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Low-cost mini bench with DC motors and encoder for feedback control practice

Mini bancada de baixo custo com motores CC e encoder para prática de controle realimentado

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ABSTRACT

This paper presents the development and application of a low-cost didactic bench based on DC motors with encoders for practical teaching of control systems in engineering. The proposal aims to overcome resource limitations in educational institutions by providing an accessible, portable, and effective platform for experimentation with fundamental concepts such as circuit analysis, electronics, mathematical modeling, instrumentation, and closed-loop control. The mathematical modeling of the DC motor is detailed, including transfer function derivations, and the design of a digital discrete-time controller for angular velocity control is presented, employing tools such as MATLAB® and Simulink™for validation. The results demonstrate the technical and pedagogical feasibility of the bench, enabling students to gain an integrated and applied experience, better preparing them for modern engineering challenges.

Keywords: Didactic bench; Mathematical modeling; Discrete-Time control; DC Motor; Closed-Loop control; Transfer function; Linear control; PID control; Digital PID; Feedback control

RESUMO

Este trabalho apresenta o desenvolvimento e aplicação de uma mini bancada didática de baixo custo, baseado em motores de corrente contínua (DC) com encoders, para o ensino prático de sistemas de controle em engenharia. A proposta visa superar as limitações de recursos em instituições educacionais ao proporcionar uma plataforma acessível, portátil e eficiente para a experimentação de conceitos fundamentais como análise de circuitos, eletrônica, modelagem matemática, instrumentação e controle em malha fechada. A modelagem matemática do motor DC é detalhada, incluindo a derivação das funções de transferência, e o projeto de um controlador digital em tempo discreto é apresentado para o controle da velocidade angular do motor, utilizando ferramentas como MATLAB® e Simulink™para validação. Os resultados mostram a viabilidade técnica e pedagógica da mini bancada, que permite aos estudantes uma experiência integrada e aplicada, preparando-os para os desafios da engenharia moderna.

Palavras-chave: Bancada didática; Modelagem matemática; Controle discreto; Motor CC; Controle em malha fechada; Função de transferência; Controle linear; Controle PID; PID Digital; Controle realimentado

1 Introduction and Motivation

The growing demand for engineers with a solid background in control and automation systems has driven the development of teaching methodologies that effectively combine theory and practice. Given the limited resources available in many educational institutions, the availability of practical tools for learning represents a significant challenge. Accessible and low-cost solutions are essential to democratize access to hands-on learning. In this context, didactic benches based on direct current (DC) motors with encoders emerge as a promising alternative for practical feedback control training.

Teaching control systems has traditionally been challenging due to its abstract nature, requiring mastery of advanced mathematical concepts and an understanding of dynamic behavior. According to (Armstrong and Perez, 2002), practical learning promotes knowledge construction through discovery and experimentation, significantly enhancing the retention of theoretical content. Similarly, (Goodwin et al., 2010) emphasize that the use of laboratories, whether physical or virtual, directly impacts the development of applied skills in engineering education.

However, linear control laboratory equipment and teaching facilities for the study of feedback control is often expensive and non-portable (Bhatta et al., 2023; Reck and Sreenivas, 2015), limiting its widespread adoption, restricting access in many universities to hands-on experimentation, which is essential for the consolidation of theoretical knowledge. In this scenario, compact and low-cost bench setups using DC motors and encoders have gained attention due to their simplicity, portability, and affordability, allowing for complete experiments covering circuit analysis, mathematical modeling, and digital controller implementation.

The great advantage of this approach is its multidisciplinary nature, providing students with integrated exposure to electronics, instrumentation, system modeling, and control. Additionally, it enables the use of well-established tools such as MATLAB® and Simulink™ for system simulation and validation, as described by (Franca et al., 2011), thereby enriching the learning process with industry-relevant computational resources. Through the analysis and control of the proposed system, students will have the opportunity to apply and consolidate theoretical concepts.

The proposal of a low-cost teaching bench, using DC motors equipped with encoders, emerges as an innovative and motivating solution, democratizing access to the practice of fundamental concepts and enabling a greater number of students to experience the real application of the principles of circuit analysis, electronics, mathematical modeling, instrumentation and control, preparing them more effectively for the challenges of modern engineering.

Initially, circuit analysis becomes essential for understanding the electrical behavior of the DC motor, covering the connections and power supply, and involving the analysis of the current, voltage, and power quantities present in the system.

Next, the study of electronics is essential to understand the operation of the components necessary for the efficient operation of the motor, such as drivers and transistors, as well as the processing of the signal coming from the encoder and its correct interface with microcontrollers or data acquisition boards.

Mathematical modeling of the DC motor allows its dynamic behavior to be described through relationships between the input voltage and the output variables, such as speed and angular position, often using differential equations and representation by transfer functions.

Instrumentation comes into play with learning about the operating principle and application of position sensors, specifically encoders, the interpretation of the generated signals and the understanding of the importance of obtaining accurate data for effective control.

Finally, the practice of feedback control enables the implementation of various control strategies, such as the widely used PID, using the encoder feedback signal to ensure that the system operates according to the desired performance, exploring crucial concepts such as steady-state error, system response time and its stability.

