor used for testing the performance of the controller. While, second part will presents all of the controller performance considered in this study

During controller simulation testing, the set point for angular position has been fixed at 90^o while the experiment duration has been set for 10 s with sampling time 0.01 s. In order to observe the robustness of the controller due nonlinearities (input saturation), the input constraint has been set lower than actual constraint for actual system which is 0V - 5V instead of 0V-12V. Meanwhile, the performance of the controller has been evaluate based on 2% band settling time and percentages overshoot for transient analysis. For steady state error analysis, mean square error (MSE) is used, and the corresponding data analysis taken are starting from 4 s up to 10 s. Apart from that, for MRAC family, only the tuning that gives the best performance among the tuning tested is presented in this article while Table 3 shows the tuning parameter that are selected for each of considered MRAC.

Table 3. Adaptation gain and sigma gain tuning for MRAC, MRACSM and MRACWI.

Controller	Adaptation Gain		Sigma Gain	
	$-\gamma$	$+\gamma$	σ_1	σ_2
MRAC	-0.01	+0.01	-	-
MRACSM	-0.06	+0.06	120	120
MRACWI	-0.01	+0.01	-	-

5.1 Modeling

The ARX transfer function obtained that describe the relationship between input voltage and angular position for DC Gear Motor JGB37 is shown in Equation (12) while Table 4 shows the validation results of the model. Based on validation results, the model produced higher percentages best fit which 99.34% and lower FPE and MSE value which is 0.2197 and 0.2153 respectively. Based on this validation results, it can be concluded that, the developed model provide good replication of true dynamic of the system thus sufficient to be used for further study such as for testing the performance of the controller in controlling position of DC motor.

$$G\ (s) = \frac{1.605s + 326.3}{s^2 + 9.85s + 12.6} \tag{12}$$

Table 4. Second Order Model Performance.

Model Validation	**Performance**
Validation data (%)	99.34
Final Prediction Error (FPE)	0.2197
Mean Square Error (MSE)	0.2153

5.2 Controller Performance

The response of all four controllers which are PID controller, standard MRAC, MRACSM and MRACWWI are as presented in Figure 4, Figure 5, Figure 6 and Figure 7 respectively while Figure 8 shows the comparative response for all of the controller. The comparative analysis of the entire controllers is as shown in Table 5.

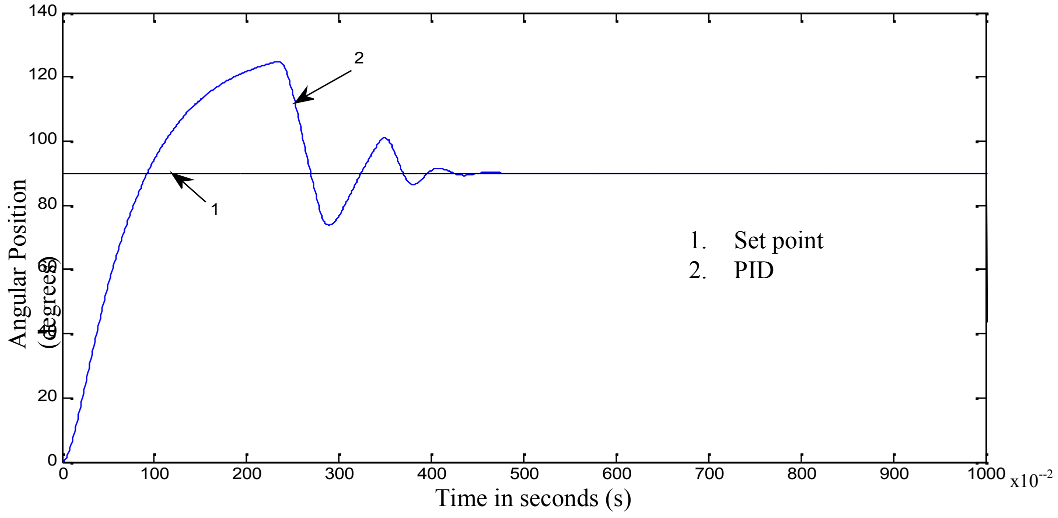


Figure 4. PID controller performance.

