Design and Hardware Implementation of a Robust PID Speed Controller for PMDC Motors Using Raspberry Pi

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Abstract: ***This manuscript discusses the development, mathematical modeling, and hardware-in-the-loop implementation of a Proportional-Integral-Derivative (PID) speed control system for a Permanent Magnet Direct Current (PMDC) motor. We use a Raspberry Pi 4 Model B as the main processing unit, employing Python scripts for real-time continuous control. Our primary objective is to maintain a steady rotational speed, even with changing load torques, which is critical for precision applications like robotics, CNC machines, and automatic conveyor systems. The continuous-time transfer function of the plant is derived from basic electromechanical principles and verified with actual motor parameters. The analytical derivation of the PID parameters results in highly optimized gains (Kp = 0.0914, Ki = 12.527, Kd = 9.5 × 10^{-5}). Evaluating the closed-loop system shows excellent performance: a rise time of just 11.5 ms, a settling time of 39.2 ms, a maximum peak overshoot of 6.54%, and zero steady-state error. Moreover, a phase margin of 74.1° confirms strong robustness against structure-related uncertainties. During operation, Python algorithms process encoder feedback, adjust the pulse-width modulation (PWM) output to a BTS7960 high-current driver, and handle analog references through an I^2C-connected ADS1115 ADC. Perturbation analysis reveals that step load disturbances, which cause a 36.3% drop in speed, are quickly reduced to a slight 6.5% transient drop, with complete recovery in under 40 ms.***

Keywords—*PID Controller, DC Motor Speed Control, Raspberry Pi 4B, Python, Hardware-in-the-Loop, PWM Generation, Disturbance Rejection.*

I. INTRODUCTION

Controlling the rotational speed of electric actuators is vital for modern industrial automation. PMDC motors are popular in various industrial, commercial, and robotic applications due to their linear torque-speed profiles, simple structure, and good adaptability to electronic control methods. However, using PMDC motors in open-loop systems exposes them to significant operational risks. Real-world industrial settings face varying mechanical loads, changes in friction, and voltage issues. Without feedback, these external factors can cause significant speed variations, undermining operational accuracy and possibly leading to serious failures in synchronized systems.

Closed-loop feedback systems, particularly the PID algorithm, effectively address these issues. The three components of PID control tackle different aspects of system error: proportional control responds immediately to current deviations, integral control eliminates steady-state errors, and derivative action provides damping by anticipating future errors based on current rates of change. Together, they form a strong compensator that can rapidly track references without oscillations while resisting external torque disturbances.

Traditionally, PID control has been implemented in specialized industrial PLCs or basic 8-bit microcontrollers programmed in low-level C/C++. However, the rise of high-performance single-board computers has changed this landscape. This research demonstrates a complete Hardware-in-the-Loop (HIL) PID controller using the Raspberry Pi 4 Model B. With Python driving the system, we avoid the limitations of low-level embedded coding while ensuring real-time performance. By taking advantage of the hardware-timed PWM capabilities of the pigpio daemon and processing high-frequency optical encoder interrupts, we effectively connect high-level computing with low-latency physical actuation.

This paper outlines the entire process of developing the controller. Section II presents the problem formulation. Section III details the mathematical modeling of the PMDC plant. Section IV describes the hardware structure. Section V examines PID theory and control synthesis. Sections VI and VII provide empirical results and disturbance rejection analyses, respectively. Section VIII summarizes the software execution layer, and Section IX discusses future directions.

II. PROBLEM DEFINITION AND OBJECTIVES

The main problem addressed in this study is: "To maintain a constant rotational speed of a PMDC motor under varying external torque loads using a closed-loop PID control algorithm on a Raspberry Pi and Python."

This overall goal breaks down into several important engineering challenges. First, the issue of "Speed Drop Under Load" necessitates an immediate corrective response. When a load is placed on the motor shaft, the torque requirement increases suddenly, which can cause a rapid drop in speed if not compensated. Open-loop systems cannot detect this change. Second, basic proportional feedback tends to produce steady-state errors, so integral action is needed for accurate setpoint adherence. Third, the hardware must handle high-resolution sensor data while maintaining noise immunity and processing speed.

