

Android-Based Smart Centrifuge with PID Speed Control

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ABSTRACT

This study aimed to design and implement an Android-based centrifuge monitoring system with Proportional Integral Derivative (PID) speed control to improve rotational speed stability and monitoring flexibility in laboratory applications. The system utilized a DC motor as the driving unit, a speed sensor for feedback acquisition, and an Android application developed using MIT App Inventor for real-time monitoring. PID parameters were determined using the Ziegler–Nichols open-loop tuning method based on the process reaction curve. From the experimental response, a dead time of 0.5 s and a time constant of 3.65 s were obtained, resulting in PID parameters of $K_p = 8.76$, $K_i = 8.76$, and $K_d = 2.19$. Experimental testing was performed using a tachometer to evaluate rotational speed performance. The results showed that the implemented PID controller provided stable speed regulation with improved response characteristics and low steady-state error. In addition, the Android application successfully displayed real-time operational data and maintained reliable communication with the centrifuge system. The proposed system demonstrated that the integration of PID control and Android-based monitoring can enhance both control accuracy and operational convenience for laboratory centrifuge applications.



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1. INTRODUCTION

Centrifuges are essential laboratory instruments used to separate components of a sample based on differences in density through the application of centrifugal force [1][2][3]. These devices are widely utilized in clinical laboratories, pharmaceutical industries, biological research, and chemical analysis, particularly for blood sample processing and other biological fluid separations. The effectiveness of the separation process is strongly influenced by the rotational speed of the centrifuge, making speed accuracy and stability important factors in achieving reliable laboratory results.

Despite their widespread application, conventional centrifuge systems often experience difficulties in maintaining stable rotational speeds under varying operating conditions. Load variations, external disturbances, and fluctuations in power supply may affect rotational performance and reduce the accuracy of the separation process[4]. In addition, many laboratory centrifuges still employ limited user interfaces and require direct manual operation, making real-time monitoring and control less practical. These limitations may reduce operational efficiency and create challenges in educational laboratory environments where interactive and user-friendly equipment is required.

Various control strategies have been developed to improve the performance of rotational systems. Among these methods, the Proportional Integral Derivative (PID) controller remains one of the most widely used control techniques because of its simple implementation, robustness, and ability to improve system stability while reducing steady-state error[5][6]. The effectiveness of PID control is highly dependent on the selection of appropriate controller parameters. One of the most commonly used tuning approaches is the Ziegler–Nichols method, which determines controller parameters based on the dynamic characteristics of the system response and has been successfully applied in various motor speed control applications[7][8].

The advancement of mobile technology has enabled the integration of laboratory instruments with Android-based applications, allowing real-time monitoring and control through smartphones[9]. In addition, MIT App Inventor facilitates rapid Android application development with minimal programming requirements[10]. Although previous studies have explored PID-based speed control and Android-based monitoring separately, their integration in centrifuge systems for clinical laboratory practicum applications remains limited. Therefore, this study aims to develop a centrifuge system that combines accurate PID speed control with an intuitive Android-based monitoring interface to enhance both performance and usability. This study proposes a PID-controlled centrifuge integrated with an Android-based monitoring application. The PID parameters were tuned using the Ziegler–Nichols open-loop method[11][12], while the Android interface was developed using MIT App Inventor. The proposed system aims to provide stable speed control, real-time monitoring, and a portable, user-friendly, and cost-effective solution for clinical laboratory practicum applications.

2. RESEARCH METHOD

a. System Design

The proposed system consists of a centrifuge unit, a PID-based speed controller, and an Android monitoring application. Speed feedback from a rotational sensor is processed by a microcontroller, which adjusts the DC motor through PID control and transmits data to an Android device via Bluetooth. The application enables real-time monitoring and setpoint control, while the PID controller minimizes speed error by continuously regulating the motor drive signal.

b. PID Controller Design

A Proportional Integral Derivative (PID) controller was implemented to regulate the rotational speed of the centrifuge. The controller generates a control signal based on the difference between the desired speed and the measured speed. The PID control law is expressed as:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$

where $u(t)$ is the controller output, $e(t)$ is the speed error, and K_p , K_i , and K_d are the proportional, integral, and derivative gains, respectively.

