Low-cost platform for real time data acquisition and fractional control with application to a DC motor

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ABSTRACT

This paper presents a low-cost experimental platform for real time data acquisition, identification and fractional order control of some low dynamic systems using Arduino-Simulink interface. As a demonstrative example, a DC motor is considered and modeled as a first order plus time delay plant (FOPTD) using data acquisition-based Arduino setup. Then, simple analytical rules are used to design a robust fractional order controller (FOC) which required a high-performance computing. Several validation tests have been carried out using Arduino–Simulink interface. The comparison between the theoretical simulation and the experimental tests confirms that the proposed interface can be used to support research and teaching of feedback control systems using experimental tests and low-cost laboratory kit.

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1. INTRODUCTION

Fractional controllers such as the widely used proportional integral derivative (PID) controllers are well-known for control and modelling in most industrial applications such as engineering, chemistry and mathematics due to their simplicity [1]–[5]. However, previous research has indicated that these controllers have limitations in performance, flexibility, and control quality [6], [7].

In recent years, the use of fractional calculus in control theory has led the development of more faster and powerful FOCs [8]–[10]. These controllers can offer many advantages such as greater flexibility and improved robustness compared to classical controllers [11]–[13]. Numerous robust control techniques have been devised, including the commande robuste d'ordre non entier (CRONE) controller as presented in [14], and the PIαDμ controller introduced by Birs *et al.* in [15]. These methods use non-integer integration and differentiation actions. These techniques can improve the performance of control systems in the presence of uncertainties or disturbances. Many researchers have already proposed various methods for PIαDμ control design and synthesis to achieve a better control performance and a higher tracking accuracy for control applications [16]–[20]. However, one of the main challenges associated with FOCs is their time-domain simulation. Therefore, algorithms and models expressed with analytical solutions are often more complex and time consuming [21]. In addition, several numerical approximation methods e.g., Grunwald-Letnikov

(GL) are commonly used for this type of simulation [15]. Recently, Djouambi *et al*. proposed faster and an efficient filter for simulating and identifying fractional operators compared to other existing methods [21]. Other difficulty facing FOCs is related to the implementation of these controllers which require high performance computing and complicated numerical calculations [21]–[23].

The MATLAB/Simulink software is widely used for implementing complex control systems [6]. Within the MATLAB suite, there are numerous toolboxes and functions already developed for data acquisition, identification, and control design. On the other hand, the Arduino-Simulink interface is an alternative low-cost interface used for real-time data acquisition and communication. Arduino is an open-source platform which includes all the necessary tools and libraries already available on its website (arduino.cc). The additional Arduino IO package needed to link both platforms (Simulink and Arduino) and can be downloaded from the MathWorks website's file exchange webpage. In this paper, a low-cost platform design using fractional speed control of a direct current (DC) motor is proposed for real-time data acquisition. This is fully motivated by the outstanding robustness and performance quality of FOCs and the challenges of high computing power required for real-time implementation.

2. APPROACH AND MODELLING

2.1. Basic concepts of fractional calculus

The most commonly used definition of fractional calculus is that provided by Riemann-Liouville as shown in (1) [24]:

$$D^{-\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_0^t (t-\tau)^{\alpha-1} f(\tau) d\tau \tag{1}$$

where $\Gamma(.)$ is the Gamma function and $D^{-\alpha}$ is the fractional integral of order α. Under zero initial conditions. So, Laplace transform of (1) is (2).

$$D^{-\alpha} f(t) = s^{-\alpha} F(s) \tag{2}$$

In an automatic control system, the generalized fractional order transfer function of a process model is given by (3):

$$\sum_{i=1}^{N} a_i \, D^{\alpha_i} y(t) = \sum_{j=1}^{M} b_j \, D^{\alpha_j} u(t) \tag{3}$$

where $D^{(.)}$ is the fractional derivative operation, α_i, α_j, a_i and b_j are real numbers.