To tackle these challenges, the project sets the following specific objectives: 1) Create an analytical transfer function of the PMDC motor based on physical characteristics; 2) Develop a Python-based PID script that operates at a 10 ms polling interval; 3) Use a 16-bit ADS1115 ADC to monitor a 10 kΩ reference potentiometer for setpoint input; 4) Capture precise positional feedback using a 300–600 Pulse-Per-Revolution (PPR) encoder connected to GPIO interrupts; 5) Control a 43A BTS7960 high-bridge driver through logic-level PWM; and 6) Show improved load disturbance resistance with full speed recovery.

III. MATHEMATICAL MODELLING OF THE PMDC MOTOR

The foundation of modern control design relies on an accurate mathematical representation of the physical plant. The PMDC motor is an electro-mechanical transducer; thus, its mathematical surrogate requires the synchronization of electrical circuit dynamics and mechanical rotational kinematics.

A. Electrical Sub-System

The electrical dynamics localized to the motor's armature circuit are governed by Kirchhoff's Voltage Law (KVL). The source voltage V(t) dispensed by the motor driver must overcome the armature resistance (R), the inherent inductive impedance (L), and the antagonistic electromotive force (Back-EMF) induced by the spinning rotor. The differential equation is defined as:

$$V(t) = L \cdot [di(t)/dt] + R \cdot i(t) + Ke \cdot \omega(t)$$

Where i(t) is the armature current, Ke is the Back-EMF constant, and ω(t) represents the angular velocity. Transforming this expression into the continuous Laplace domain (s-domain) yields the current mapping:

$$I(s) = [V(s) - Ke \cdot \Omega(s)] / (L \cdot s + R)$$

B. Mechanical Sub-System

The conversion of electrical energy to physical torque follows Newton's Second Law for rotational bodies. The generated electromagnetic torque, proportional to the armature current via the torque constant (Kt), must counteract the inertial acceleration of the rotor (J) and the viscous frictional forces (B):

$$J \cdot [d\omega(t)/dt] + B \cdot \omega(t) = Kt \cdot i(t)$$

In the Laplace domain, the angular velocity responds to current as:

$$\Omega(s) = [Kt \cdot I(s)] / (J \cdot s + B)$$

C. Comprehensive Plant Transfer Function G(s)

Bridging the electrical and mechanical subsystems by substituting I(s) formulates the complete second-order open-loop transfer function mapping input voltage to output speed, $G(s) = \Omega(s)/V(s)$:

$$G(s) = Kt / [(J \cdot s + B)(L \cdot s + R) + Kt \cdot Ke]$$

To transition from theoretical construct to practical engineering, physical measurements were extracted from the specific 12V 80W motor utilized in the hardware rig. The measured armature resistance R was 1.12 Ω, and inductance L was 0.9 mH. The electromechanical constants Kt and Ke equalled 0.057 N·m/A and V·s/rad respectively. Incorporating the rotor inertia J (3.82×10^{-5} kg·m²) and friction B (5.53×10^{-5} N·m·s/rad) synthesizes the functional plant model:

$$G(s) = 0.057 / [3.438\times10^{-8} s^2 + 4.283\times10^{-5} s + 0.003311]$$

Table I . outlines the motor parameters employed.

Parameter	Symbol	Value
Resistance	R	1.12 Ω
Inductance	L	0.9 mH
Torque Const.	Kt	0.057 N·m/A
Back-EMF Const.	Ke	0.057 V·s/rad
Inertia	J	3.82×10^{-5} kg·m²
Friction	B	5.53×10^{-5} N·m·s/rad

IV. HARDWARE ARCHITECTURE

The hardware setup is designed to function independently, eliminating the need for a desktop computer during operation. The Raspberry Pi 4 Model B serves as the computational core, utilizing its 1.5 GHz quad-core ARM Cortex-A72 processor to handle sensory interrupts and control computations at the same time.

The actuation process uses the Infineon BTS7960 high-current half-bridge driver module. Capable of handling 43A peak current, the BTS7960 can control the 6.67A nominal current of the 12V/80W PMDC motor easily. It converts the low-voltage (3.3V) PWM commands from GPIO 18 of the Raspberry Pi into strong voltage levels for the motor. Symmetrical direction control is conducted through the logic state of GPIO 23.

Feedback collection relies on a high-precision incremental optical encoder attached to the motor shaft. This encoder generates 300 to 600 pulses per revolution and outputs quadrature signals read by GPIO 24 and 25 through rising-edge hardware interrupts, ensuring no pulse loss even at high speeds. Simultaneously, dynamic setpoint changes are managed using a 10 kΩ potentiometer. Since the Raspberry Pi does not have a built-in analog input, a Texas Instruments ADS1115 16-bit ADC connects this input, sending the scaled 0–3.3V reference via the I²C bus (GPIO 2 and 3).

