

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

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Abstract: A direct current (DC) motor is an important actuator and has been used extensively in many industries such as for positioning machines and robotic systems. Proper position regulation of DC motor is inherently important in the industry due to several factors such as the requirement for accurate positioning and safety measures. Therefore, this paper focuses on the development of model reference adaptive control without integral (MRACWI) to achieve a better position regulation of DC motor. Based on the results, it is shown that the MRACWI is capable to provide robust and precise performance in controlling the position of DC motor and produce better performance in terms of settling time, percentage overshoot and mean square error as compared with PID controller, standard MRAC and MRAC with sigma modification.

Keywords: ARX model; DC motor; Model reference adaptive control; PID controller; Position control.

1. INTRODUCTION

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

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 fulfil industrial demands. This is because the controller's design of position control of DC motor is not straightforward. 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 a precise position regulation of DC motor such as time varying dynamic [7], uncertainties [8], model mismatch [9] and nonlinearities [7,10]. Besides, several studies [11-14] on DC motor position regulation has shown that the implementation of a conventional PID controller family generated high percentage of overshoot. With that, Mamani et al. [9] have proposed continuous sliding mode control (SMC) to compensate the effect of payload variations and a model mismatch for providing excellent position trajectory of DC motor. On the other hand, Kumar et al. [15] applied quadratic controller for DC motor position control to solve the existence of nonlinearities dynamic while Wong et al. [16] proposed PI anti windup (SIPIC) for minimising overshoot produced by PI controller during regulating the position of DC motor. Other advanced controllers used in improving position control of DC motor are model predictive controller (MPC) [10], fuzzy Logic [12] and artificial neural network (ANN) controller [13].

Apart from that, several researchers in [17-20] emphasised 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 factors that contribute on the implementation of MRAC in improving DC motor position control. However, the implementation of a conventional MRAC such in [18-19] does not guarantee robust tracking performance. The existence of nonlinearities or uncertainties will lead to a mismatch between the reference input and actual output, and caused adaptation gain of MRAC to drift away. This condition can cause MRAC to produce high overshoot or even unstable response. For that reason, Humaidi et al. [8] implemented L_1 -Adaptive to achieve precise position control of DC motor against uncertainties. Meanwhile, Pathak et al. [21] replaced the standard Lyapunov adaptation law of MRAC with ANFIS to prevent MRAC adaptation gain from drifting away whilst improving tracking performance of DC motor position control. This method, however demand computational complexities [22] apart from time required for training and determining parameter [21]. In line with these, this work focuses 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 the position of DC motor, a system's nonlinearity namely input constraint is initiated along the experiment. Besides that, the performance of MRACWI is compared with conventional MRAC, MRAC with sigma modification (MRACSM) and PID controllers. The MRACSM has been chosen as one of the benchmarks in this study since this robust MRAC design has popularly been used for handling the presence of nonlinearities and uncertainties such presented in [23-25].

The remaining parts of this article are organised as follows. Section 2 describes the characteristics of DC motor used in this study followed with the interfacing DC motor with Arduino and computer (MATLAB). Section 3 describes the modeling strategy used for modelling the DC motor, and Section 4 provides descriptions on the controller design that is considered in this study. The simulation results and discussion of this work are presented in Section 5, while the findings are concluded in Section 6.

2. SYSTEM DESCRIPTION

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

The input and output data has been collected for modelling purpose by interfacing the DC motor to the computer via Arduino Uno. The general configuration of the interfacing is as shown in Figure 1. Figure 2 shows the complete configuration between the 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 a sampling time of 0.01 secs.

3. MODELLING STRATEGY

The transfer function that describes the relationship between the input voltage and position for the DC motor is developed using auto-regressive with exogenous (ARX) model. To obtain open loop data, a square wave signal with magnitude of 5 V and -5 V is injected into the DC motor via MATLAB software set up and the experiment is carried out for 10 secs. The corresponding open loop experimental data collected is as shown in Figure 3. Prior modelling stage, the data has been divided