The Bode's ideal transfer function also known as the optimal loop can be expressed as a fractional integral of a certain type as given by (4) [24]:

$$L(s) = \left(\frac{\omega_\alpha}{s}\right)^{\alpha}, 1 < \alpha < 2 \tag{4}$$

the desired unity gain crossover frequency is represented as ω_α. The loop's Bode plot demonstrates a magnitude with a fixed slope of -20α dB/dec and a phase with a constant value of -α π/2. The phase margin relies only on the fractional order α and can be expressed as $\varphi_m = \pi(1 - \alpha/2)$ which results in the robust control systems' iso-damping property.

2.2. Description of the experimental platform

The experimental platform proposed in this study as shown in Figure 1 consists of the following components: 1) a personal computer, 2) Arduino uno (Atmel board) utilized as a data acquisition system (DAQ) for sending and receiving data to and from the computer, performing tachometer calculations, and generating pulse width modulation (PWM) signals, 3) a full-bridge motor driver L298N utilized for the smooth operation of the DC motor, 4) a 12-volt DC motor utilized as the actuator, 5) a DC motor (generator) utilized as a tachometer for measuring rotational speed, 6) an encoder wheel, and 7) power supply. The input/output configuration of the Arduino is provided in Table 1.

Table 1. Arduino I/O configuration

Pin	Type	Description	Pin	Type	Description
2	Digital input	Incremental encoder	11	Digital output	PWM signal
5	Digital output	PWM signal	12	Digital output	Used for output relay
7	Digital output	Forward direction	A0	Analog input	Measured generator voltage
9	Digital output	Backward direction			

3. SETUP MODELLING AND IDENTIFICATION

The setup used in this study consists of a DC motor-generator which includes two DC motors connected to each other through a shaft, as illustrated in Figure 1. The first motor, operating at a maximum output shaft speed of 4200 rpm, is a 12-volt DC motor that serves as the actuator for the plant. It is fed with a voltage-to-current PWM signal that is converted into angular speed. The second motor, on the other hand, is a 5-volt DC motor that serves as a tachometer to measure the speed of the first motor. It converts the rotational speed back into a voltage, allowing for measurement of the angular speed. Together, the motor-generator set produces a system that takes a voltage input and generates a voltage output.

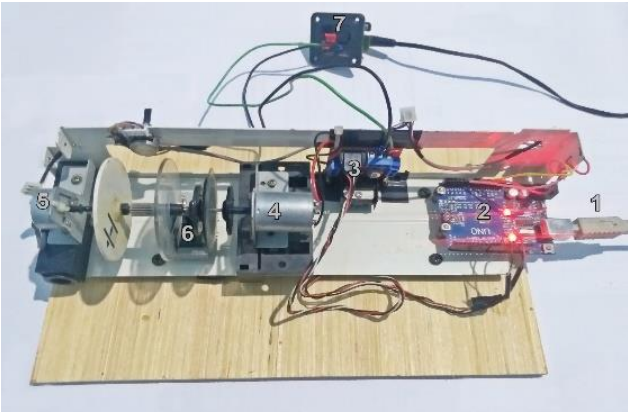

Figure 1. The experimental setup: 1) computer, 2) Arduino board, 3) H-Bridge, 4) DC motor, 5) DC generator, (6) encoder wheel and (7) power supply

The configuration of voltage-in/voltage-out is user-friendly and is well-matched with DAC/ADC computer-based instruments like the Arduino board which has gained popularity in recent years as a micro-controller. In addition, a feedback/speed sensor can be implemented using a photo-interrupter sensor mounted below the encoder wheel (refer to component 6) in Figure 1). The proposed block diagram of the experimental setup is described in Figure 2.