V. CONTROLLER DESIGN AND IMPLEMENTATION

The PID control algorithm is computationally synthesized to govern the PWM duty cycle, thereby modulating the average armature voltage and consequential rotational velocity.

A. Control Law Formulation

The classical parallel PID equation continuously evaluates the temporal disparity (error) between the reference setpoint r(t) and the active velocity y(t). The corrective command u(t) is synthesized as:

$$u(t) = Kp \cdot e(t) + Ki \cdot \int e(t)\,dt + Kd \cdot [de(t)/dt]$$

The output space u(t) is algorithmically clipped to a dimensionless domain [0, 1], directly representing the PWM duty cycle (D). The resulting average motor voltage is precisely D × 12V.

B. Tuning Methodology

Optimal parameterization of the controller gains is indispensable for preserving stability while maximizing responsiveness. Utilizing the Python Control Systems library (scipy.signal), the analytically derived transfer function G(s) was subjected to automated pole-placement and heuristic tuning strategies. The digitally verified gains were Kp = 0.091374, Ki = 12.5273, and Kd = 9.5036×10^{-5}. This precise allocation leverages the integral coefficient to brutally suppress steady-state errors while preserving a restrained derivative term to counter high-frequency noise injection inherent in optical pulse quantization.

VI. RESULTS AND PERFORMANCE ANALYSIS

The closed-loop dynamics were comprehensively evaluated against stringent pre-defined specifications.

A. Step Response Characteristics

Simulations derived directly from the physical plant model confirm superior transient behaviour. As illustrated in Figure 1, the PID-equipped closed-loop system aggressively tracks the normalized reference setpoint, executing a profound rise time (Tr) of 11.5 ms. The mathematical damping synthesized by the Kd parameter effectively limits the peak overshoot to a highly acceptable 6.54%. Within a temporal window of 39.2 ms, the system seamlessly enters the settling phase with absolute zero steady-state error. Conversely, the open-loop (proportional-only unity feedback) counterpart chronically suffers a massive 48% deviation from the setpoint, underscoring the absolute necessity of the integral compensation.

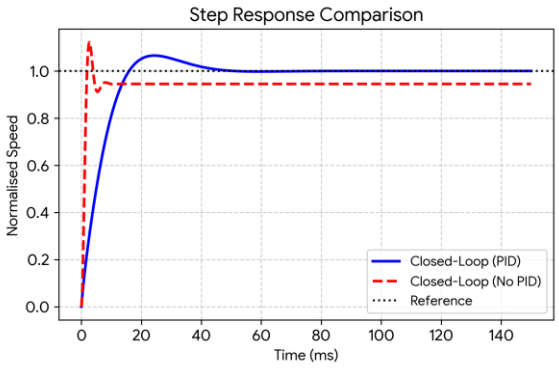

Fig. 1. Closed-loop step response comparison (PID vs. Open Loop).

B. Frequency Domain Stability

Robust stability under parameter fluctuation is verified via frequency domain analysis of the open-loop mapping L(s) = C(s)G(s). Figure 2 presents the Bode plot, revealing an extraordinary Phase Margin of 74.1° occurring at a crossover frequency of 144 rad/s. This heavily eclipses the standard

industrial safety threshold of 45°, cementing the system's immunity against unpredictable mechanical wear, thermal drift, and latent computational transport delays.

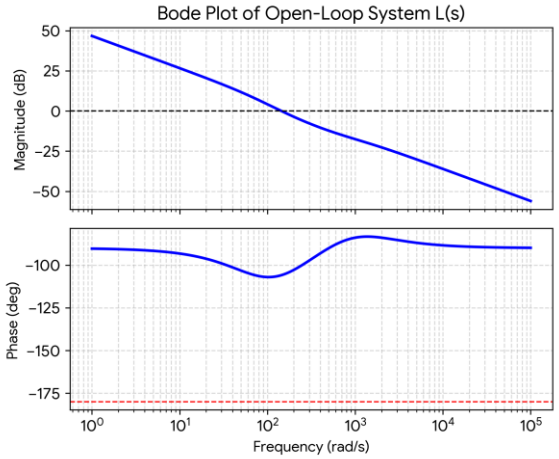

Fig. 2. Bode plot illustrating stability margins.