This paper presents the design and application of a low-cost didactic bench aimed at enabling hands-on feedback control practice with DC motors and encoders, learning about modeling a DC motor with simulation in MATLAB® and Simulink™, covering key concepts in motor and electromechanical system modeling, demonstrating both its technical feasibility and pedagogical potential in engineering education environments.

2 Bibliographic Review

Historically, linear control laboratory equipment has been expensive, bulky and, in most cases, non-portable (Bhatta et al., 2023; Reck and Sreenivas, 2015), posing a significant challenge for universities with limited budgets. This financial barrier often restricts students' access to hands-on experiences, which are essential for consolidating theoretical knowledge.

However, the importance of integrating theoretical knowledge with practical application in engineering education, especially in control systems training, is widely recognized in the literature. Numerous studies, such as (Goodwin et al., 2010) and (Apkarian and Astrom, 2004), emphasize that combining theory and hands-on laboratory practice enhances students' understanding and retention of complex concepts, highlighting the educational benefits of a more integrated approach for effective learning (Gunasekaran and Potluri, 2012).

Despite consensus on the value of practical exercises to reinforce control theory, the nature of laboratory experiments and configurations adopted varies considerably among educators. Experiment selection is often guided by the specific control technologies instructors wish to emphasize. For example, some focus on real-time control implementations (Lim, 2005; 2006), while others prioritize embedded control systems (Moallem, 2004; Srivastava et al., 2010).

Alternatively, some instructors prefer simulation-based experiments (Goodwin et al., 2010; Hassapis, 2003), with varying degrees of model complexity, whereas others advocate for physical hardware experiments, as seen in (Apkarian and Astrom, 2004), to expose students to real system behaviors.

Furthermore, laboratory objectives can range from exposing students to a wide range of real-world applications of control theory to simply demonstrating the practical utility of control principles (Braae, 1996). The teaching methodology considered most effective also influences the design of experiments, along with financial constraints and resource availability (Armstrong and Perez, 2002).

Recent studies have specifically addressed this demand by proposing innovative and low-cost experimental platforms. For instance, (Sozański, 2023) designed a digital PID controller for laboratory use based on widely available Arduino and STM32 modules. This setup enables students to directly implement digital control algorithms in a practical context, reducing the complexity and cost traditionally associated with control hardware.

Another notable initiative is the “Lab in a Box” project by (Benatiro and Cañete, 2023), which provides a portable electronics trainer kit developed specifically for computer engineering education. Compact, affordable, and suitable for remote or in-person instruction, this platform exemplifies a growing trend toward mobile laboratory solutions that do not compromise educational value.

In addition to portable kits for general electronics and digital control, (Supriyono et al., 2024) developed a laboratory trainer for DC motor speed control using a PID controller integrated with Arduino and MATLAB. Their work highlights how modern tools and open-source hardware can be utilized to build highly functional, cost-efficient control teaching platforms.

On a similar note, (Cazarotto, 2021) proposed a didactic module for liquid level control using Arduino technology. His project, developed for use in Brazilian engineering programs, serves as a clear example of how educators can create contextually relevant laboratory setups aligned with curricular goals and budget constraints.

In summary, the development of control systems laboratories reflects a balance between pedagogical priorities, technological focus, and resource limitations. Educators leverage their expertise and institutional context to select experiments that best support students in acquiring the desired skills (Gunasekaran and Potluri, 2012). This diversity of approaches underscores the ongoing need for accessible, low-cost, and portable laboratory solutions that facilitate practical learning in control systems education.

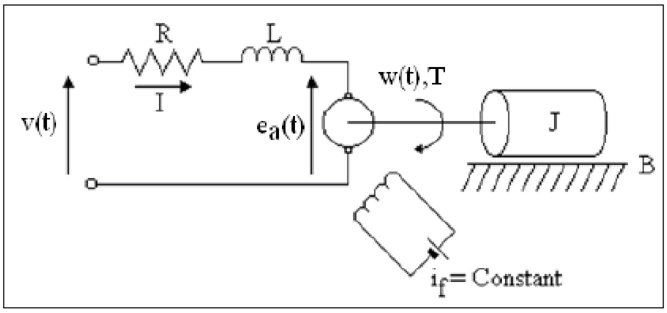
3 Mathematical Model

In this section, we present the derivation of the linear model of a direct current (DC) motor, highlighting its industrial relevance and the fundamental steps involved in its mathematical representation. The modeling process is carried out through differential equations, from which the motor's transfer function formulation is obtained.

A basic DC motor, or dynamo, consists primarily of an armature (rotor), brushes, and field coils arranged in series, parallel, or a combination of both configurations. The field coils are responsible for generating the magnetic field necessary for the motor's operation. They create a magnetic flux that interacts with the electric current in the armature, producing torque and enabling rotation, and are wound around iron cores to increase the intensity of the magnetic field. These machines have been widely used for decades as fundamental energy converters. Due to their reliable speed control characteristics, DC motors are commonly employed in applications such as electric elevators, rolling mills, electric vehicles, and pumps requiring variable speed operation.

The most important elements of a DC motor are represented by the Figure 1 below.