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

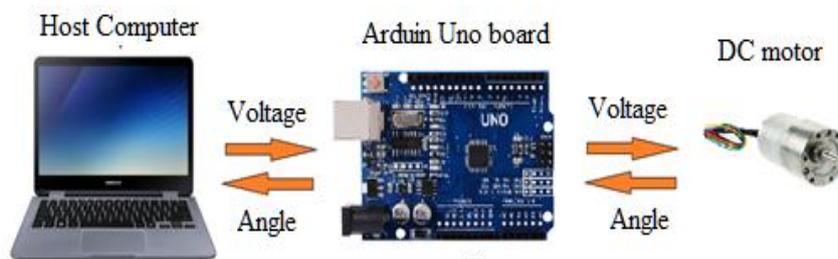


Figure 1. Configuration of system interfacing

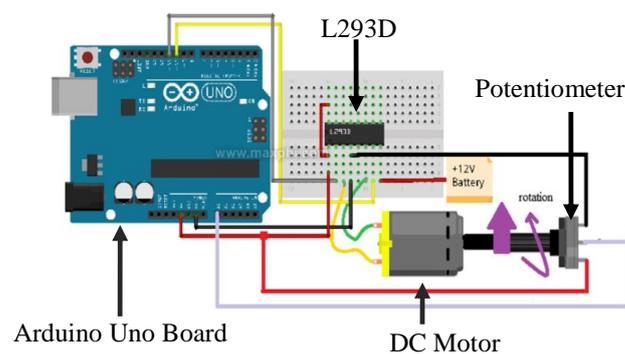


Figure 2. Hardware setup

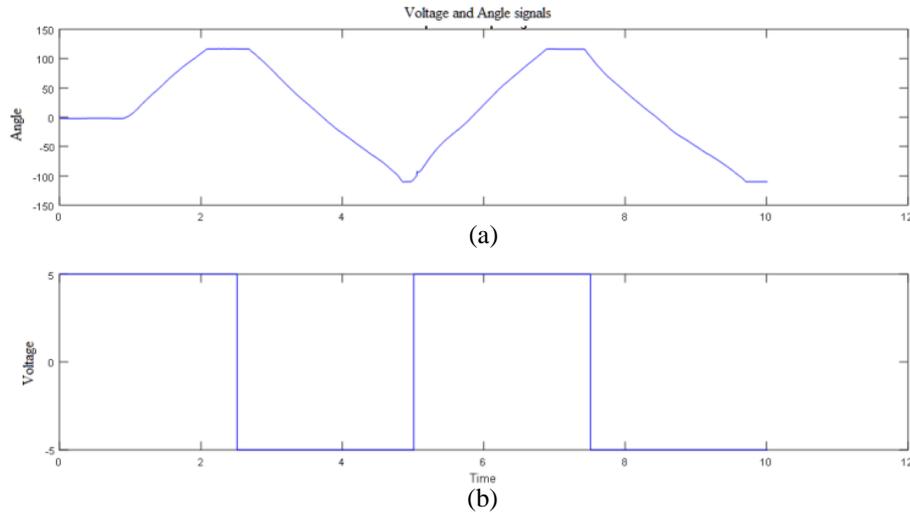


Figure 3. Open loop experimental data: (a) Output data (b) Input data

into two groups using the interlacing technique. Even data set is allocated for training the model while odd data set is reserved for model validation. Subsequently, the following MATLAB coding is used to develop the model:

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

where Yk and Uk represent output and input data respectively. Parameters na , nb and nk indicate the transfer function's denominator order, numerator order and time delay separately. It is sufficient to describe the DC motor with a second order model. Thus, parameter na is set into 2 while nb and nk are set to 1.

To validate the model, three different validation tests are considered in this study. Those are best fits, Akaike's final prediction error (FPE) and mean square error (MSE). Through the best fit technique, model accuracy can be reflected via the resulting best fits percentage. The developed model would have higher accuracy as its best fit reading getting closer to 100%. However, for the FPE and MSE techniques, higher accuracy is being portrayed as the test value getting closer to 0. High model accuracy is necessary to guarantee the capability of the model to replicate the real system's dynamic.

4. CONTROLLER DESIGN

This section describes the entire controller used in this study and it is divided into five subsections. These subsections describe the PID controller, the standard MRAC based on Lyapunov theorem, the MRAC with sigma modification, the proposed MRAC without integral and the reference model used in this study.

