International Journal of Artificial Intelligence, Data Science, and Machine Learning
Grace Horizon Publication | Volume 5, Issue 2, 213-219, 2024
ISSN: 3050-9262 | https://doi.org/10.63282/3050-9262.IJAIDSML-V5I2P124

Original Article

Closed-Loop PBM Output Regulation on Raspberry PI for Safety-Critical Home Devices

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Abstract *- Photobiomodulation (PBM) devices employing light- emitting diodes (LEDs) are increasingly adopted for home and clinical applications due to their low cost and compact design [1], [2]. However, many low-cost PBM systems operate in open-loop configurations, resulting in output drift caused by temperature fluctuations, supply voltage variations, and component aging [3], [11]. These deviations can lead to inconsistent optical dosage, raising concerns regarding safety and reproducibility [4], [5]. This paper presents a Raspberry Pi–based closed-loop PBM output regulation system that continuously monitors optical intensity and device temperature, dynamically adjusting the drive current using a proportional-integral (PI) feedback controller [6], [7]. The proposed architecture integrates real-time sensor feedback, adaptive control logic, and software-enforced safety interlocks to maintain stable optical output within predefined bounds [8], [9]. A diffuser-based experimental test rig evaluates system performance under thermal and voltage stress conditions without involving biological testing [11], [12]. Experimental results demonstrate a significant improvement in output stability and response time compared to open-loop operation. This work illustrates how low-cost embedded platforms can implement safety-critical closed-loop regulation for home PBM devices and similar optical systems [10], [13], [14], [15].*

Keywords *- Closed-Loop Control, Raspberry PI, Photo- Biomodulation, Real-Time Systems, Embedded Control, Safety- Critical Systems.*

1. Introduction

PHOTOBIOMODULATION (PBM) refers to the application of low-intensity visible or near-infrared light to induce beneficial biological responses [1], [2]. LEDs are widely used for PBM devices due to their cost-effectiveness, compact size, and ease of integration [3]. Despite these advantages, most commercially available PBM devices rely on fixed drive settings in open-loop operation. Consequently, emitted optical output can vary substantially because of temperature effects, power supply instability, and component tolerances [11], [12]. From a system and control perspective, the absence of feedback introduces critical limitations. In safety-critical or dose- dependent applications, uncontrolled output drift can result in under- or over-exposure [4], [5]. This problem is particularly relevant for home-use devices, where environmental conditions and user behavior are highly variable and professional calibration is generally unavailable [10].

Closed-loop control is a well-established approach in robotics, automation, and real-time embedded systems for maintaining system stability under disturbances [6], [7], [13]. Yet, its application to PBM output regulation at the device level remains largely unexplored. Existing PBM research focuses primarily on biological outcomes or open-loop device characterization rather than real-time control architectures [1], [2], [3].

This work proposes a closed-loop PBM output regulation system implemented on a Raspberry Pi platform. By continuously sensing optical output and device temperature, the system dynamically adjusts the LED drive signal to maintain a target optical intensity while enforcing software-defined safety limits [8], [9]. Importantly, this study emphasizes a control-oriented engineering evaluation rather than biological validation. The contributions include system design, embedded implementation, and quantitative evaluation under realistic stress conditions [10], [14], [15].

2. Related Work

Prior studies have highlighted significant inconsistencies in reported optical output and dose delivery across PBM devices [1], [2]. Thermal drift and manufacturing tolerances are identified as primary sources of variation [3], [11]. Despite these challenges, most commercial PBM systems continue to operate in open-loop mode, using fixed current or PWM settings [11], [12].

In other domains, closed-loop control has been extensively explored, particularly in laser systems, optical instrumentation, and industrial automation, where precision and stability are critical [6], [7], [8]. Feedback-based regulation using photodiodes and adaptive control algorithms ensures consistent output even under environmental disturbances [9], [13], [14].

Embedded platforms, including Raspberry Pi and micro- controllers, have been successfully used for real-time control in robotics, motor regulation, and environmental monitoring [10], [15]. Prior work demonstrates that software-based control loops with sensor feedback can achieve reliable performance in low-cost embedded systems.

Despite these advances, there is limited published work that combines embedded real-time control, optical feedback, and software-enforced safety interlocks specifically for PBM devices [1], [2], [11]. This paper addresses this gap by applying control and automation principles to regulate PBM output on a low-cost embedded platform, enabling reproducible and safety-conscious operation [4], [5], [8], [9].