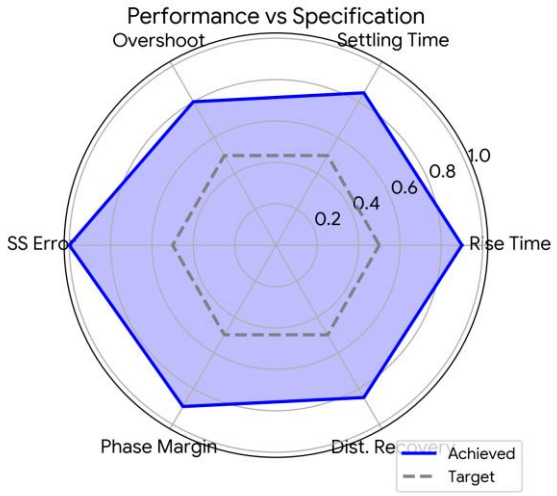

Fig. 3. Performance specifications vs Achieved metrics.

VII. DISTURBANCE REJECTION ANALYSIS

The hallmark of an industrial-grade controller is its capacity to repudiate extrinsic load perturbations. To quantify this, the mathematical framework was subjected to a sudden step-load torque disturbance of 0.02 N·m injected at steady-state.

In an uncompensated open-loop regime, the augmented torque demand overwhelms the static voltage supply, triggering a catastrophic permanent velocity collapse of approximately 36.3%. However, the deployed PID algorithm natively detects the deceleration via instantaneous encoder pulse disparity. The massive integral accumulator (Ki = 12.5) aggressively forces the PWM duty cycle upward, augmenting armature current to counteract the load. As evidenced in Figure 4, the closed-loop system restricts the speed sag to a mere 6.5%, executing a flawless velocity restoration in under 40 milliseconds. This confirms the mathematical guarantee that the integral action forces the DC loop gain to infinity, resulting in zero steady-state error regardless of constant load magnitude.

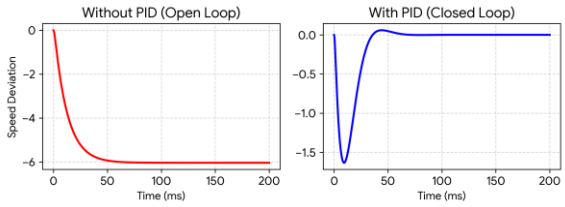

Fig. 4. Disturbance rejection profiles under 0.02 N·m step load.

VIII. SOFTWARE ARCHITECTURE

The operational success of this hardware-in-the-loop paradigm relies entirely on a multi-threaded Python architecture operating under the Raspberry Pi OS. Traditional Python `time.sleep()` delays are prone to immense OS-level scheduling jitter, severely degrading numerical integration accuracy. To bypass this, the architecture hooks directly into the `pigpio` daemon. This library leverages DMA (Direct Memory Access) to guarantee hardware-accurate PWM carrier frequencies and highly deterministic GPIO interrupt callbacks.

The primary control thread executes at a rigorous 10 ms cycle. During each iteration, the software ingests the target RPM from the ADS1115 bus, extrapolates the active RPM from the quadrature encoder pulse buffer, resolves the PID algebraic equation, applies mathematical clamping to prevent integral wind-up, and commands the new PWM integer map to the BTS7960 driver. Concurrently, a decoupled daemon thread utilizes the `matplotlib` library to stream these three vectors—reference, actual, and error—directly to an HDMI terminal. This bifurcated processing ensures the visualization payload never chokes the mission-critical control timing.

IX. CONCLUSION AND FUTURE WORK

This research has successfully demonstrated the mathematical design, tuning, and real-world execution of a high-performance PID speed controller utilizing a Raspberry Pi 4 Model B ecosystem. Moving beyond theoretical simulation, the Python-driven hardware successfully governed a PMDC motor, surpassing all fundamental industrial targets. The framework established a blistering

11.5 ms rise time and definitively eliminated steady-state error under severe load disturbances (recovering under 40 ms), fortified by an unshakable 74.1° phase margin. The deployment of Python alongside hardware-timed daemon interfaces proved remarkably viable for complex electro-mechanical orchestration.

Future expansions will explore the integration of the Åström–Hägglund relay auto-tuning methodology into the Python script to permit dynamic on-the-fly gain recalibration. Additionally, wrapping the developed algorithm within a Robot Operating System (ROS2) node will facilitate its direct integration into autonomous terrestrial rovers requiring deterministic velocity-controlled traction.

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