4.1 PID Controller

In this work a parallel PID structure is used and the block diagram of PID controller is as shown in Figure 4. The formula of the controller is given as:

$$G_{pid}(s) = \frac{U(s)}{E(s)} = \left(K_p + \frac{K_i}{s} + K_d s \right) \quad (1)$$

where K_p , T_i and T_d are proportional gain, integral time constant, and derivative time constant respectively. To determine the K_p , T_i and T_d parameters, Ziegler Nichols (ZN) tuning formula is used. The values of process gain K , time delay θ and time constant τ are estimated based on process reaction curve second methods as described in [26]. From the experimental data shown in Figure 3, the PID controller parameter setup is obtained as in Table 2.

Table 2. PID controller parameter

Controller	K_p	T_i	T_d
PID	0.5373	0.124	0.031

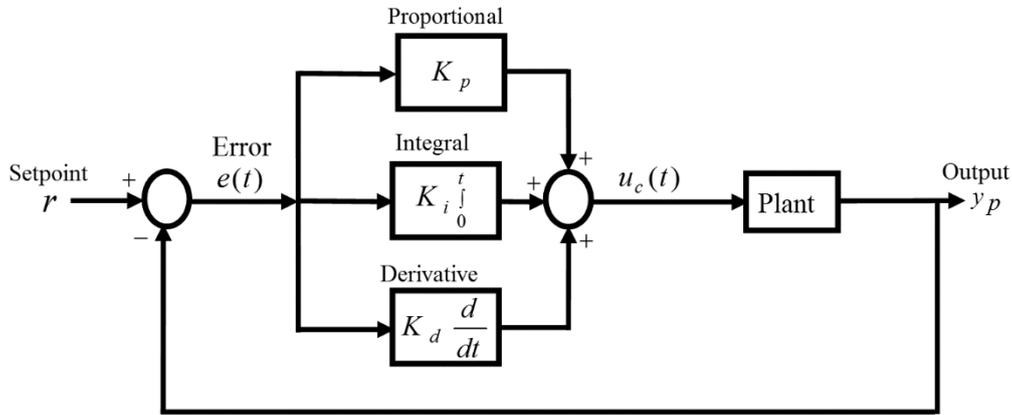


Figure 4. PID structure

4.2 Model Reference Adaptive Controller (MRAC)

This work focuses on the model reference adaptive control (MRAC) based on Lyapunov approach and the design of MRAC is based on the controller output equation:

$$U_c = \theta_1 r - \theta_2 y_p \quad (2)$$

where θ_1 and θ_2 are the adaptation laws for updating the controller and the equation of adaptation law can be obtained through derivation based on Lyapunov theorem. The parameters, r and y_p are dedicated for desired and actual outputs respectively. In this work, the adaptation law described in [27] is used for developing MRAC with the following equations:

$$\theta_1 = -\gamma_1 \frac{r e}{s} \quad (3)$$

$$\theta_2 = \gamma_2 \frac{y_p e}{s} \quad (4)$$

e is the error between the actual output and reference model ($e = y_p - y_m$). Parameter γ is the adaptation gain with $\gamma > 0$ and can be selected via trial and error approach. The block diagram for MRAC is shown in Figure 5.

4.3 Model Reference Adaptive Controller with Sigma Modification (MRACSM)

MRAC with sigma modification (MRACSM) is a popular modification of MRAC. The modification is intended to provide a robust MRAC design due to the existence of nonlinearities or other factors that lead to a mismatch between actual output and reference model output. The deviation between the actual and reference model outputs will cause the adaptation gain to drift away. This condition would produce a poor or unstable response characteristic. The modification involves another extra term $-\sigma\theta$ in Equations (3) and (4). The new equation can be written as:

$$\theta_1 = -\gamma_1 \frac{r e}{s} - \sigma_1 \frac{\theta_1}{s} \quad (5)$$

$$\theta_2 = \gamma_2 \frac{y_p e}{s} - \sigma_2 \frac{\theta_2}{s} \quad (6)$$

where γ and σ are the adaptation and sigma gains respectively. The values are set according to the condition, γ and $\sigma > 0$. Similar with MRAC, appropriate values of γ and σ can be achieved through trial and error approach. A block diagram for MRACSM is as shown in Figure 6.