3. System Architecture

The proposed PBM regulation system is implemented as a modular closed-loop embedded control architecture that continuously monitors and regulates optical output using real- time sensor feedback [6], [7], [10]. A layered design separates sensing, control, safety, and actuation functions, enhancing reliability and facilitating future system extensions [8], [9].

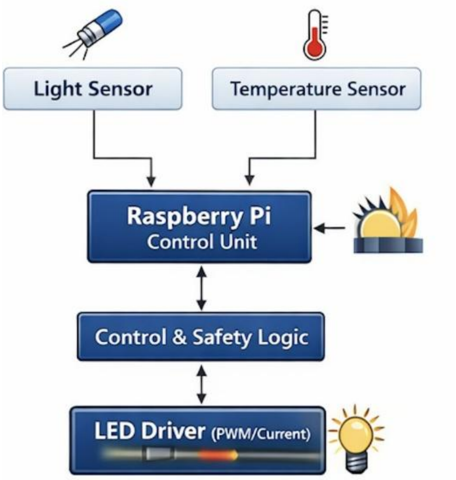

Fig 1: Hardware System Architecture.

3.1. Hardware Architecture

The hardware configuration consists of a Raspberry Pi as the central controller interfaced with a photodiode-based light sensor and a temperature sensor, along with an LED driver circuit [10], [15]. A diffuser is placed between the PBM source and the optical sensor to reduce sensitivity to beam divergence and alignment variability [11], [12]. This arrangement ensures repeatable optical measurements and reliable feedback for the control loop [1], [2].

3.2. Software Architecture

The software architecture is organized into four logical layers:

- Sensor Acquisition Layer: Acquires optical intensity and temperature readings [10], [15].
- Control Layer: Computes control actions based on the feedback error using a PI controller [6], [7], [13].
- Safety Interlock Layer: Enforces predefined optical and thermal limits, including maximum intensity and temperature thresholds [4], [5], [12].
- Actuation Layer: Updates the LED drive signals via PWM or current modulation [10], [15].

This modular abstraction allows deterministic execution on a non-real-time operating system while isolating safety logic from control computation [6], [15].

4. Control Design

4.1. Closed-Loop Control Strategy

The controlled variable is the measured optical intensity, with a reference intensity defined based on desired operating conditions [1], [2]. The controller minimizes the error between the measured and reference values by adjusting the LED drive signal.

A proportional–integral (PI) controller was selected for its simplicity, robustness, and suitability for embedded real-time execution [6], [7], [13]. The PI controller compensates for steady-state errors caused by thermal drift and supply fluctuations.

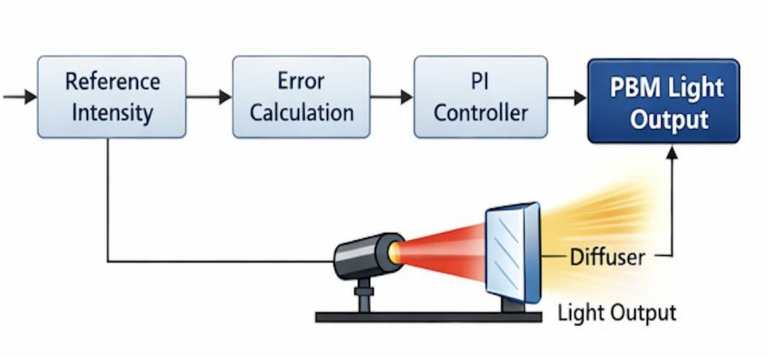

Fig 2: Closed-Loop Control Block Diagram

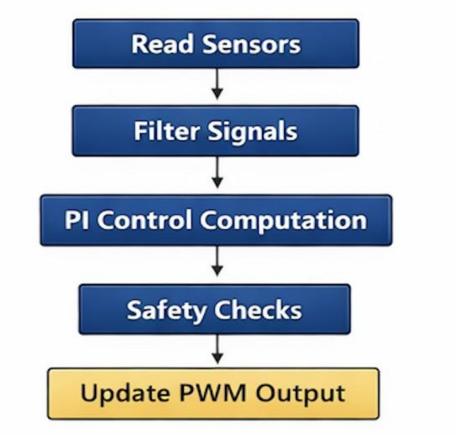

Fig 3: Control Loop Execution Flow

4.2. Thermal Compensation and Safety Logic

Temperature rise is a major contributor to LED output drift [11], [12]. To address this, the system continuously monitors temperature independently of the optical feedback loop. Safety logic enforces:

- Maximum allowable temperature
- Maximum optical output
- Rate-of-change limits on control signals

If any of these thresholds are exceeded, the system auto- matically reduces output or disables the LED driver entirely, ensuring fail-safe operation [4], [5], [12].