c. PID Parameter Tuning

The PID parameters were determined using the Ziegler–Nichols open-loop tuning method. The tuning process was performed by applying a step input to the motor system and observing the resulting process reaction curve. The dead time (L) and time constant (T) were identified from the response characteristics. Based on the experimental results, the dead time was measured as 0.5 s and the time constant was determined as 3.65 s. The PID parameters were calculated according to the Ziegler–Nichols open-loop tuning rules. The obtained controller parameters were: $K_p = 8.76$, $K_i = 8.76$, $K_d = 2.189$. These parameters were applied to all speed settings during system testing.

d. Android Application Development

The Android monitoring application was developed using MIT App Inventor and connected to the centrifuge via Bluetooth. It enables users to set speed targets, monitor real-time rotational speed, and check connection status through a simple and user-friendly smartphone interface.

e. Experimental Procedure

System performance was evaluated through experimental testing under several rotational speed setpoints. During each experiment, the rotational speed was measured using a tachometer and compared with the desired setpoint. The system response was recorded to evaluate the effectiveness of the PID controller. In addition, Bluetooth communication tests were conducted to evaluate the stability of the wireless connection and the operational range between the centrifuge system and the Android application.

f. Data Collection and Analysis

The dataset consisted of experimental data collected from the developed centrifuge system, including rotational speed (RPM), speed setpoints, response time, PID parameters, and Bluetooth communication performance. The data were analyzed to evaluate speed control accuracy, PID controller performance, and the reliability of the Android-based monitoring system by comparing the measured speed with the desired setpoint and assessing communication stability during operation.

2.1. Data Collection

Data collection was conducted through experimental testing of the developed centrifuge prototype operating under a closed-loop control system, as shown in Fig. 1. Rotational speed (RPM) was measured using a calibrated tachometer at several predefined setpoints to evaluate system performance and dynamic response. For each test, the centrifuge was operated until steady-state conditions were reached, and the RPM data were recorded for analysis. An Android application developed using MIT App Inventor was used to set the desired rotational speed and monitor system performance in real time via Bluetooth communication. Wireless communication performance was also evaluated by varying the distance between the mobile device and the centrifuge system to determine the effective operating range and communication stability.

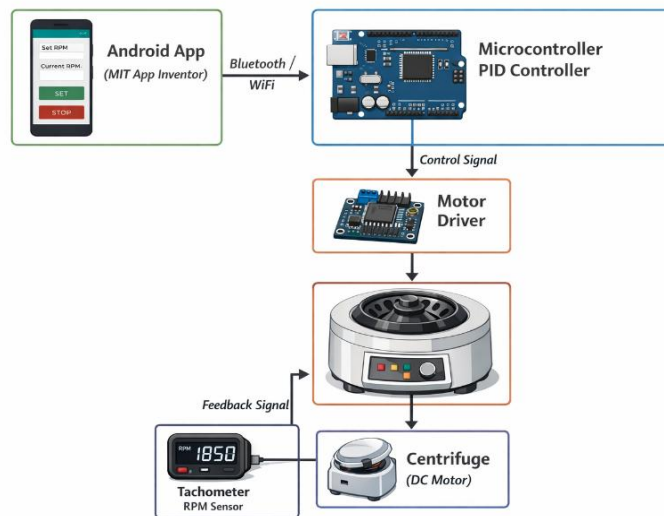


Figure 1. Block diagram of the PID-based closed-loop centrifuge control system with wireless interface and tachometer

2.2. Data Processing

The collected experimental data were processed to evaluate the performance of the centrifuge closed-loop control system under PID regulation. The recorded rotational speed (RPM) data were categorized based on different setpoint conditions and experimental runs. Both transient and steady-state responses were analyzed to characterize the dynamic behavior of the system.

Steady-state performance was evaluated by identifying the interval where the RPM output remained within a stable fluctuation band. The steady-state error (SSE) was computed as :[13]

$$SSE = r - y_{ss} \quad (1)$$

where r is the reference setpoint and y_{ss} is the measured steady-state output.

The centrifuge system was approximated using a first-order plus dead-time (FOPDT) model, as it provides a simple yet effective representation of real process dynamics and is widely applied in control system analysis and design [14][15][16][14]:

$$G(s) = K \cdot \frac{e^{-Ls}}{\tau s + 1} \quad (2)$$

where K is system gain, L is dead time, and τ is the time constant. The model parameters were identified from the step response curve obtained experimentally.