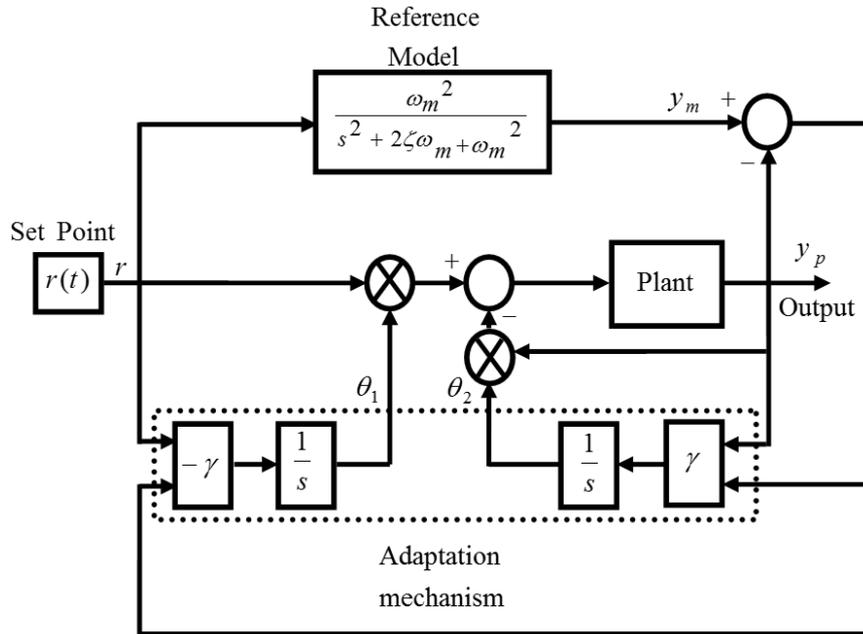


Figure 5. Block diagram for MRAC

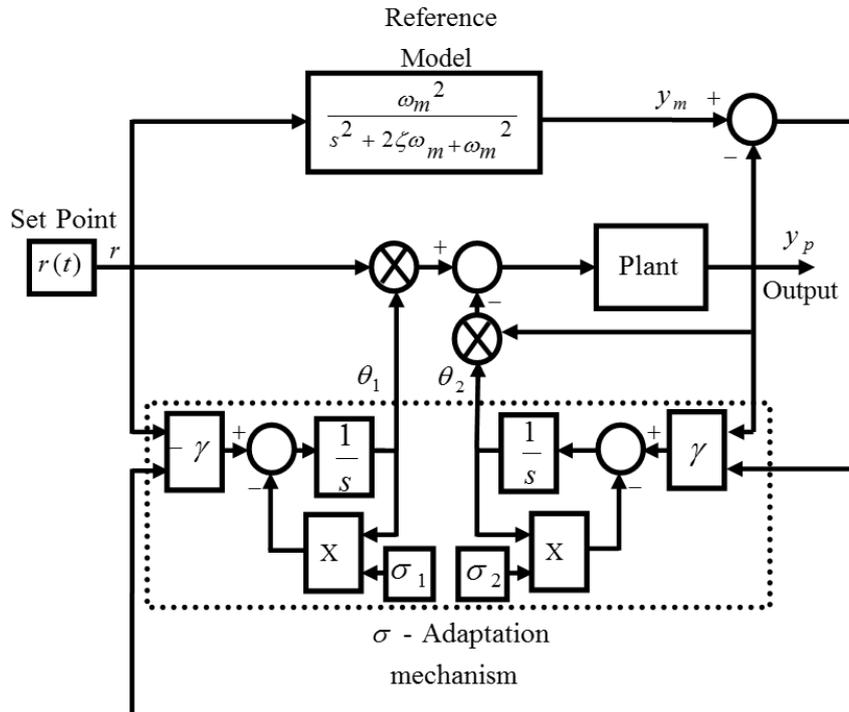


Figure 6. Block diagram for MRACSM

4.4 Model Reference Adaptive Controller without Integral (MRACWI)

This MRAC modification has been proposed in [28] towards preventing the MRAC from windup phenomenon. This phenomenon would occur due to the mismatch between the reference and actual models that is driven by the existence of input constraint during temperature regulation of glycerin bleaching process. With this modification, the integral term inside the adaptation law is totally removed. To implement MRAC without integral on position control of DC motor, the adaptation law described in [28-29] is used as:

$$\theta_1 = -\gamma_1 r e \tag{7}$$

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

where γ is the adaptation gain with $\gamma > 0$ and can be chosen via the trial and error approach. A block diagram for MRACWI is as given by Figure 7.

