ROBUST ADAPTIVE SPEED CONTROL FOR THE DC MOTOR BASED ON A MODIFIED MRAC

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Resume

The aim of this research was to develop a high performance adaptive control strategy based on the model reference adaptive control (MRAC) approach, using the MIT (Massachusetts Institute of Technology) law rule as an adjustment mechanism to control the speed of a DC motor. In this work, we propose a modified model reference adaptive control (MRAC) to exploit the advantages of adaptive control within the classical feedback loop. This new control strategy is a hybrid between the classical control loop and MRAC, designed specifically for the control of a DC motor system. The modified MRAC demonstrates remarkable robustness and superior control performance, particularly in terms of overshoot percentage, settling time, rise time and disturbance rejection. The effectiveness of the proposed control strategy was evaluated with the use of various reference signals.

Available online: https://doi.org/10.26552/com.C.2024.055

Article info

Received 28 June 2024
Accepted 26 August 2024
Online 19 September 2024

Keywords:

model reference adaptive control (MRAC)
DC motor
MIT rule
adaptive control
modified MRAC

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Direct current (DC) motors are electrical machines that convert the DC energy into mechanical energy [1-2]. The speed of a DC motor can be set over a large range. They have excellent control characteristics, such as ease of control and high performance. The fact that the DC motors are simpler to control than AC motors is a major reason for their wide application. In addition, the DC motor drive circuits are both simple and cost-effective compared to AC motors. The DC variable speed drives have made their mark in variable speed applications, due to their simplicity of design. DC motors are often used in industrial applications requiring speed and position control, such as electric trains, winding machines, winches and robot arms, as a result of their very good speed characteristics [3-4]. The DC motors have certain disadvantages, such as the need for periodic maintenance caused by contact between brush and commutator, and they cannot be used in all environments, as well.

The DC motors are widely used in industry. There are several ways to control the speed of these motors, by varying the armature resistance, the field resistance or the armature voltage, depending on the motor structure. For DC motors, the most effective method is to vary the armature voltage, as varying the armature resistance and field resistance increases losses. There are several methods for varying armature voltage, which can be divided into two broad categories: classical methods, such as the use of a PID controller, and intelligent methods, such as neural networks, genetic algorithms and fuzzy control [5-6]. Sensitivity to system uncertainty is a challenge for the commonly used PID controller. Faced with time-varying system parameters and external disturbances, the control performance of the traditional PID method degrades considerably and may even fail. However, the use of a hybrid PID controller with different methods of setting, the PID controller values is the most common method for controlling a DC motor [3, 7]. The authors designed

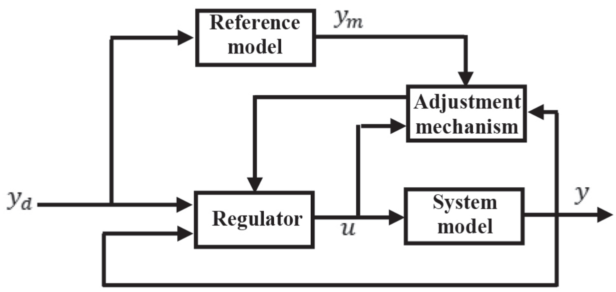


Figure 1 *Schematic block diagram of the MRAC*

an adaptive PID controller for motor speed control and adopted the gradient descent method for on-line control gain adjustment. When the motor parameters change, the PID parameters are automatically adjusted to the optimum value [8-9]. Adapting, the PID parameters using optimization methods can result in high energy consumption. For this reason, researchers are looking to design a controller that is easy to calculate and robust in the face of uncertainties, such as variations in motor parameters and loads.

For systems that are partially unknown or whose parameters vary, adaptive control has proved to be an effective control solution. In this context, MRAC has become very attractive due to its algorithmic simplicity, easy implementation, and the fact that it requires neither identifiers nor observers in the control loop [9-11]. However, these algorithms are limited in noisy or disturbed environments, which can make them inefficient or uncompetitive. Unfortunately, very few industrial control processes are free from these practical problems, which can adversely affect product quality and process performance.