The control strategy for the centrifuge system was implemented using a Proportional–Integral–Derivative (PID) controller to regulate the rotational speed according to the desired setpoint[17]. The controller generates a control signal based on the error between the reference input and the measured output [18].

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (3)$$

where K_p , K_i , and K_d represent the proportional, integral, and derivative gains, respectively. The proportional term provides an immediate response to the current error, the integral term eliminates steady-state error by accumulating past errors, and the derivative term predicts future error trends to improve system stability and damping. The initial tuning of the PID parameters was performed using the Ziegler–Nichols closed-loop method. In this approach, the proportional gain was gradually increased while the integral and derivative gains were set to zero until the system reached a condition of sustained oscillation. The corresponding gain at this condition is defined as the ultimate gain (K_u), and the oscillation period is referred to as the ultimate period (P_u)[19].

Based on these experimentally obtained parameters, the: These initial values provide a baseline controller configuration that typically yields a fast response with acceptable stability[20]. However, due to the nonlinear characteristics and disturbances present in the centrifuge system, further fine-tuning was carried out experimentally. The tuning process aimed to minimize overshoot, reduce settling time, and improve overall stability while maintaining a small steady-state error.

The final PID parameters were selected based on the best trade-off between response speed and system stability under various setpoint conditions[21]. System performance was evaluated using standard time-domain parameters, including rise time (t_r), settling time (t_s), overshoot (M_p), and steady-state error (SSE). Rise time indicates response speed, settling time reflects stability within a $\pm 2\%$ tolerance band, overshoot measures the maximum response exceeding the setpoint, and SSE represents steady-state accuracy. Stability was assessed from response convergence and damping behavior, ensuring asymptotically stable responses at all tested setpoints.[22].

2.3. Calibration and Measurement Uncertainty

This is how to start another subsection Calibration of the tachomete based RPM measurement system was performed to ensure the accuracy and reliability of rotational speed measurements. The calibration process was conducted by comparing the tachometer readings with reference rotational speed values at several predefined setpoints. At each calibration point, repeated measurements were carried out under identical operating conditions to minimize external disturbances and random errors. For each reference point, a set of n repeated measurements was collected. The statistical parameters, including the mean value ($\bar{x}$), standard deviation (SD), and number of observations (n), were calculated to characterize the measurement distribution. The mean value represents the best estimate of the measured RPM, while the standard deviation indicates the spread or variability of the data. The standard uncertainty due to random effects (Type A uncertainty) was evaluated using[23]:

$$u = \frac{SD}{\sqrt{n}} \quad (4)$$

This value reflects the uncertainty associated with measurement repeatability. To express the uncertainty at a higher confidence level, the expanded uncertainty was calculated using a coverage factor $k = 2$, corresponding to a confidence level of approximately 95%:

$$U = k \cdot u = 2 \frac{SD}{\sqrt{n}} \quad (5)$$

The expanded uncertainty provides an interval within which the true value of the measured RPM is expected to lie with a 95% level of confidence[24]. In addition to Type A uncertainty, the calibration procedure also considered potential sources of systematic error, such as instrument resolution and calibration reference limitations. These components can be incorporated into a combined uncertainty analysis if required. An uncertainty budget table was constructed to summarize the calibration results for each reference point. The table includes the reference RPM, measured mean RPM, standard deviation, standard uncertainty, and expanded uncertainty. This comprehensive evaluation ensures traceability and supports the validity of the measurement system used in the experimental analysis[25].

Type B uncertainty was estimated based on instrument characteristics, such as the resolution of the tachometer and manufacturer specifications. Assuming a rectangular (uniform) distribution, the Type B uncertainty can be expressed as[23]:

$$u_B = \frac{a}{\sqrt{3}} \quad (6)$$

where a represents the half-width of the measurement interval (e.g., instrument resolution or tolerance). The combined standard uncertainty (u_c) was then calculated using the root-sum-square (RSS) method[24]:

$$= \sqrt{u_A^2 + u_B^2} \quad (7)$$

To express the uncertainty with a higher confidence level, the expanded uncertainty (U) was calculated using a coverage factor $k = 2$, corresponding to a confidence level of approximately 95%:

$$U = K \cdot U_c \quad (8)$$

The combined uncertainty provides a more realistic estimation of the measurement error by incorporating both random and systematic components. This approach ensures that the reported RPM measurements are supported by a rigorous uncertainty analysis, improving the reliability and credibility of the experimental results[24]. An uncertainty budget table was constructed to summarize all contributing components, including Type A uncertainty, Type B uncertainty, combined uncertainty, and expanded uncertainty for each calibration point.