Figure 1 – Equivalent circuit diagram of the armature of a DC motor



Source: Franca et al. (2011)

The DC motor armature is modeled as having a constant resistance R in series with a constant inductance L, which represents the armature coil inductance, a power supply v representing the voltage generated across the armature, and a power supply $E_{a(t)}$ representing the back electromotive force (EMF). In addition, the field circuit is generally represented as a voltage source that supplies the field winding. Due to the relatively high inductance and resistance of the field winding, the resulting field current i_f, and, therefore, the magnetic field, is considered constant and is treated as separated from the armature circuit, which simplifies the analysis of the armature circuit and ensures the magnetic field necessary for the motor's operation.

The presented equations describe the electrical behavior of the armature winding of the direct current motor. By applying Kirchhoff's Voltage Law to the armature circuit, the following equation is obtained:

$$v(t) = Ri(t) + L\frac{di(t)}{dt} + E_a(t), \tag{1}$$

where $v(t)$ represents the voltage applied to the armature terminals, $Ri(t)$ is the voltage drop caused by the internal resistance of the armature, $L\frac{di(t)}{dt}$ corresponds to the voltage induced by the coil inductance, which opposes variations in current, and $E_{a(t)}$ is the back electromotive force (Back EMF), generated by the motor's rotation in a magnetic field established by the field current i_f. Reorganizing the terms, we obtain:

$$\frac{di(t)}{dt} = v(t) - Ri(t) - E_a(t). \tag{2}$$

This form shows that the variation of the armature current $\frac{di(t)}{dt}$ depends directly on the difference between the applied voltage and the sum of the resistive voltage drop and the back electromotive force. Physically, the Back EMF is proportional to the rotor's angular velocity and acts as a self-regulating mechanism: as the motor accelerates, $E_{a(t)}$ increases, reducing the current and balancing the system. This phenomenon is essential for the natural speed control of direct current motors.

Naturally, all mechanical power developed in the rotor iSome of the developed power is lost due to the resistance of the rotor winding, which causes heating by the Joule effect, where electrical energy is converted into heat as current flows through a resistive material, friction losses caused by mechanical resistance from the contact and movement between parts such as the rotor shaft and bearings, hysteresis losses that occur because the magnetic domains have an intrinsic resistance to realigning instantly when the magnetic field changes direction, resulting in energy dissipation during the repeated magnetization and demagnetization of the rotor iron, and eddy current losses caused by circulating currents induced within the conductive rotor iron due to varying magnetic fields, generating heat and reducing overall efficiency. From here, friction losses and some of the developed energy are stored as kinetic energy in the rotating mass of the rotor. The equation for the mechanical part is given by the model.

$$T_m(t) = J\frac{d\omega(t)}{dt} + B\omega(t)$$
$$J\frac{d\omega(t)}{dt} = T_m(t) - B\omega(t), \tag{3}$$

where $T_m(t)$ is the torque of the DC motor, B is the coefficient of friction equivalent to the DC motor and load mounted on the motor shaft, J is the total moment of inertia of the rotor and load relative to the motor shaft, $\omega(t)$ is the angular velocity of the motor and $\frac{d\omega(t)}{dt}$ is the angular acceleration. The product of the moment of inertia J and the angular acceleration $\frac{d\omega(t)}{dt}$ represents the torque required to accelerate the rotor and load.

In order to achieve the interaction between the equations 2 and 3, the following relationships are proposed that assume that there is a proportional relationship, K_a Back electromotive constant $(v/(rad/s))$, between the voltage induced in the armature and the angular velocity of the motor shaft.

$$E_a(t) = K_a\omega(t), \tag{4}$$

and the following electromechanical relationship is assumed, which establishes that the mechanical torque is proportional, K_m Torque Constant (Nm/A), to the electric current that circulates through the DC motor.

$$T_m(t) = K_m i(t). \tag{5}$$

3.1 DC Motor Transfer Functions

We start by applying the Laplace transform to equations 1 to 5, which is a mathematical technique that converts differential equations in the time domain into algebraic equations in the complex frequency domain, simplifying the analysis and solution of dynamic systems (Abou-Hayt and Dahl, 2023). Where s is the complex frequency variable defined as $s = \sigma + j\omega$, with σ representing the exponential decay or growth rate and ω the oscillatory component of the signal (not to be confused with the angular velocity $\omega(t)$ used previously).

$$LsI(s) = V(s) - RI(s) - E_a s, \tag{6}$$

$$Js\omega(s) = T_m(s) - B\omega(s), \tag{7}$$

$$E_a(s) = K_a\omega(s), \tag{8}$$

$$T_m(s) = K_m I(s), \tag{9}$$

Substituting equations 8 and 9 in 6 and isolating the voltage, we have:

$$V(s) = \frac{(R + Ls)\,T_m(s)}{K_m} + K_a\omega(s). \tag{10}$$

From equation 7, we obtain the angular velocity:

$$\omega(s) = \frac{T_m(s)}{Js + B}. \tag{11}$$

Substituting equation 11 in 10 and simplifying, the resulting expression is:

$$V(s) = \frac{(R + Ls)(Js + B) + K_a K_m}{K_m(Js + B)} T_m(s). \tag{12}$$

From equation12 it is possible to derive the transfer function that relates the DC motor torque output to the input voltage:

$$\frac{T_m(s)}{V(s)} = \frac{K_m(Js + B)}{LJs^2 + (RJ + LB)s + RB + K_m K_a}. \tag{13}$$

Similarly, the equations 6, 7, 8 and 9 can be used to obtain the transfer functions that relate the input voltage to different motor output variables (Nagrath and Gopal, 2006). The main derived transfer obtained are presented below.