In this article, we present a solution based on modified robust adaptive control, designed for applications with an unknown or changing model over time and circumstances. This solution uses the fundamental stability property and exploits the MIT law rule as a function of an adaptation mechanism [11-12]. This is achieved by calculating and constructing a control vector, also known as a regression vector, to satisfy the desired condition of "almost ideal tracking" taking into account parametric changes in the model. This approach guarantees the robust stability of the nonlinear adaptive controller [10, 13].

The main contribution of this work is to improve the robustness of the adaptive approach by implementing a hybrid control strategy that combines model reference adaptive control (MRAC) with classic state feedback action. The effectiveness of the proposed MRAC controller, and its advantages over other algorithms, were clearly demonstrated through comparative analysis of transient responses. The results are illustrated with a simulation example of a DC motor model using different reference curves.

This paper is structured as follows: In section 2 presents the definitions and theory of MRAC. Section 3 the mathematical modeling of a DC motor is formulated and introduces the principles of modified adaptive control based on the concept, then the main results of modified MRAC are presented in section 4.

2 Model reference adaptive control (MRAC)

The MRAC is a control system that adapts to process variations. Its aim is to automatically make real-time adjustments in the control loop to achieve or maintain a specified level of performance, even as the parameters of the controlled process change. This usually means minimizing the deviation between the reference and actual performance [14-15]. Figure 1 shows a diagram illustrating the MRAC approach.

The parameter adjustment mechanism can be achieved in two ways: by the gradient method or by applying the stability theory [11, 15]. The main challenge of MRAC is to define an adjustment mechanism that stabilizes the system, while reducing the error to zero, which is not a simple task. In the original MRAC, the parameter adjustment mechanism, known as the MIT rule, was used.

The MIT rule is the original approach to MRAC, so named because it was developed at the MIT Instrumentation Laboratory. To illustrate the MIT rule [11, 16], consider a closed-loop system where the controller has a vector of adjustable parameters, θ. The desired system response is defined by the output y_m of the reference model. We denote by e the error between the output y of the closed loop and that of the reference model y_m. The parameters are adjusted to minimize a cost function J defined by Equation (1) [11, 17]:

$$J(\theta) = \frac{1}{2}e^2 . \tag{1}$$

Therefore, to minimize J, one must change the parameters in the direction of the negative gradient of J, i.e.:

$$\frac{d\theta}{dt} = -\gamma\frac{\delta J}{\delta\theta} = -\gamma e\frac{\delta e}{\delta\theta} . \tag{2}$$

It is assumed that

$$\frac{d\theta}{dt} = \gamma e\varphi , \tag{3}$$

where $\varphi = -\frac{\delta e}{\delta \theta}$ is the regression (or measures) vector and γ is the adaptation gain.

Equation (2) is the famous MIT rule. The influence of the adjustable parameters on the error is expressed by the partial derivative $\frac{\delta e}{\delta \theta}$, known as the sensitivity derivative of the system. Assuming that the variation of the parameters is slower than the other variables in the system, the derivative $\frac{\delta e}{\delta \theta}$ can be evaluated by considering θ to be constant, as illustrated in Figure 2.

The control problem based on the reference model can be described as follows: $G_m(s)$ is the transfer function of the reference model that defines the desired performance. $G_{CL}(s, \theta)$ represents the transfer function of the closed-loop process, where θ is the vector of adjustable parameters and y_d is the reference control signal, using a feedforward controller defined by Equation (4) as input of the system model.

$$u = \theta y_d \,. \tag{4}$$

To set an adaptation feedforward gain, assuming that the process is linear, with the transfer function, $k_1G(s)$, where $G(s)$ is known and k_1 is an unknown parameter. The design problem is to find a feedforward controller that gives a system with the transfer function $k_0G_m(s)$, where k_0 is a given constant, and the feedforward controller is given by:

$$u = \left(-\frac{\gamma}{s}\right) y_m e y_d \,. \tag{5}$$

3 Proposed model reference adaptive control (MRAC) controller

3.1 Mathematical model of the DC motor

DC motors are electrical machines that convert electrical energy into mechanical energy. In accordance with Faraday's law, an electric motor can function both as a motor and a generator, when the appropriate conditions are met [2, 18-19]. Figure 3 shows a DC motor model.