2.4. Wireless Communication Performance

Wireless communication between the Android application and the centrifuge system was evaluated by varying the transmission distance[26]. The effective control range was defined as the maximum distance at which the system maintained stable command execution without packet loss or significant delay[27][28]. Communication latency and stability were qualitatively observed to assess real-time control feasibility.

3. RESULTS AND DISCUSSION

a. Result

The centrifuge system was successfully transformed from an open-loop control system into a closed-loop control system by integrating an optocoupler sensor and a Proportional-Integral-Derivative (PID) controller. In the original open-loop configuration, the microcontroller generated Pulse Width Modulation (PWM) signals based solely on user-defined speed and time settings. Since no feedback mechanism was available, the system could not detect or correct deviations between the desired rotational speed and the actual motor speed. After the implementation of the closed-loop architecture, the optocoupler sensor continuously measured the motor rotational speed and transmitted the feedback signal to the controller. The PID controller processed the measured speed and adjusted the PWM output according to the calculated error between the setpoint and the actual speed.

Experimental testing was conducted at three setpoints: 1500 RPM, 2000 RPM, and 3000 RPM. The results showed that the centrifuge successfully reached all target speeds and maintained stable operation throughout the testing period. The response curves indicate that the motor speed increased rapidly toward the desired setpoint and remained within an acceptable tolerance range after reaching steady-state conditions. Furthermore, the system demonstrated low steady-state error and stable speed regulation. The measured speed fluctuations remained within $\pm 2\%$ of the setpoint, indicating effective control performance. The dynamic response characteristics obtained from the experiments included a short rise time, low overshoot, and fast settling time. The response characteristics for all tested setpoints are illustrated in Fig. 2.

b. Discussion

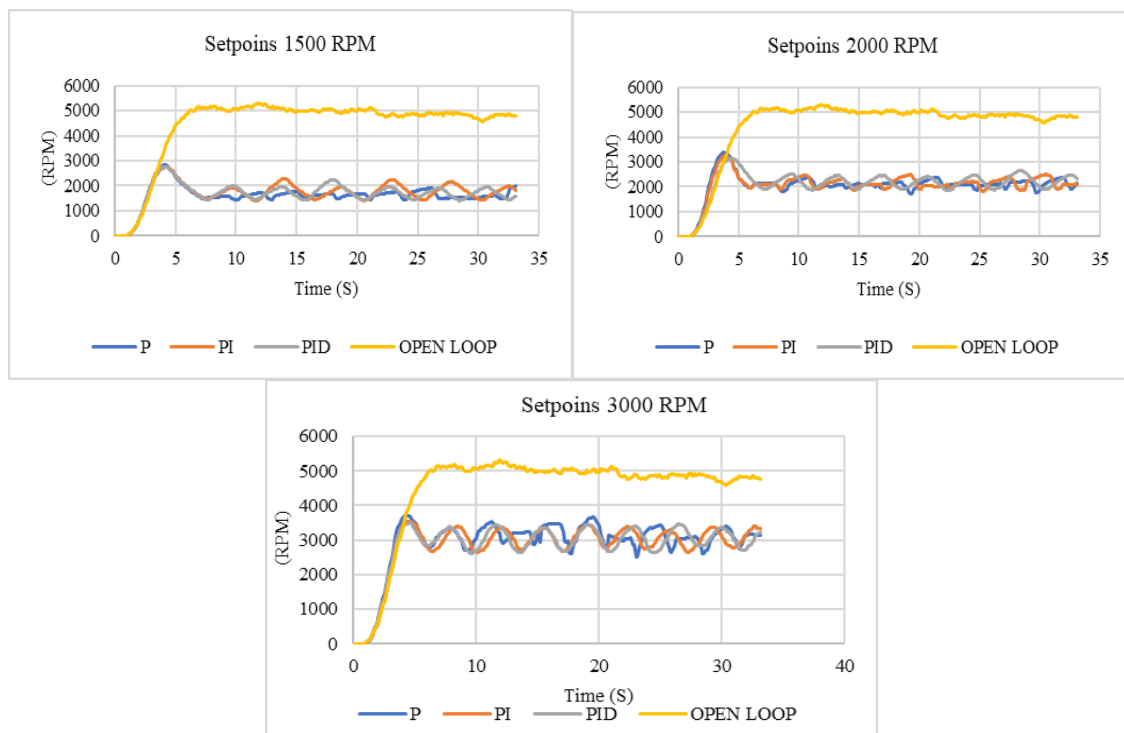


Figure 2. Dynamic responses of P, PI, PID, and open-loop controls at setpoints of (a) 1500 RPM, (b) 2000 RPM, and (c) 3000 RPM