Back EMF transfer function relative to voltage:

$$\frac{E_a(s)}{V(s)} = \frac{K_m K_a}{LJs^2 + (RJ + LB)s + RB + K_m K_a}, \tag{14}$$

armature current transfer function with respect to voltage:

$$\frac{I(s)}{V(s)} = \frac{K_m(Js + B)}{LJs^2 + (RJ + LB)s + RB + K_m K_a}, \tag{15}$$

transfer function of angular velocity with respect to voltage:

$$\frac{\dot{\theta}(s)}{V(s)} = \frac{K_m}{LJs^2 + (RJ + LB)s + RB + K_m K_a}, \tag{16}$$

transfer function of the angular position with respect to voltage:

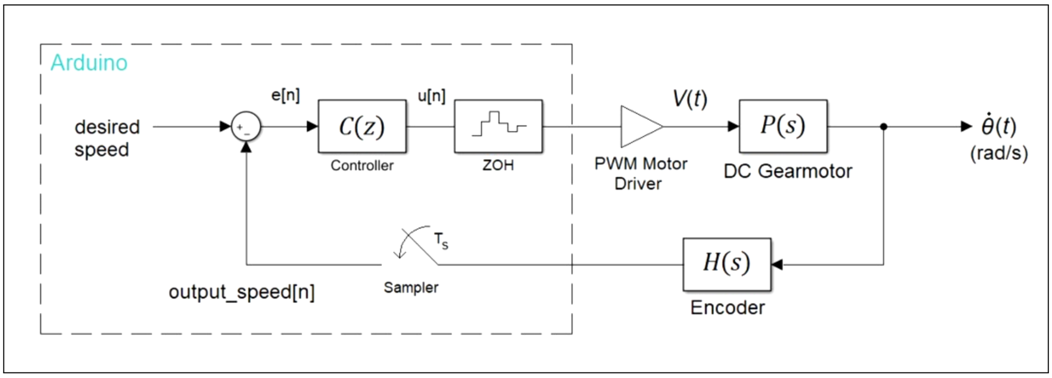
$$\frac{\theta(s)}{V(s)} = \frac{K_m}{s\,(LJs^2 + (RJ + LB)s + RB + K_m K_a)}. \tag{17}$$

In this article, use equation 16 to set a digital controller for the angular speed of the DC motor.

4 Digital Feedback Control Applied to Angular Speed Control of DC Motor

In this section, we will detail the design of a digital feedback control system to regulate the speed of a real DC motor. Figure 2 shows the block diagram of the control loop.

Figure 2 – Diagram of a digital feedback control to regulate the angular speed of a real DC motor