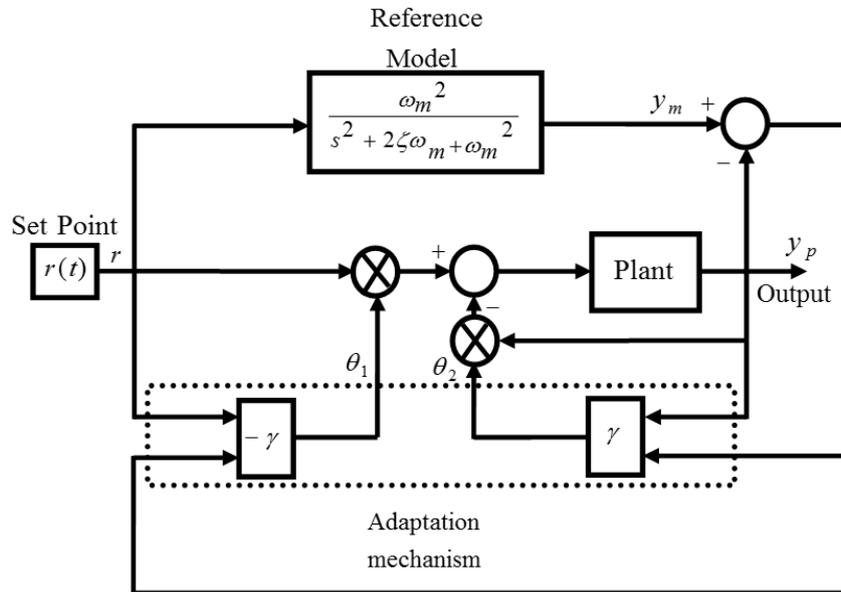


Figure 7. Block diagram for MRACWI

4.5 Reference Model

The reference model is an important part of MRAC design since it represents the desired system performance. The design of the reference model can be done by selecting the desired system performance involving several parameters such as desired settling time, overshoot and damping ratio, ζ . Based on the selected information, the transfer function of the reference model can be obtained through formula described in Equations (9) and (10). In this work, the desired settling time is set to 0.915 secs with damping ratio $\zeta = 0.9$. Based on the chosen parameter and by adapting Equations (9) and (10), the resulted reference model transfer function used in this work can be obtained as in Equation (11).

$$T_s = \frac{4}{\zeta\omega_n} \quad (9)$$

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

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

5. RESULTS AND DISCUSSION

This section is divided into two parts. The first part describes the modelling results of DC motor that is used to test the performance of the controller. While the second part presents all of the controller performance considered in this work.

During controller simulation tests, the set point for the angular position is fixed to 90° while the experimental duration has been set to 10 secs with a sampling time of 0.01 secs. In order to observe the robustness of the controller towards nonlinearities (input saturation), the input constraint has been set to a lower range than the actual system's constraint which is 0 V - 5 V instead of 0 V - 12 V to intensify the effect of nonlinearities. Meanwhile, the performance of the controller has been evaluated based on 2% band settling time and percentages overshoot for transient analysis. For the steady state error analysis, MSE is calculated between 4 secs - 10 secs. Apart from that, among all of the tuning combinations tested for MRAC cluster, only tuning that gives the best performance is presented in this paper. Table 3 shows the tuning parameters that are selected for each of MRAC considered.

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 Modelling

The transfer function that describes the relationship between the input voltage and angular position for DC Gear Motor JGB37, as expressed by ARX, is shown in Equation (12). In addition, Table 4 shows the validation results of the model. It is shown that the model developed produced a high percentage best fit, which is 99.34%, and low final prediction error (FPE) and MSE values, which are 0.2197 and 0.2153 respectively. It can be concluded that the developed model provides a good replication of the true system's dynamic. Thus this model is sufficient to be used for further investigating purpose, such as for testing the performance of the controller in controlling the 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
Best Fit	99.34 %
Final Prediction Error (FPE)	0.2197
Mean Square Error (MSE)	0.2153

5.2 Controller Performance

The responses of all four controllers (PID controller, standard MRAC, MRACSM and MRACWWI) are presented in Figures 8-11 respectively while Figure 12 shows the comparative responses for all of the controllers. The comparative analysis of the entire controllers is shown in Table 5.