According to [1, 20-21], the open loop transfer function of a DC motor (for T_L = 0 N . m) is given by:

$$G_{DCM}(s) = \frac{K_m}{(L_a s + R_a)(Js + f) + K_b K_m} \,. \tag{6}$$

Substituting the DC motor parameter values into

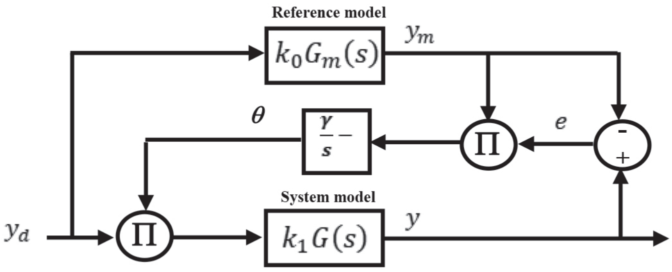


Figure 2 *Scheme of the classic MRAC algorithm*

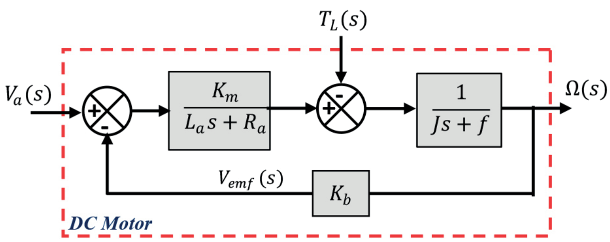


Figure 3 *DC Motor model*

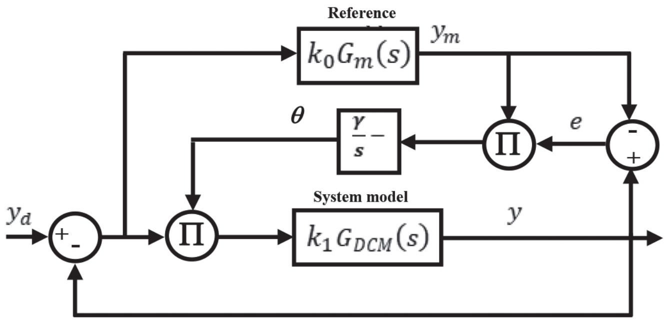


Figure 4 *Scheme of the proposed MRAC algorithm*

Equation (6) yields the following open loop transfer function:

$$G_{DCM}(s) = \frac{\Omega(s)}{V_a(s)} = \frac{15}{1.08s^2 + 6.1s + 1.63}. \tag{7}$$

The DC motor parameters are shown in Appendix (Table A).

3.2 Proposed MRAC controller

In this work, we propose a modification of the adaptive control scheme (Figure 2). The aim of this modification is to achieve a hybridization between the classical state feedback action and the Model Reference Adaptive Control (MRAC) action. Figure 4 shows the Modified MRAC of DC motor, where, k_1, k_0 and γ are constants to be defined. The first step in the conception of the adaptive control of a DC motor is to choose the reference model.

According to Figure 4, Equation (5) becomes:

$$u = \left(-\frac{\gamma}{s}\right) y_m e (y_d - y). \tag{8}$$

By distributing Equation (8) we obtain the equation below:

$$u = \left(-\frac{\gamma}{s}\right) y_m e y_d - \left(-\frac{\gamma}{s}\right) y_m e y. \tag{9}$$

Furthermore, we note that Equation (9) is composed of two parts, the first representing the classical MRAC control, the second takes the form of a high-gain control [22], so that it tends towards zero when the system reaches permanent state and the system response stabilizes.

The DC motor is modelled in the form of the second-order transfer function Equation (7). Equation (10) shows the second order transfer function:

$$TF(s) = \frac{k}{\left(\frac{s}{\omega_n}\right)^2 + 2\xi \frac{s}{\omega_n} + 1} \tag{10}$$

By writing Equation (7) in its canonical form Equation (10)), we obtain:

$$G_{DCM}(s) = \frac{9.2025}{\left(\frac{s}{1.2285}\right)^2 + 2(2.2987)\frac{s}{1.2285}s + 1} \tag{11}$$

and then we deduce the transfer function parameters of the DC motor as follows:

$k = 9.2025, \omega_n = 1.2285$ and $\xi = 2.2987$.