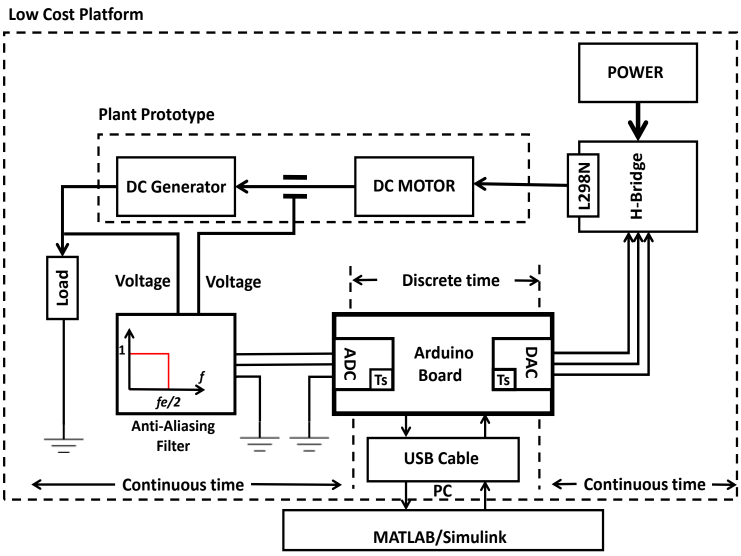

Figure 2. Schematic of the proposed experimental setup

To simplify this setup, dynamic characteristics of the generator can be ignored and considered simply as a speed sensor. Figure 3 shows the simplified scheme of the considered setup. This unknown configuration is approximately modeled by a first-order plus time delay as (5).

$$G(s) = \left(\frac{k_n}{\tau s+1}\right) e^{-Ls} \tag{5}$$

To identify the parameters k_n, τ and L, the setup was excited by a pseudo random binary signal (PRBS) input signal. The following MATLAB command is used to generate the PRBS sequence: idinput (1001,'PRBS', [0 1/1], [0 5]); using the MATLAB ident ToolBox for identification, the transfer function of the setup's model (voltage-voltage) of "DC motor" was identified experimentally to a FOPTD as (6).

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = \left(\frac{0.4540}{0.591s+1}\right) e^{-0.132s} \tag{6}$$

As shown in Figure 3, the transfer function of the setup voltage-speed can be given by (7):

$$\frac{\omega(t)}{v_{in}(t)} = \left(\frac{0.4540/K_{gen}}{0.591s+1}\right) e^{-0.132s} \tag{7}$$

where K_{gen} is the voltage/angular speed ratio, this constant was found to be $K_{gen} \cong 1/1000$. Then, the angular speed of the DC motor is obtained as the voltage of the generator multiplied by 1000. Figure 4, presents the response excited by a PRBS signal.

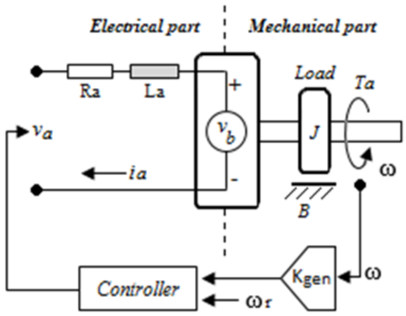

Figure 3. Simplified setup scheme

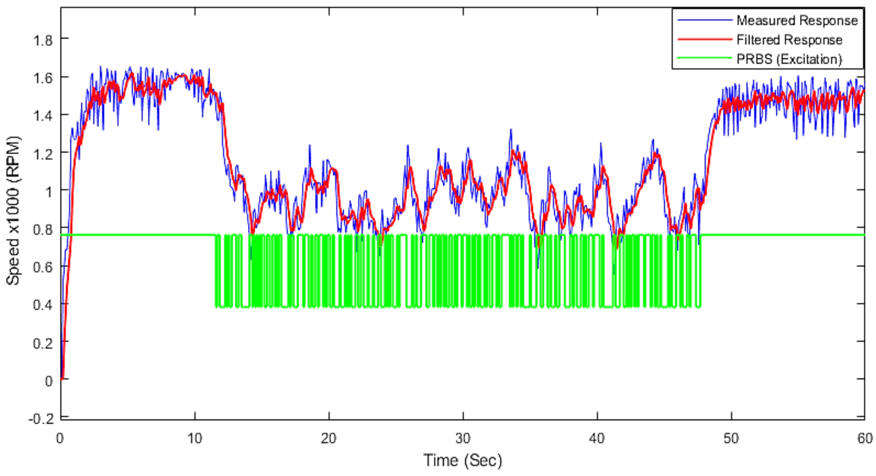

Figure 4. Excitation signal (PRBS) and measured speed response (identification data)

4. FRACTIONAL-ORDER CONTROLLER DESIGN

A basic analytical design approach relies on gain and phase margin specifications was used to design a robust fractional order speed controller for the aforementioned DC motor. The transfer function of the designed fractional controller is given by [25] and shown as (8).