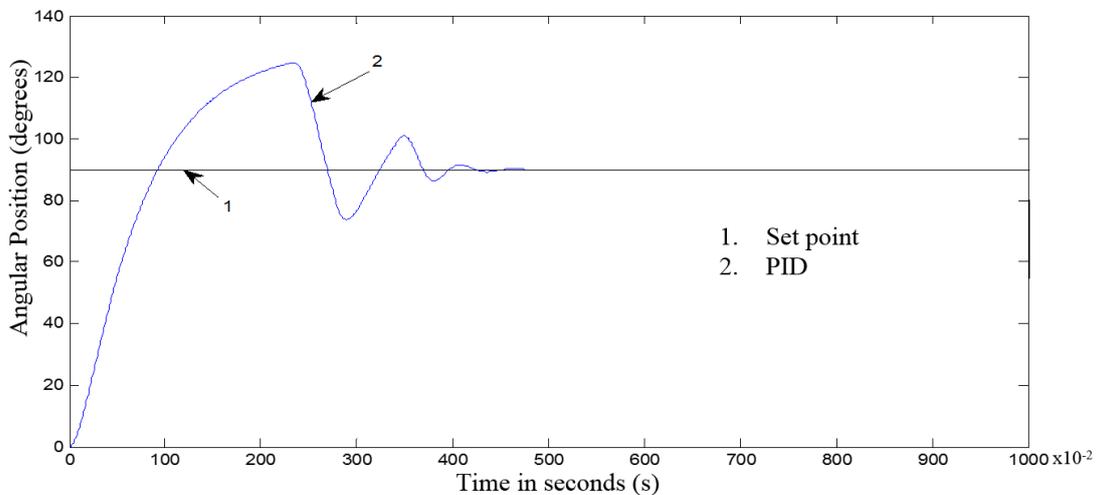


Figure 8. PID controller performance

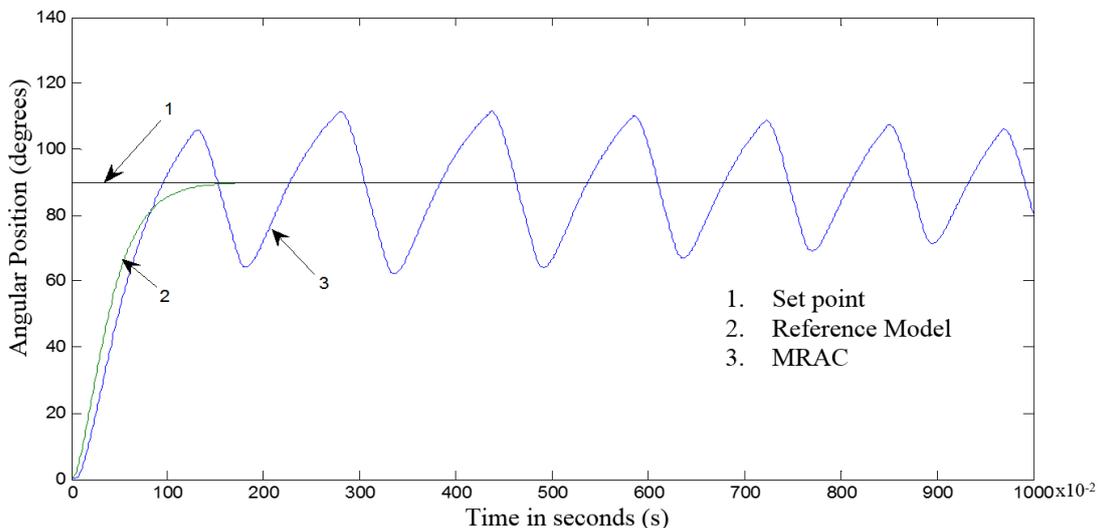


Figure 9. MRAC controller performance

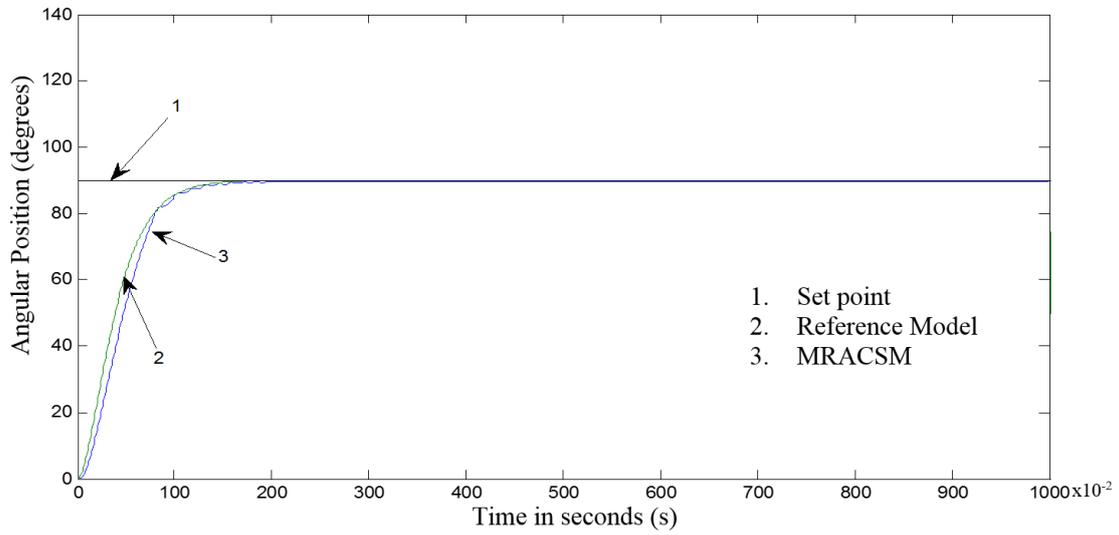


Figure 10. MRACSM controller performance

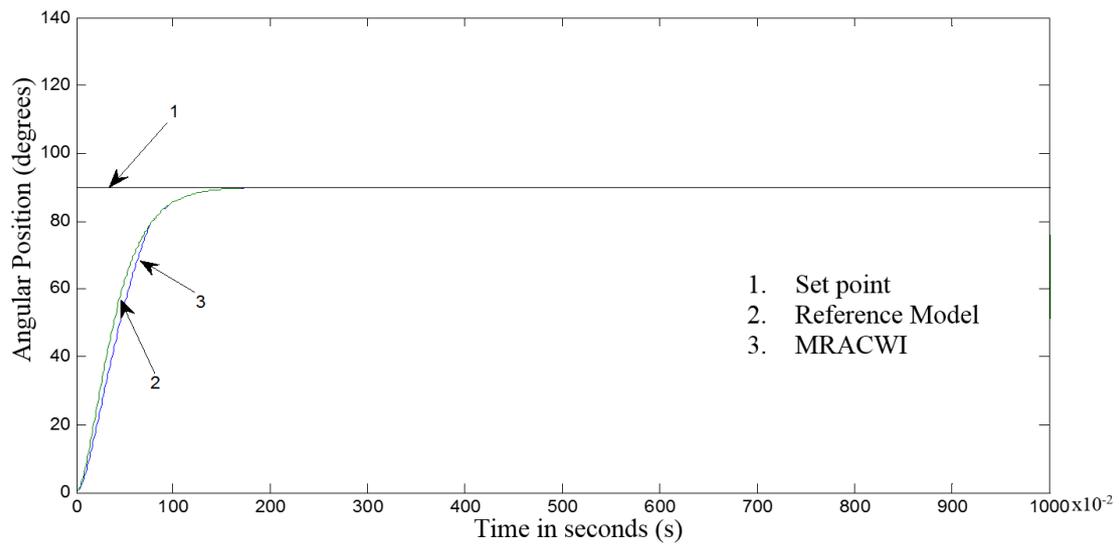


Figure 11. MRACWI controller performance

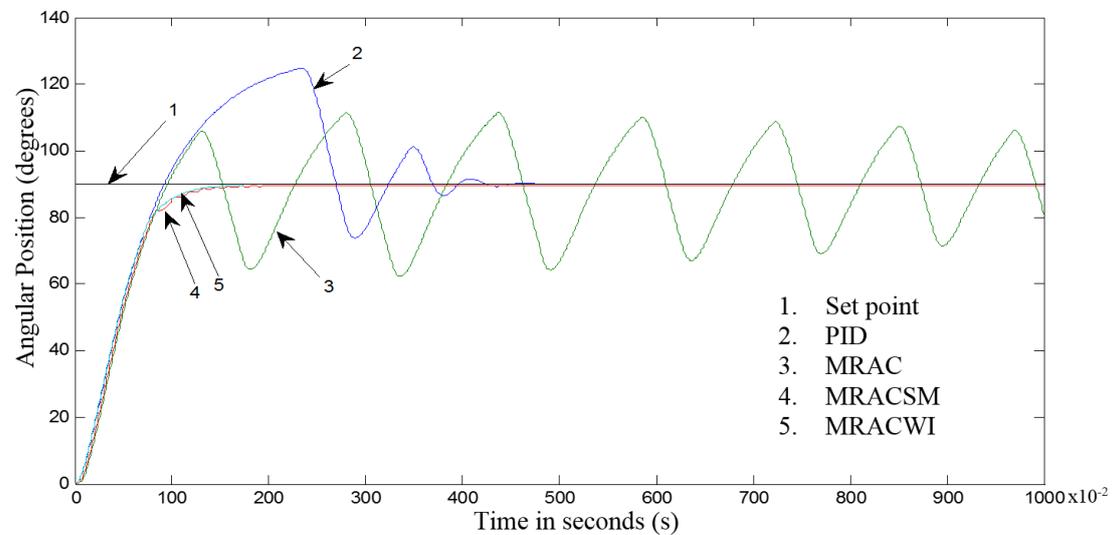


Figure 12. Comparative controller performance

Table 5. Performance analysis of controllers

Type of controller	Settling time in seconds (secs)	Overshoot (%)	MSE
PID	3.9	39	0.0669
MRAC	-	24	183
MRACSM	1.3	0.02	0.184
MRACWI	1.23	0.13	4.6×10^{-4}

The results indicated that with the presence of input constraint, conventional MRAC provides poor performance during regulating the position of DC motor. This controller produces oscillating performance throughout the experiment as shown in Figure 9. This demonstrates that the conventional MRAC is not capable to provide robust performance when input constraint exists. Besides that, results shown in Figure 8 also point out that, the existence of input constraint caused the PID controller to provide large overshoot. This is due