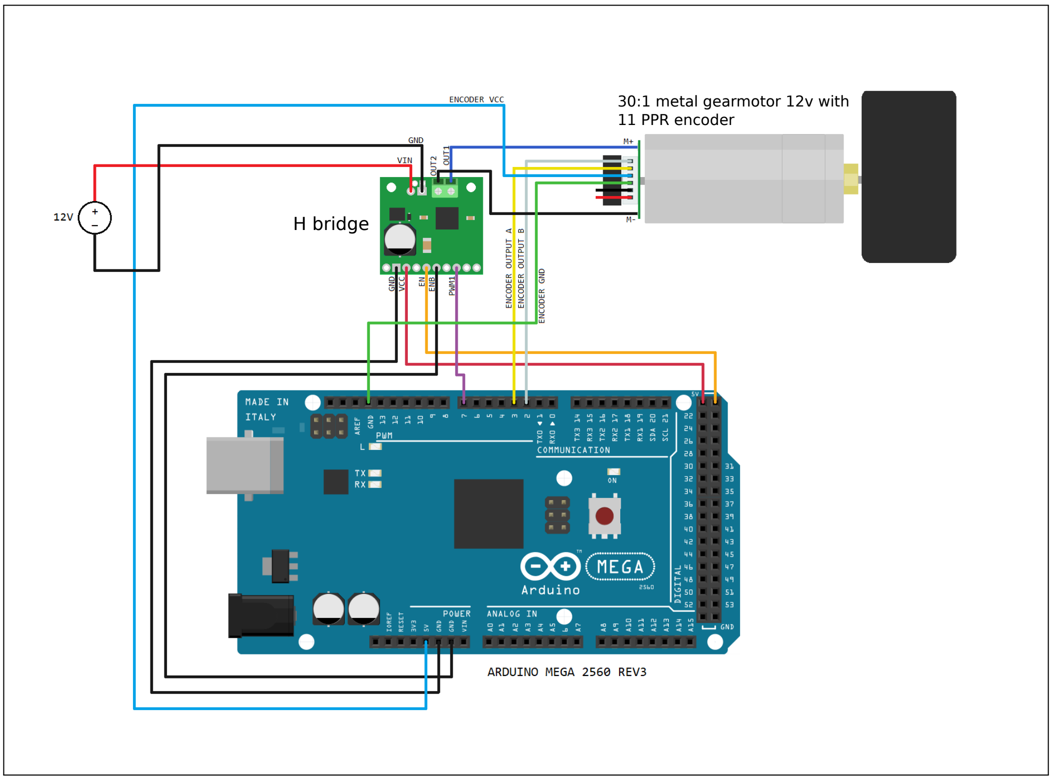


Source: Authors, May 2025

The diagram illustrates the digital control system implemented to regulate the speed of a DC gearmotor using a controller embedded in an Arduino. The rotary encoder, modeled by the transfer function $H(s)$, is used to obtain the motor speed by converting the angular motion of the motor shaft into digital pulses proportional to the speed. This continuous signal is then sampled by the system, generating a discrete variable, which is called the output_speed$[n]$. The input signal to the system is the desired speed, defined as the reference for the control loop. This reference is compared to the output speed, generating the error signal $e[n]$ in the discrete domain. This error signal is processed by the discrete controller $C(z)$, implemented on the microcontroller as a difference equation, to generate a control signal $u[n]$, also in the discrete domain. To drive the motor, the control signal must be converted to the continuous domain and this is accomplished by a zero-order hold (ZOH) block, which maintains the signal value constant during each sampling period T_s. The resulting signal is then generated as a PWM (Pulse Width Modulation) signal that is applied to the motor driver, which modulates the pulse width of the voltage supplied to the motor, generating the signal $V(t)$. The plant of the system, represented by $P(s)$, corresponds to the transfer function of the DC gearmotor shown in equation 16, relating the input voltage $V(t)$ to the output angular velocity $\dot{\theta}(t)$, expressed in rad/s. The motor driver applies an input voltage to adjust the motor's speed to the desired value, thus closing the feedback loop.

A schematic diagram of the connections is shown in Figure 3.

Figure 3 – Connection diagram



Source: Authors, May 2025

An Arduino is used to act as our digital controller, the PWM output is connected to a motor driver (H-bridge). Connected to the DC motor is an integrated encoder that sends pulse data. An algorithm to convert these pulses into angular velocity is used. The motor driver is powered by a 12V DC voltage source and has the power required for the application.

4.1 Real DC Motor Transfer Function

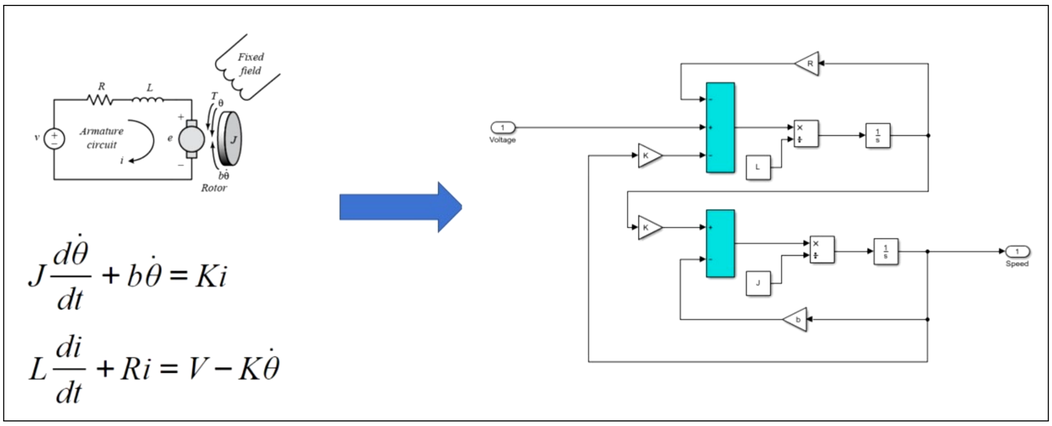
As detailed in the modeling section, the transfer function $P(s)$ of the DC motor, which relates angular velocity to voltage, is presented in equation 16. Let us consider that $K_m = K_a$ and use only K, so that equation 16 can be redefined as:

$$\frac{\dot{\theta}(s)}{V(s)} = \frac{K}{LJs^2 + (RJ + LB)s + RB + K^2}, \tag{18}$$

where $K = \frac{V(t)}{\dot{\theta}(t)} = \frac{12}{35} = 0.34\ V/rad/s$, $R = 4\Omega$ and $L = 2.3\ mH$with 12 V and 35 rad/s representing the motor's maximum voltage and angular velocity, respectively, as specified in the datasheet. The resistance R and inductance L values were measured directly using a multimeter. The J and B parameters are very difficult to obtain accurately, to get around this, we will use the MATLAB®/Simulink™parameter estimation toolbox (Mathworks, 2025).

To estimate the parameters, the linear model shown in Figure 4 is used to capture the dynamics of the DC motor.