$$C(s) = k_p \frac{(Ts+1)}{s^{\lambda}} = k_p \left(\frac{1}{s^{\lambda}} + Ts^{1-\lambda}\right) \tag{8}$$

The controller depicted in (8) is, in fact, a modification of a fractional $PI^{\lambda}D^{\mu}$ controller. Where $\mu = 1-\lambda$. The technique presented in [25] was applied to adjust the values of k_p, T, and λ. To achieve specific gain and phase margins (A_m=10, φ_m=55°) for the control loop specifications, the subsequent fractional order controller was designed as in (9):

$$C(s) = 3.5653\left(\frac{0.591s+1}{s^{1.38}}\right) \tag{9}$$

to obtain a practical form of the fractional controller in (9), the approximation method [25] was applied to approximate the fractional integration operator into workable filters. A Simulink model of the fractional controller was developed, followed by a validation of its performance using pure software and hardware-in-the-loop (HIL) real-time simulations prior to implementation [25]–[27].

5. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, results from simulation and experimental experiments are presented in order to validate the performance (robustness) of the investigated system using the designed fractional order controller. There are two communication modes between the Arduino board and MATLAB/Simulink: online and offline. In an online mode, the Arduino board runs the IO "server" package while the Simulink model runs on the host computer. The package runs in the background, listening for MATLAB commands from the Simulink model and responding via the serial port if necessary. In an offline mode, the Simulink model is transformed into code that runs on the Arduino board independently of the host computer, allowing the board to be disconnected from it. Figure 5 shows the components used to set up the application platform while Figure 6 and Figure 7 show the Simulink model and simulation results of the feedback loop with the designed fractional controller, respectively.

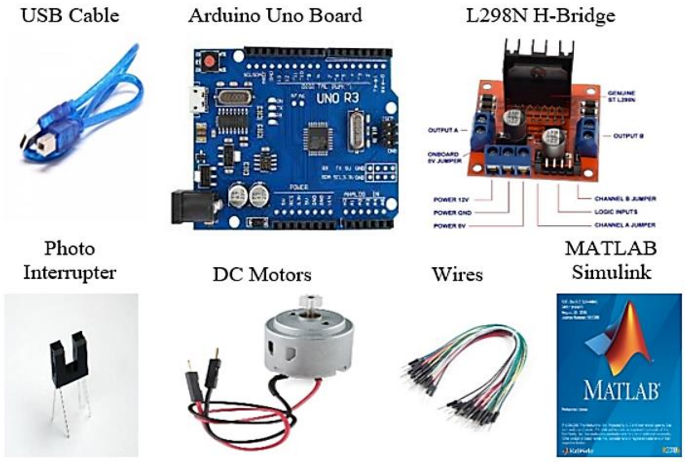

Figure 5. The components of the proposed platform

5.1. Robustness to gain variation test

To assess the robustness of the control system, the nominal plant gain k_n was varied by ±50%. The resulting step responses are illustrated in Figure 8 and Figure 9. As shown in Figures 8 and 9, the simulation results are in agreement with the experimental results, indicating a high degree of consistency and similarity between them. Also, the overshoots of the closed-loop step responses are almost constant for different nominal plant gain values k_n, indicating that the control system is damping. This implies that the closed-loop system can maintain stability and performance even under varying gain conditions.

5.2. Robustness to load disturbances test

To perform the load disturbance test, the plant was introduced with a change in electrical load during steady-state operation. Specifically, the electrical load was set with the following values of RL = 55 Ω at t = 20 seconds to induce a parameter variation. Then, the plant was set back to RL = 0 Ω at t = 40 seconds. The results of this test are presented in Figures 10, 11, and 12.