to the windup phenomenon that takes place while regulating the position of DC motor. On the other hand, results in Figures 10 and 11 clearly imply that both MRACSM and MRACWI are capable to provide robust performance, against the existence of input constraint during regulating the position of DC motor. These controllers are capable to provide an excellent trajectory of the reference model.

The comparative analysis provided in Table 5 confirmed that MRACWI promotes the fastest response with a settling time of 1.23 secs. This is 0.07 secs faster than the MRACSM and 2.67 secs faster than the PID controller. In addition, the results indicated that the conventional MRAC does not reach settling time due to continuous 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 0.13% and 0.02% overshoot respectively. The percentage of overshoot produced by MRACWI is slightly higher than MRACSM. This is due to the characteristics of reference model response itself which possess 0.15% overshoot. However, when the output response is compared to the reference model, MRACWI provide overshoot that is closer to the reference model response overshoot as compared with MRACSM. This indicates that MRACWI provides better tracking capability, to mimic the reference model, as compared with MRACSM in term of percentages overshoot. On top of these, the analysis leads to another finding where MRACWI produced the lowest MSE, which is 4.6×10^{-4} . This is 0.18354 lower than the MSE value produced by MRACSM and 0.06644 lower than the MSE produced by the PID controller.

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

6. CONCLUSION

The aim of this study is to investigate the capability of MRACWI in providing accurate and precise position control of DC motor. To evaluate the performance of MRACWI, the controller has been tested on the DC Gear Motor JGB37. The simulation results obtained reveal that MRACWI accommodates 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 a better response as compared to PID controller, conventional MRAC and MRACSM. This indicates that MRACWI controller can be recommended as one of the candidates that could be used for precise position regulation of DC motor. 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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