Figure 4 – Linear DC motor model



Source: Authors, May 2025

After open-loop testing of a real DC motor and using the parameter estimator toolbox, we obtain the following values:

$$J = 0.004893, \quad B = 5.8147 \times 10^{-5},$$

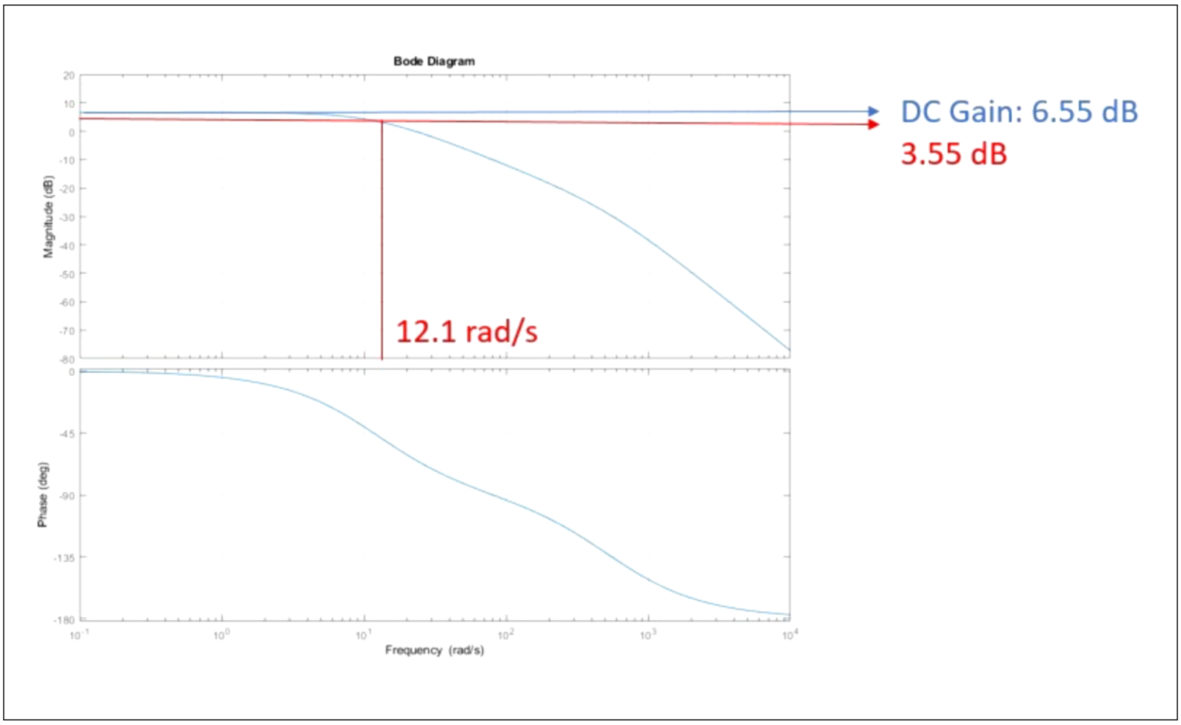
and the open-loop transfer function of the DC motor after substituting the parameter values in equation 16 is:

$$P(s) = \frac{0.47}{3.425 \times 10^{-5}s^2 + 0.01859s + 0.2211} \tag{19}$$

4.2 Definition of Sampling Time - T

There are several methods for defining sample time; in this article, the Bode diagram approach is adopted, as illustrated in Figure 5. According to this method, the sampling frequency should be approximately $5 - 10\times$ times higher than the bandwidth of the open-loop system.

Figure 5 – Bode diagram for calculating the sampling period - T



Source: Authors, May 2025

From the Bode plot in Figure 5, the DC gain is approximately 6.55 dB. The bandwidth is found at the frequency where the magnitude drops 3 dB from the DC gain, which corresponds to 3.55 dB. This occurs at a frequency 12.1 rad/s, or 1.93 Hz. Therefore, the bandwidth of our system is 1.93 Hz, or about 2 Hz. Multiplying this value by ten yields a sampling frequency of 20 Hz, corresponding to a sampling period of 50 ms ($T = 0.05$ s).

4.3 Zero-order hold and Pade Approximation

The zero-order hold (ZOH) is a mathematical model of the practical signal reconstruction done by a conventional digital-to-analog converter (DAC) (Moir and Moir, 2022). That is, it describes the effect of converting a discrete-time signal to a continuous-time signal by holding each sample value for one sample interval. The transfer function of a ZOH is defined by:

$$G_{ZOH} = \frac{1 - e^{-sT}}{sT}. \quad (20)$$

It can be seen in equation 20 that the G_{ZOH} transfer function has an exponential (irrational) term, which would make the control design step very difficult. To simplify this step, a rational approximation of equation 20. MATLAB®'s control design tools tend to work better with rational transfer functions than with transfer functions that have exponential terms. Therefore, using an approximation technique known as Padé approximation, the exponential term can be approximated as a rational function with increasing orders of precision, so that the higher the order, the better the approximation (Hanta and Procházka, 2009). Of course, doing this by hand is impractical, but MATLAB® has a function called **pade(sys,n)** that, if you give it the irrational transfer function and a desired order n, will produce the approximated rational transfer function.