The main finding of this study is the successful conversion of the centrifuge from an open-loop to a closed-loop control system using a PID controller. By integrating an optocoupler sensor as feedback, the controller continuously adjusted the PWM signal based on the error between the setpoint and measured speed, resulting in improved accuracy and stability. As shown in Fig. 2, the system achieved fast setpoint tracking, low overshoot, short settling time, and stable operation within a $\pm 2\%$ tolerance band. Consistent performance at 1500, 2000, and 3000 RPM demonstrates the robustness and reliability of the implemented PID controller under varying operating conditions.

3.1. System Response of the Centrifuge

The dynamic response of the centrifuge system was first analyzed to observe its general behavior under operating conditions. As shown in Fig. 2, the centrifuge system exhibits a gradual increase in rotational speed from the initial condition until it approaches the steady-state region. The response shows a relatively smooth rise without abrupt changes, indicating stable system behavior. However, slight oscillations are observed near the steady-state region, suggesting that the system experiences minor fluctuations before reaching full stability. This behavior highlights the importance of implementing an appropriate control strategy to improve response stability and reduce oscillations.

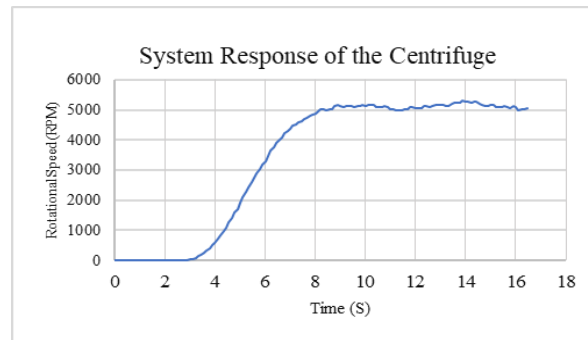


Figure 3. System response of the centrifuge

3.2. The performance comparison of P, PI, and PID controllers

As shown in Table 1, all controllers exhibit similar rise times, indicating comparable initial response speeds. However, differences are observed in overshoot and stability. The PI controller achieves the lowest overshoot at 1500 RPM, while the PID controller performs best at 2000 and 3000 RPM by reducing overshoot and oscillations. Overall, the PID controller provides the most stable and balanced performance across all operating conditions, demonstrating greater robustness for a wide range of rotational speeds.

Table 1. Performance comparison at various setpoints

Setpoint (RPM)	Controller	Rise Time (s)	Overshoot (RPM)	Oscillation (RPM)
1500 RPM	P	2.6	2798	400
	PI	2.6	2210	500
	PID	2.6	2235	500
2000 RPM	P	3.0	3364	500
	PI	3.0	3191	500
	PID	3.0	3127	500
3000 RPM	P	3.5	3686	800
	PI	3.5	3548	700
	PID	3.5	3489	700

3.3. Experimental Validation of Sample Separation

To validate the practical performance of the centrifuge, a separation experiment was conducted using a mixture of water, milk, and food coloring as a blood-like fluid model. Two identical 5 mL samples were prepared: one processed using open-loop PWM control and the other using closed-loop PID control. The PWM system operated at the minimum duty cycle required for rotation ($T_{ON} = 5.8\%$), while the PID system was set to 3000 RPM. Both experiments were conducted for 30 minutes.

The results, shown in Fig. 4, indicate that both control methods produced comparable separation outcomes, likely due to similar average rotational speeds and processing times. However, the PID-controlled system provided superior speed regulation and operational stability by continuously maintaining the desired rotational speed. This improves process consistency, repeatability, and robustness against disturbances, making the closed-loop approach more reliable for centrifugation applications. Future studies should evaluate the system using fluids with different viscosities or real biological samples.