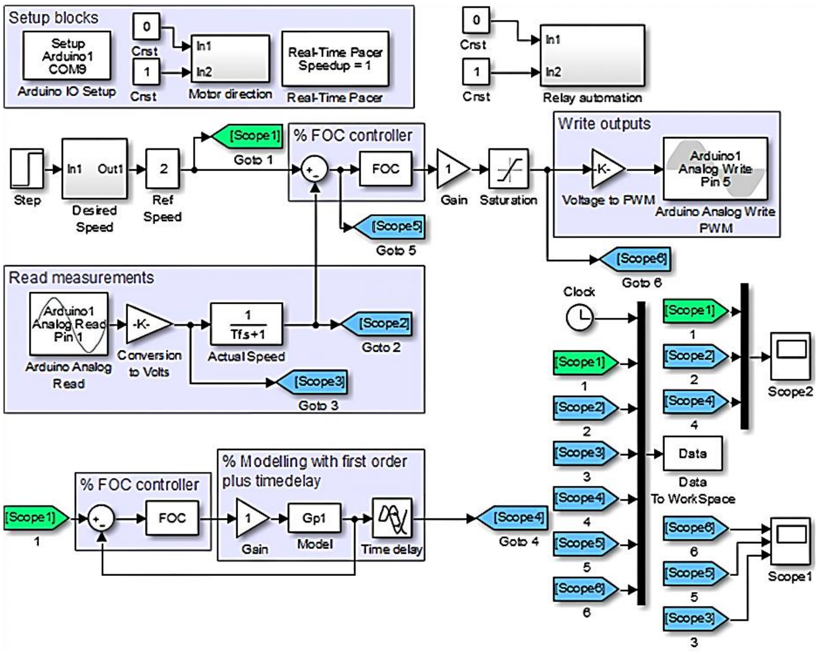

Figure 6. Simulink model of the proposed platform

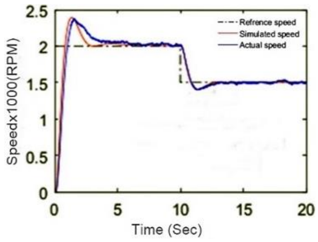

Figure 7. Simulated vs experimental results of speed responses (with Ts = 0.1)

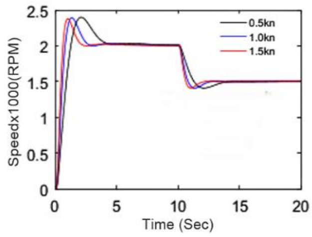

Figure 8. Robustness test for a gain variation (simulation results)

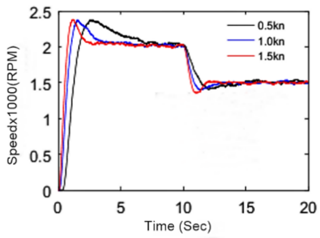

Figure 9. Robustness test for a gain variation (experimental results)

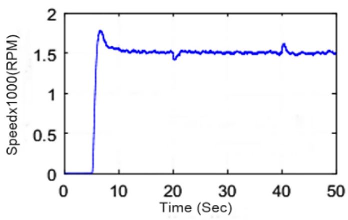

Figure 10. Robustness test to load disturbance of speed response

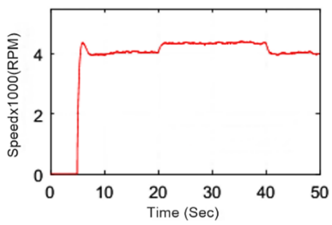

Figure 11. Control effort with load disturbance (experimental results)

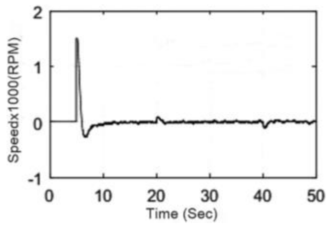

Figure 12. Control error with load disturbance (experimental results)

6. CONCLUSION

In this paper, a low-cost platform containing the necessary tools to deal with real time data acquisition and control using Arduino board has been developed. Arduino is the DAQ between Simulink and an experimental setup. Important robustness tests have been carried out to validate the proposed system. The validation has been successfully achieved through the use of a DC motor control. Therefore, the proposed architecture can be applied to other plants of FOPTD model. The experimental tests seem to be in agreement with the simulation and confirms that the proposed Arduino-Simulink interface can be used to support similar research applications. Also, the versatility and low cost of this platform make it a great option for hobbyists, students, and professionals alike, and it will be an excellent starting point for learning about control systems and automation.

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