Using the Padé approximation function with $n = 3$, in equation 20 (with T=0.05) we obtain:

$$G_{ZOHP} = \frac{40s^3}{s^4 + 240s^3 + 24000s^2 + 960000s}. \quad (21)$$

4.4 Controller Design C(s)

Now we can proceed with the design of the continuous controller C(s) using classical control techniques such as root locus, frequency response analysis, and practical methods. Most conventional DC motors have their output speed regulated using a PI controller, defined as:

$$C(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s}, \tag{22}$$

where $U(s)$ is the controller output (control signal) and $E(s)$ is the input (error signal). The constant K_p corresponds to the proportional gain, which produces a control action directly proportional to the error magnitude, improving the transient response of the system. The term $\frac{K_i}{s}$ represents the integral component of the controller, with K_i being the integral gain, which accumulates the error over time and eliminates steady-state error, ensuring that the system output eventually matches the desired reference. In this article, the MATLAB® **pidTuner** function is used to design the PI controller. The transient and steady-state performance criteria that are to be met are:

- settling time less than 2 seconds.
- overshoots and undershoots should be under 5%.
- steady-state error should be less than 3%.

After using the **pidTuner** function to meet the criteria mentioned, the following PI controller is obtained:

$$C(s) = \frac{U(s)}{E(s)} = 0.427 + \frac{5.114}{s}. \tag{23}$$

For discretization of 23, bilinear transformation is used (also known Tustin's method) (Ogata, 1995), resulting in

$$C(z) = \frac{U(z)}{E(z)} = \frac{0.5548z - 0.2991}{z - 1} = \frac{0.5548 - 0.2991z^{-1}}{1 - z^{-1}}. \tag{24}$$

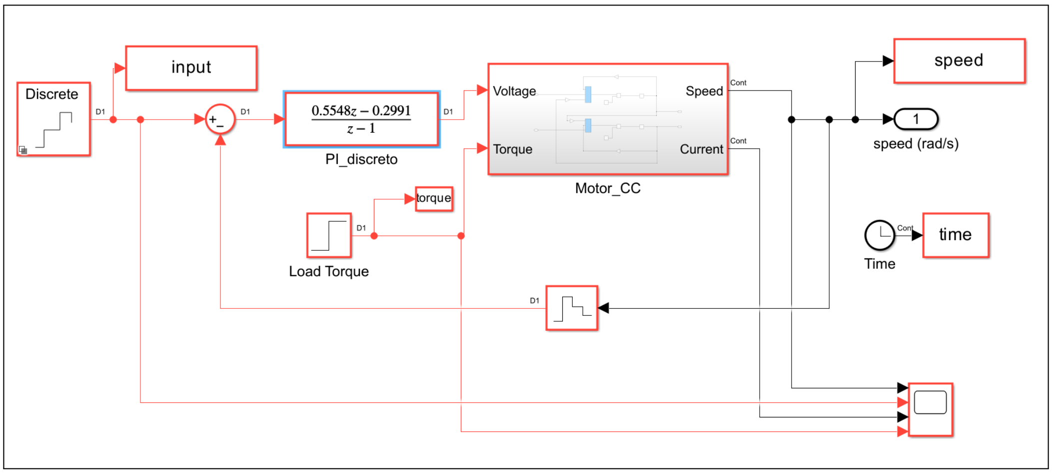
Applying the inverse Z transform at 24, we obtain the difference equation:

$$u[n] = u[n-1] + 0.5548e[n] - 0.2991e[n-1]. \tag{25}$$

The difference equation 25 that is applied in Arduino microcontroller for the system to work.

A schematic of the control design in MATLAB®/Simulink is shown in Figure 6

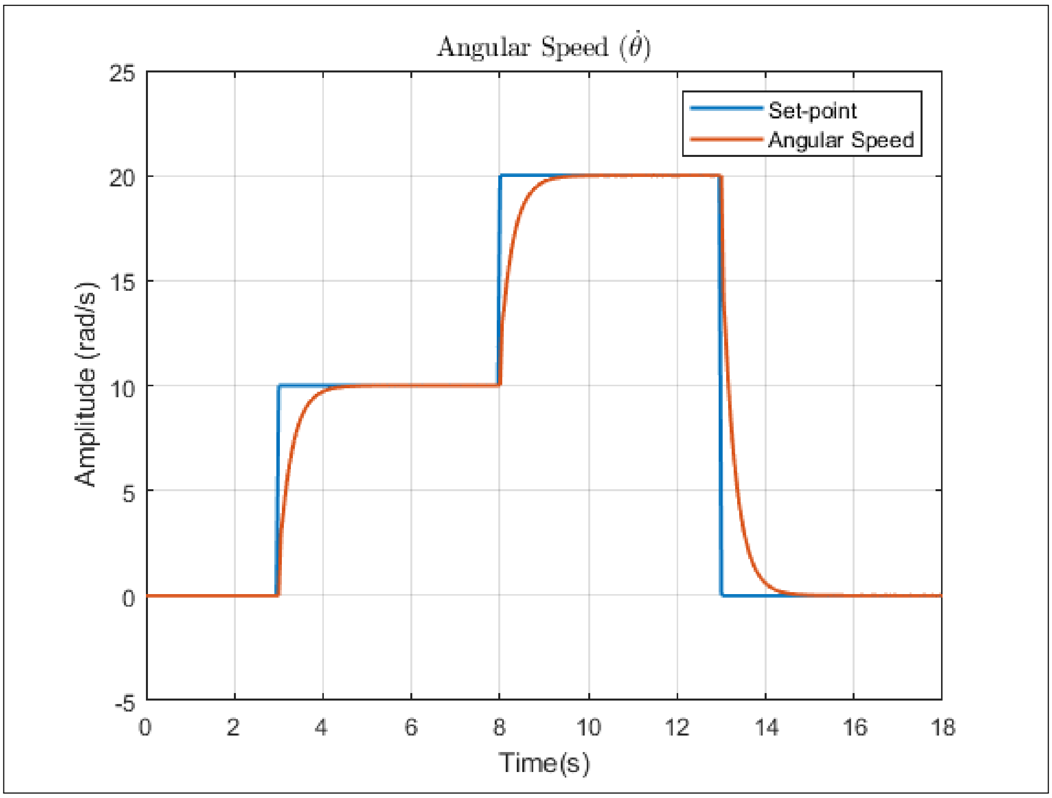
Figure 6 – A schematic of the control design