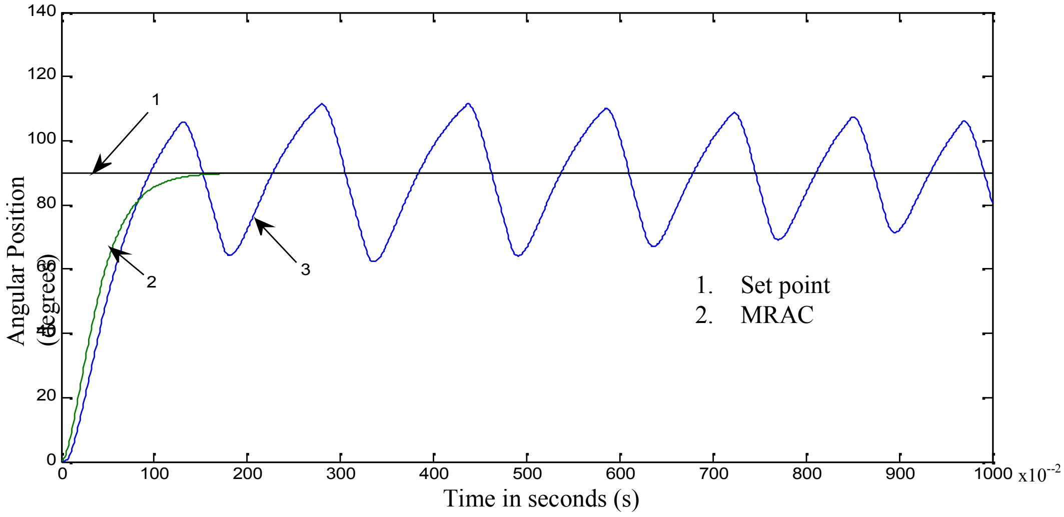


Figure 5. MRAC controller performance.

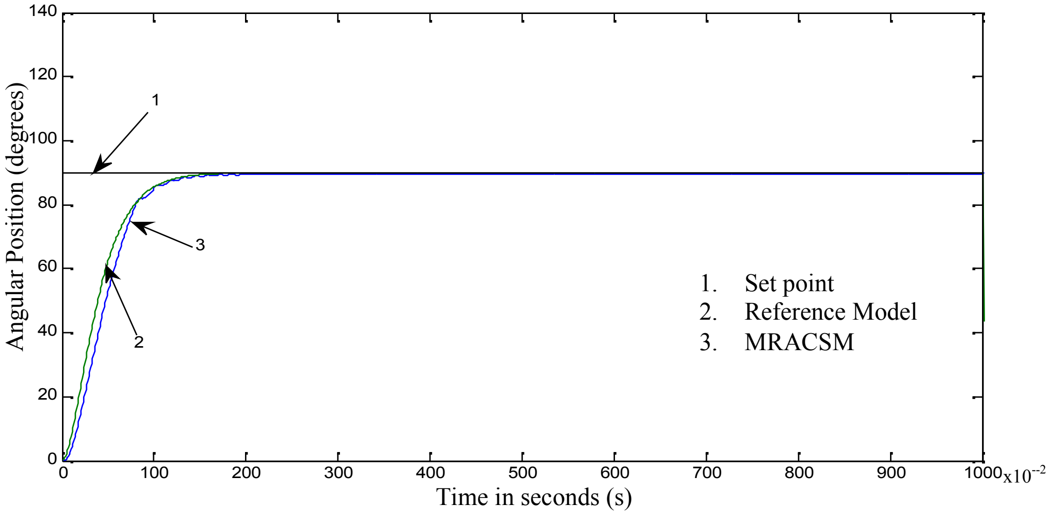


Figure 6. MRACSM controller performance.

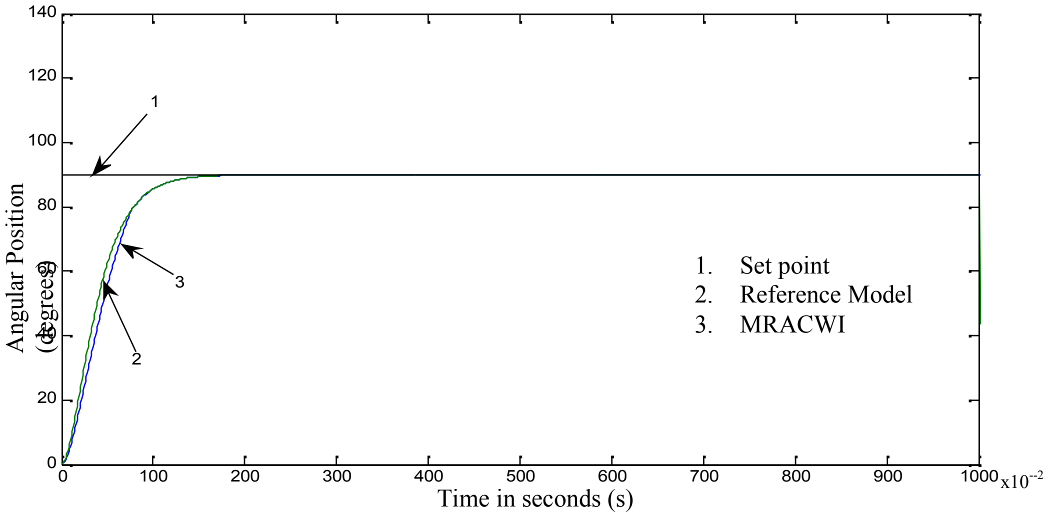


Figure 7. MRACWI controller performance.