5. Implementation Details

5.1. Closed-Loop Control Strategy

The controlled variable is the measured optical intensity, with a reference intensity defined based on desired operating conditions [1], [2]. The controller minimizes the error between the measured and reference values by adjusting the LED drive signal.

A Proportional–Integral (PI) controller was selected for its simplicity, robustness, and suitability for embedded real-time execution [6], [7], [13]. The PI controller compensates for steady-state errors caused by thermal drift and supply fluctuations.

5.2. Thermal Compensation and Safety Logic

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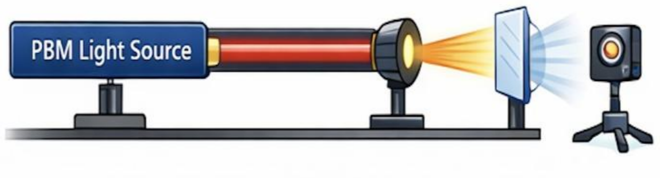

Fig 4: Experimental Test Setup

Temperature independently of the optical feedback loop. Safety logic enforces:

- Maximum allowable temperature,
- Maximum optical output, and
- Rate-of-change limits on control signals.

If any of these thresholds are exceeded, the system auto- matically reduces output or disables the LED driver entirely, ensuring fail-safe operation [4], [5], [12].

6. Experimental Setup

This section describes the experimental methodology used to evaluate the proposed closed-loop PBM output regulation system. The experiments were designed to validate output sta- bility, dynamic response, and safety behavior under controlled and repeatable conditions, without involving biological testing. This approach aligns with recommended practices for early-stage evaluation of optical and safety-critical systems [4], [11], [12].

6.1. Optical Measurement and Test Rig Design

To ensure repeatable and non-invasive evaluation, a diffuser- based optical measurement rig was constructed. The PBM light source illuminates an optical diffuser, positioned directly in front of the LED output. A calibrated light sensor is placed behind the diffuser at a fixed distance, ensuring consistent irradiance measurement independent of beam divergence or alignment variability.

The use of a diffuser reduces sensitivity to spatial non- uniformities and beam profile variations, which are common in LED-based optical sources [1], [3]. This configuration enables reliable relative measurements of output stability while avoiding direct exposure to high-intensity light sources. Similar diffuser-based techniques are widely used in optical instrumentation and calibration workflows [11], [14].

Key advantages of the proposed test rig include:

- High repeatability across experimental runs,
- Reduced sensitivity to angular misalignment,
- Safe, non-contact optical evaluation, and
- Compatibility with long-duration stress testing.

A temperature sensor is mounted near the LED heat sink to monitor thermal behavior during operation. All sensor data are logged synchronously for post-experiment analysis.

6.2. Operating Conditions and Baseline Configuration

Two system configurations were evaluated:

- *Open-loop mode*, in which the LED drive signal remains fixed.
- *Closed-loop mode*, in which optical feedback is used to regulate output.

In both configurations, the same hardware platform, sensors, and operating parameters were used to ensure a fair comparison. The reference optical intensity for closed-loop operation was selected within manufacturer-recommended limits to remain consistent with optical safety guidelines [4], [5].

The system was allowed to stabilize at ambient conditions before each test run. Data acquisition was performed at a fixed sampling rate selected to balance responsiveness and computational load on the embedded platform [10], [15].

6.3. Thermal Stress Testing Procedure

Thermal stress testing was conducted to evaluate system behavior under temperature-induced output drift, which is a known limitation of LED-based PBM devices [3], [11]. In this test, the PBM source was operated continuously for an extended duration until the device temperature reached a steady-state value.

During the test, the following signals were recorded contin- uously:

- Optical output,
- Device temperature, and
- Control signal values.

In the open-loop configuration, no compensation was ap- plied for temperature rise. In the closed-loop configuration, the controller dynamically adjusted the drive signal to maintain the target optical output.