Figure 5 shows the indicial response of the open-loop DC motor transfer function. It can be observed that the response is very slow, with a settling time of 14.1039 seconds and a static error of 9.1981 p.u. (the parameters of this response are summarized in Table 1). To effectively control the DC motor, it is necessary to select the second-order transfer function as a reference model, to simulate the desired motor response.

The chosen reference model is represented by the transfer function of Equation (12), with the following parameters, selected to guarantee a very fast, overshoot-free response for the DC motor.

$k = 1, \omega_n = 1500$ and $\xi = 1$,

$$G_m(s) = \frac{1}{(4.444 \cdot 10^{-7})s^2 + (1.333 \cdot 10^{-3})s + 1}. \tag{12}$$

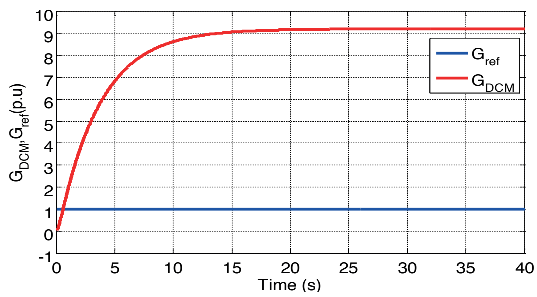


***Figure 5** Indicial response of the DC motor transfer function*

***Table 1** Step Response characteristics of a DC motor's transfer function*

Criteria	Value
RiseTime	7.8262
SettlingTime	14.1039
SettlingMin	8.3104
SettlingMax	9.1981
Overshoot	0
Undershoot	0
Peak	9.1981
PeakTime	27.4446

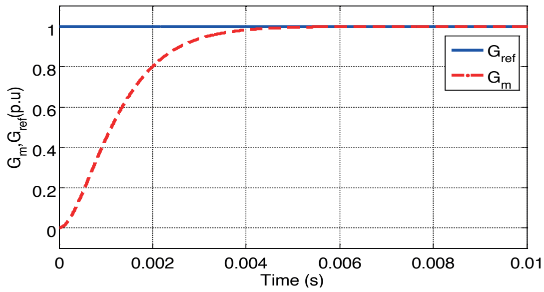


Figure 6 *Indicial response of the reference model transfer function*

Table 2 *Step Response characteristics of the reference model transfer function*

Criteria	Value
RiseTime	0.0022
SettlingTime	0.0039
SettlingMin	0.9024
SettlingMax	1.0000
Overshoot	0
Undershoot	0
Peak	1.0000
PeakTime	0.0091

Table 3 *Comparative transient response results*

Controller type	D [%]	T_s [s]	T_r [s]
MRAC [Proposed]	0.0000	0.002	0.0012
[1]	0.0000	0.0339	0.0214
[21]	0.0000	0.0780	0.0429
[23]	0.0000	0.0616	0.0376

Figure 6 shows the indicial response of the transfer function of the reference model. The parameters associated with this response are summarized in Table 2.