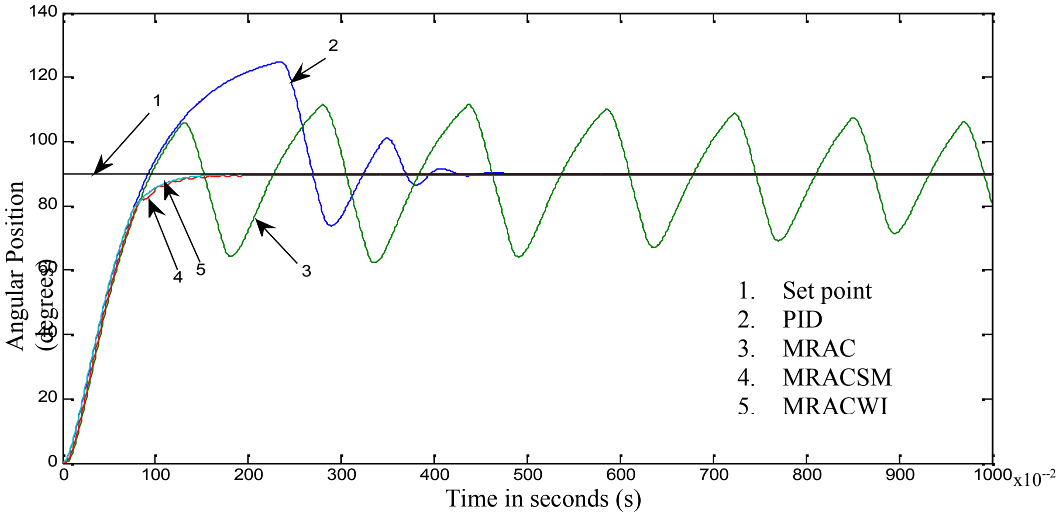


Figure 8. Comparative controller performance.

Table 5. Performance analysis of controllers.

Type of controller	Settling time in seconds (s)	Overshoot (%)	MSE
PID	3.9	39	0.0669
MRAC	NA	24	183
MRACSM	1.3	0	0.184
MRACWI	1.23	0	$4.6\ x10^{-4}$

Based on the results, it is indicated that, conventional MRAC provide poor performance during regulating position of DC motor due to present of input constraint. This controller provides oscillating performance throughout the experiment as shown in Figure 5. Thus, demonstrates that conventional MRAC does not capable to provide robust performance due to existence of input constraint. Besides that, results shown in Figure 4 also point out that, the existence of input constraint caused PID controller to provide large overshoot. This is due to windup phenomenon while regulating the position of DC motor. On the other hand results shown in Figure 6 and Figure 7 clearly imply that both MRACSM and MRACWI are capable to provide robust performance against existence of input constraint during regulating position of DC motor. These controllers are capable to provide excellent trajectory of reference model.

In addition, the comparative analysis shown in Table 5 confirmed that MRACWI provide the fastest response to reach settling time which is at 1.23 s. This is 0.07 s faster than MRACSM and 2.67 s faster than PID controller. However, the results also indicated that conventional MRAC does not reach settling time due to continues oscillation. The highest percentages overshoot is produced by PID controller which is 39%, followed by conventional MRAC that produced 24% overshoot. In contrast, MRACWI and MRACSM produced 0% overshoot. On top of these, the analysis leads to another finding where MRACWI produced the lowest MSE, which is 4.6 x 10^{-4}. This is 0.18354 lower than MSE produced by MRACSM and 0.06644 lower than MSE produced by PID controller.

Based on these results, it can be concluded that MRACWI is capable to provide the positioning control system with a robust controller operations. MRACWI also promote the best performance in terms of precision and accuracy while controlling position of DC motor as compared to PID controller, conventional MRAC and MRACSM due to existence of input constraint. This is due to the facts that MRACWI provide the fastest settling time, lowest value of MSE and its ability to provide stable performance throughout the experiments.

3. CONCLUSION

The aim of this study is to investigate the capability of MRACWI in providing accurate and precise position control of DC motor. The simulation results obtained reveal that MRACWI accommodate accurate and precise position regulation of DC motor. On the other hand, MRACWI also capable to cope with one of the common nonlinearities existed on the system namely input constraint. Whilst considering the input constraint nonlinearities, MRACWI provides better response as compared to PID controller, conventional MRAC and MRACSM. In conjunction with the findings, for the future work, MRACWI will be implemented in real time to validate its capability and robustness during DC motor position control execution.

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