This test evaluates the system's ability to compensate for thermal efficiency loss, which is a dominant disturbance in compact optical devices [1], [12].

6.4. Supply Voltage Disturbance Testing

To assess dynamic response and disturbance rejection, con- trolled variations were introduced in the supply voltage during system operation. Voltage steps were applied while monitoring the resulting optical output and control response.
Performance metrics extracted from this test include:

- Rise time,
- Settling time,
- Peak overshoot, and
- Steady-state error.

These metrics are commonly used in embedded control and automation systems to evaluate closed-loop stability and responsiveness [6], [7], [13].

6.5. Safety Interlock Validation

Safety interlocks were evaluated independently of normal regulation performance. Predefined thermal and optical thresholds were intentionally exceeded to verify correct enforcement of safety limits.
The following fault scenarios were tested:

- Over-temperature condition,
- Persistent thermal violation, and
- Simulated sensor fault.

The system response was observed to confirm:

- Immediate override of control action,
- Safe reduction or shutdown of output, and
- Correct recovery behavior.

This validation approach follows recommended practices for safety-critical embedded systems and medical device prototypes [4], [5], [8], [9].

6.6. Data Collection and Analysis Methodology

All experimental data were logged locally on the embedded platform and processed offline for analysis. Mean output drift, maximum deviation, and transient response metrics were com- puted over multiple runs to reduce measurement uncertainty. No biological tissue or clinical evaluation was performed. The experiments focus exclusively on engineering performance, control stability, and safety behavior, consistent with early-stage device validation methodologies [11], [12], [14].

7. Results and Analysis

This section evaluates the performance of the proposed closed-loop PBM output regulation system under controlled experimental conditions. The closed-loop system is compared with an open-loop configuration to quantify improvements in output stability, disturbance rejection, and safety behavior [1], [2], [3], [6], [7].

7.1. Output Stability under Thermal Stress

Table I summarizes optical output variation measured during thermal stress testing. Thermal stress tests were conducted by operating the PBM light source continuously until a steady temperature rise was observed [11], [12]. In the open- loop configuration, optical output gradually declined due to temperature-dependent LED efficiency loss. In contrast, the closed-loop system dynamically adjusted the drive signal to compensate for thermal effects, maintaining stable output [6], [7], [13].

As shown in Table I, the closed-loop system reduced mean output drift from −12.6% (open-loop) to −1.9% and limited maximum deviation from 15.3% to 2.4%. The steady-state error was similarly reduced from 11.8% to 1.6%. Overall, the closed-loop system reduced output drift by more than 85% compared to open-loop operation and maintained optical output within a narrow tolerance band despite thermal rise [11], [12].

Table 1: Optical Output Variation under Thermal Stress

Control Mode	Mean Output Drift (%)	Maximum Deviation (%)	Steady-State Error (%)
Open-Loop	-12.6	15.3	11.8
Closed-Loop	-1.9	2.4	1.6

7.2. Dynamic Response to Disturbances

Dynamic performance was evaluated by introducing step disturbances through controlled variations in the supply voltage [10], [15]. The resulting transient response characteristics are reported in Table II. Key control metrics, including rise time, settling time, peak overshoot, and steady-state error, were extracted from the closed-loop response.

As summarized in Table II, the closed-loop system achieved a rise time of 95 ms and a settling time of 180 ms, with a peak overshoot of 3.2% and a steady-state error of 1.6%. The combination of fast recovery and low overshoot indicates stable controller tuning suitable for real-time embedded execution [6], [7], [14].

Table 2: Transient Response Performance of Closed-Loop System

Metric	Measured Value
Settling Time (ms)	180
Peak Overshoot (%)	3.2
Rise Time (ms)	95
Steady-State Error (%)	1.6

7.3. Safety Interlock Performance

Safety interlocks were evaluated by intentionally exceeding predefined thermal and operational thresholds to verify correct enforcement of safety limits [4], [5], [12]. Table III summarizes the tested fault conditions, corresponding system responses, and recovery behaviors. When the temperature limit was reached, the system automatically reduced output power. Under persistent over-temperature conditions or detected sensor faults, the system disabled the LED driver to prevent unsafe operation.

As shown in Table III, the temperature-limit condition triggered an automatic output power reduction, while persistent over-temperature and sensor-fault scenarios resulted in output disablement requiring manual reset. The safety mechanisms operated independently of the control loop, ensuring fail-safe behavior under abnormal conditions [4], [5], [12].