Figure 4. Sample separation result using PWM control (TON = 5.8%, 30 minutes)

3.4. Centrifuge Calibration Result (RPM Measurement)

The calibration of the centrifuge was performed using a tachometer at three predefined setpoints: 1500 RPM, 2000 RPM, and 3000 RPM. The performance was evaluated in terms of average measured rotational speed, correction value, standard deviation (STDEV), and expanded uncertainty (U95).

Table 2. Centrifuge calibration results

Setpoint (RPM)	Average (RPM)	Correction (RPM)	STDEV (RPM)	U95 (RPM)
1500	1511	+11	1.50	±1.5
2000	2031	+31	1.98	±1.5
3000	3012	+12	1.45	±1.5

The calibration results in Table 2 indicate a consistent positive deviation from the setpoints, showing that the centrifuge tends to slightly overestimate rotational speed. The largest correction was observed at 2000 RPM (+31 RPM). Despite this systematic error, the system demonstrated high precision, with standard deviations below 2 RPM and a constant expanded uncertainty (U95) of ±1.5 RPM across all test points. These results confirm that the centrifuge provides stable and repeatable measurements. However, applying calibration correction factors is recommended to improve accuracy, especially at critical operating speeds. Overall, the system is reliable in terms of precision but requires calibration adjustment to enhance accuracy.

3.5. Wireless Communication Performance

Table 3 presents the Bluetooth communication performance at various distances. The system operated reliably without noticeable delay up to 7 m under minimal obstruction conditions. When the signal passed through a concrete wall, a delay of approximately 0.2 s was observed at distances of 10–15 m, while the connection was lost at 20 m. These results indicate that the Bluetooth-based control system provides stable communication within typical laboratory environments, with an effective range of up to 15 m under obstructed conditions.

Table 3. Bluetooth communication performance at various distances

Distance Range	Environment	Connection Status	Delay (s)
1–7 m	Indoor	Stable	0
10–15 m	Outdoor	Slight delay	0.2
20 m	Outdoor	Disconnected	—

The transition from an open-loop to a closed-loop centrifuge system significantly improved speed control accuracy and stability. By integrating optocoupler-based feedback and a PID controller, the system was able to continuously minimize speed error and maintain operation within a ±2% tolerance band. The PID controller provided the best overall performance, particularly at higher setpoints, where derivative action effectively reduced oscillations and improved damping. Although a consistent measurement bias was observed during calibration, the low standard deviation values (<2 RPM) indicate high precision and repeatability. Experimental validation demonstrated that the proposed system achieved reliable sample separation and stable speed regulation throughout operation. While visual separation results were similar between PWM and PID control methods, PID control ensured

greater consistency and reproducibility. Wireless communication tests showed that Bluetooth-based monitoring remained functional within a typical laboratory range, although communication delays increased in the presence of physical obstacles. These findings are consistent with previous studies showing that closed-loop PID control outperforms open-loop and PI-based approaches in accuracy, stability, and disturbance rejection. The results also demonstrate that low-cost embedded systems can provide reliable centrifuge performance for laboratory applications. However, this study is limited by the use of simplified fluid samples, the presence of systematic measurement bias, and Bluetooth range constraints. Future work should focus on advanced calibration methods, testing with real biological samples.

4. CONCLUSION

This study successfully transformed a conventional centrifuge system from an open-loop control configuration into a closed-loop control system integrated with a Proportional-Integral-Derivative (PID) controller. The implementation of feedback control enabled the system to continuously monitor and adjust the motor speed, thereby improving rotational speed regulation and overall system performance. The experimental results demonstrated that the proposed PID-based control system achieved the desired objectives by providing accurate and stable speed control. The centrifuge maintained operation within $\pm 2\%$ of the target speed, exhibited low steady-state error, and showed favorable dynamic response characteristics, including fast settling behavior and minimal overshoot. Calibration and validation tests further confirmed the reliability and repeatability of the speed measurement system. In addition, the wireless Android-based control interface operated successfully within the tested communication range, allowing remote monitoring and control with minimal delay. These findings indicate that the developed system offers improved stability, accuracy, and operational convenience compared with the previous open-loop configuration. Therefore, the proposed closed-loop PID-controlled centrifuge can be considered an effective solution for applications requiring precise and consistent rotational speed control. Future research may focus on evaluating performance using real biological samples and implementing advanced control algorithms to further enhance system adaptability and accuracy.

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