4 Simulation results and discussion

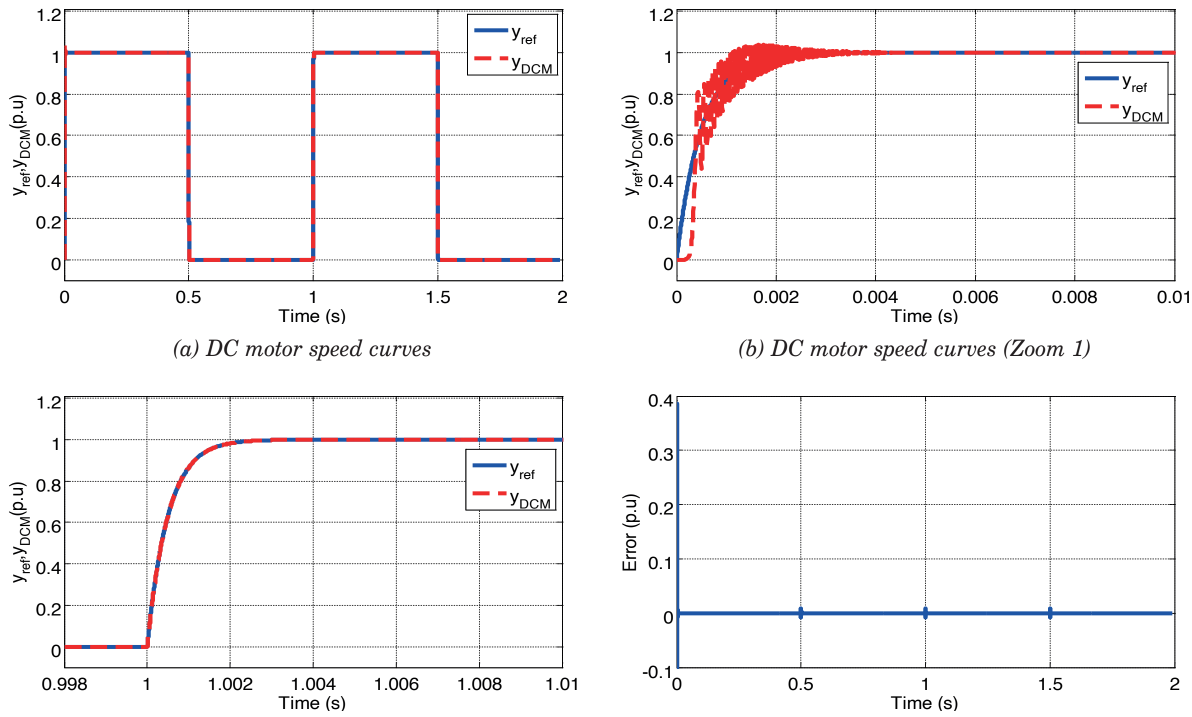
To evaluate the effectiveness and robustness of the proposed control approach for the DC motor, various simulation scenarios in the Simulink Matlab environment were carried out. Then the results were compared to other studies.

We began by choosing a square-wave reference signal, which we passed through a low-pass filter to avoid singularities. Figure 7 shows that the DC motor follows the reference perfectly without the overshoot, demonstrating the robustness of our control approach.

The MRAC (Model Reference Adaptive Control) approach has a learning effect, as illustrated in Figure 7b, where the speed curve corresponds to the ideal response. Figure 7c reveals that the frequency response of the DC motor is very fast, with a settling time of 0.002 s and no overshoot. The parameters in this figure are summarized and compared to the results of other studies in Table 3, where we list indicators such as maximum overshoot in percent (D [%]), settling time (T_s [s], with a tolerance of ±2%), and rise time (T_r [s], for 10%→90%).

The simulation results obtained with the parameter set of the modified MRAC approach were compared to other recent methods, such as those described in [1] and [21], to verify the design, as explained in the following subsections. Those methods were chosen because they use the same motor parameters and parameter limits. In addition, they have determined the best controller parameters so far. The results of this study can be easily verified by the reader with the use of MATLAB commands. In summary, the modified MRAC approach is slightly easier to implement and requires slightly more computing time than the optimal PID controller. However, it offers the shortest stabilization and rise times, without the overshoot. The hybrid algorithm developed (modified MRAC) offers significant advantages over conventional MRAC, including better operational capabilities, the ability to find the solution closest to the global optimum without getting stuck in a local minimum, and a faster convergence rate.

Then, at this stage, a sinusoidal function is applied and considered as a reference signal at the system