Source: Authors, May 2025

Applying the digital PI controller defined in 24, the behavior of the closed-loop system using the model can be seen in Figure 7.

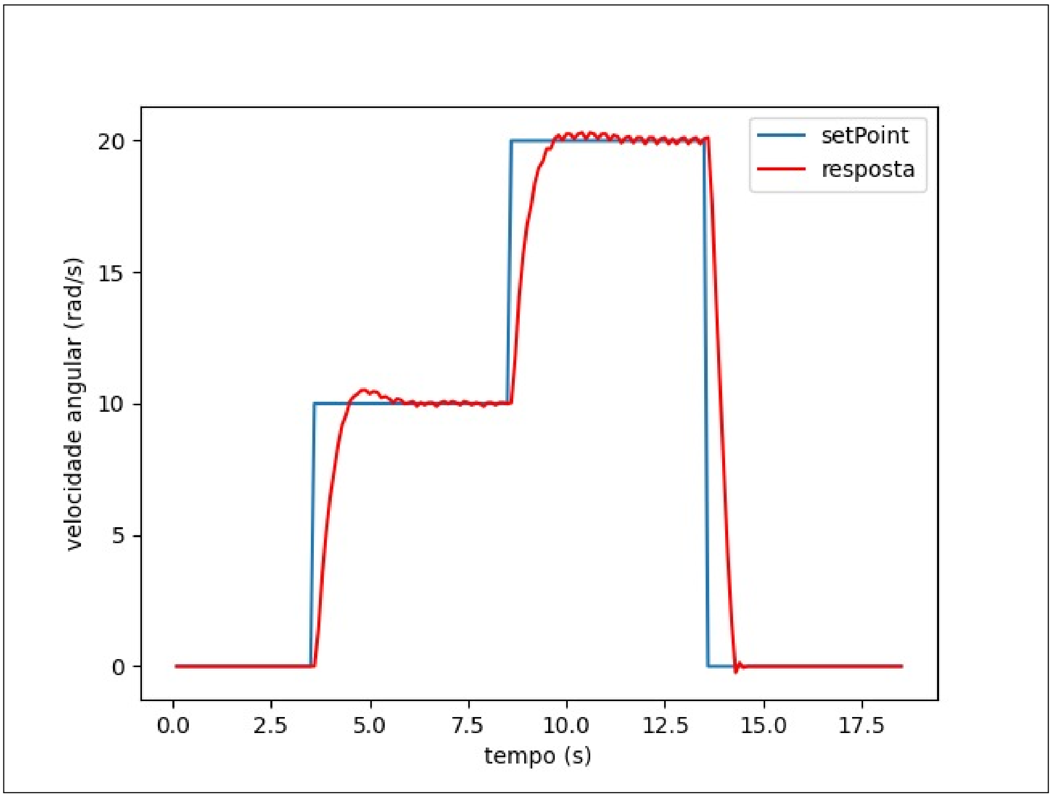
Figure 7 – Closed-loop system behavior for step-type input using the DC motor model



Source: Authors, May 2025

The implementation of the difference equation 25 using an Arduino microcontroller on the real DC Motor is shown in Figure 8. It is observed that in both cases, the digital PI controller was effective. The real DC motor presented white noise in the speed measurement. In future work, a moving average filter will be applied.

Figure 8 – Closed-loop system behavior for step-type input using real DC motor



Source: Authors, May 2025

5 Conclusions

The development of the didactic bench utilizing DC motors with encoders proved to be an innovative and affordable solution for hands-on teaching of control systems.

The mathematical modeling of the DC motor was developed and validated using parameter estimation techniques, ensuring an accurate and reliable system representation for effective controller design. A digital PI controller was successfully implemented using an Arduino platform, demonstrating precise regulation of the motor's angular velocity with satisfactory transient and steady-state performance.

This integration of theoretical modeling, digital control implementation, and practical experimentation allows students to consolidate fundamental concepts in circuit analysis, electronics, instrumentation, dynamic system modeling, and control strategies, integrating theoretical knowledge with hands-on experimentation. The use of computational tools such as MATLAB® and Simulink™further enriches the learning experience by bridging the gap between academic environments and industry practices.

Moreover, the low cost and portability of the didactic bench broaden access to practical control systems education, democratizing learning and increasing student engagement. This accessible and motivating educational tool addresses the challenges posed by expensive, bulky and non-portable laboratory equipment, fostering the development of engineering skills critical for modern technological contexts.

Future work may focus on further enhancements, including integration with virtual laboratories and expansion to other types of electromechanical systems, to broaden the bench's educational scope and applicability.

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