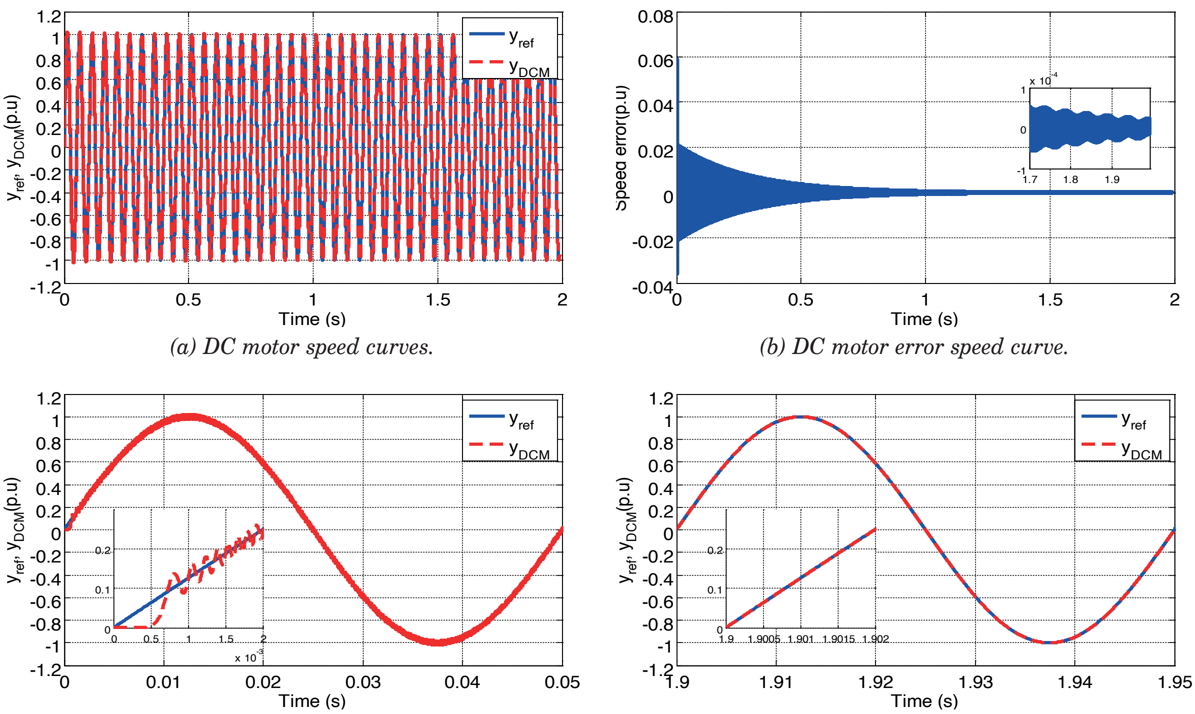
(a) DC motor speed curves

(b) DC motor speed curves (Zoom 1)

(c) DC motor speed curves (Zoom 2)

(d) DC motor error speed curve

Figure 7 *The DC motor response under square wave reference signal*



(a) DC motor speed curves.

(b) DC motor error speed curve.

(c) DC motor speed curves (Zoom 1)

(d) DC motor speed curves (Zoom 2)

Figure 8 *The DC motor response under sinusoidal wave reference signal*

input. The results of simulating the DC motor control using the proposed MRAC approach are shown in Figure 8.

As Figure 8a clearly shows, the modified MRAC approach provides faster and more accurate reference signal tracking, with minimal learning time (Figure 8c illustrates the learning phase). A comparison of Figure 8c and 8d shows that our control method improves over time. This learning effect is due to the self-adjustment of controller parameters, meaning that the proposed MRAC approach adapts to parametric variations and automatically adjusts controller parameters.

Figure 8b shows the desired speed tracking error. It can be seen that the error curve presents continuous damping, indicating that the control strategy, based on learning and parameter self-adaptation, is effective.

5 Conclusion

In this work, a Model Reference Adaptive Control (MRAC) approach is presented to control the speed of a DC motor under conditions of model changes and unknown uncertainties affecting the base model. The proposed modified MRAC control strategy is applied to the DC motor control, and its performance is evaluated and compared to other studies in the literature.

Based on the obtained simulation results, several criteria such as percentage overshoot, settling time, rise time, and disturbance rejection can be highlighted. We found that the proposed modified MRAC control outperforms other techniques illustrated in the literature due to its superior performance and robustness. The steady-state performance of the proposed modified MRAC control is better than that of other conventional techniques, thanks to its adaptive parameters and the learning effect inherent in the MRAC control.

The proposed modified MRAC approach is slightly easier to implement and exhibits superior performance in terms of speed and tracking accuracy compared to traditional methods. The results of this study can be easily reproduced and verified with the use of MATLAB commands, thus offering a practical and efficient solution for the DC motor control.

Acknowledgment

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A *DC motor parameters [21]*

Parameter	Value
Armature resistance (R_a)	0.4 Ω
Armature inductance (L_a)	2.7 H
Motor moment of inertia (J)	4 x 10^{-4} Kgm^2/s^2
Coefficient of friction (f)	0.0022 $Nm\ .\ s/rad$
Motor torque constant (K_m)	0.015 $kg\ m/A$
Back EMF constant (K_b)	0.05 s