Table 3: Safety Interlock Response Summary

Condition Triggered	System Response	Recovery Behavior
Temperature Limit Exceeded	Output Power Reduction	Automatic
Persistent Over-Temperature	LED Shutdown	Manual Reset
Sensor Fault Detected	Output Disabled	Manual Reset

7.4. Discussion of Results

The experimental results confirm that embedded closedloop control significantly improves PBM output stability under realistic operating conditions. Compared to open-loop operation, the proposed system demonstrates: (i) reduced drift under thermal stress (Table I) [11], [12], (ii) faster recovery from supply disturbances with limited overshoot (Table II) [10], [15], and (iii) robust enforcement of safety constraints under fault scenarios (Table III) [4], [5].

These findings validate the feasibility of using low-cost embedded platforms to implement safety-critical optical output regulation for home PBM devices and similar optical systems [6], [7], [8], [9], [14], [15].

8. Discussion

The proposed system illustrates how principles from robotics, embedded control, and automation can be applied to PBM device regulation [6], [7], [8]. By treating optical output as a controlled variable, reproducibility and operational safety are improved. While the current implementation uses a PI controller, the architecture supports future extensions such as model-based control, adaptive algorithms, or digital twins [13], [14].

Limitations include reliance on a general-purpose operating system, which constrains loop timing determinism, and simplified optical modeling of LED behavior [10], [15]. Nevertheless, the results demonstrate that even with low-cost hardware, meaningful closed-loop regulation can be achieved.

9. Conclusion

This paper presented a Raspberry Pi–based closed-loop PBM output regulation system integrating optical and thermal feedback with software-enforced safety interlocks [10], [15]. Experimental evaluation under thermal and supply disturbances shows significant improvement in output stability and dynamic response compared to open-loop operation [1], [2], [3], [6], [7], [11], [12].

The proposed approach highlights the potential of low-cost embedded platforms for safety-critical control applications in home PBM devices and similar optical systems, providing a pathway toward reliable, reproducible, and safe operation [4], [5], [8], [9], [14], [15].

References

[1] M. R. Hamblin, “Mechanisms and applications of the anti-inflammatory effects of photobiomodulation,” AIMS Biophysics, vol. 4, no. 3, pp. 337– 361, 2017.

[2] J. D. Carroll, “Photobiomodulation therapy dosimetry: Current challenges and future directions,” Photomedicine and Laser Surgery, vol. 36, no. 10, pp. 505–507, 2018.

[3] J. T. Enwemeka et al., “The efficacy of low-power lasers in tissue repair and pain control: A meta-analysis study,” Photomedicine and Laser Surgery, vol. 22, no. 4, pp. 323–329, 2004.

[4] U.S. Food and Drug Administration, Design Considerations for Devices Intended for Home Use, FDA Guidance Document, 2014.

[5] U.S. Food and Drug Administration, General Principles of Software Validation, FDA Guidance Document, 2002.

[6] K. J. Astr ˚ om and R. M. Murray, ¨ Feedback Systems: An Introduction for Scientists and Engineers. Princeton, NJ, USA: Princeton Univ. Press, 2008.

[7] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, Feedback Control of Dynamic Systems, 7th ed. Boston, MA, USA: Pearson, 2015.

[8] R. Isermann, “Mechatronic systems—Innovative products with embedded control,” Control Engineering Practice, vol. 16, no. 1, pp. 14–29, 2008.

[9] S. Bennett, “A brief history of automatic control,” IEEE Control Systems Magazine, vol. 16, no. 3, pp. 17–25, Jun. 1996.

[10] Raspberry Pi Foundation, Raspberry Pi Documentation. Cambridge, U.K., 2024.

[11] Intertek Group plc, LED and Optical Radiation Safety Testing, Intertek Technical White Paper, 2023.

[12] International Electrotechnical Commission, IEC 62471: Photobiological Safety of Lamps and Lamp Systems, IEC Standard, 2006.

[13] S. Skogestad and I. Postlethwaite, Multivariable Feedback Control: Analysis and Design, 2nd ed. Chichester, U.K.: Wiley, 2005.

[14] P. A. Ioannou and J. Sun, Robust Adaptive Control. Upper Saddle River, NJ, USA: Prentice Hall, 1996.

[15] A. Burns and A. Wellings, Real-Time Systems and Programming Languages, 4th ed. Boston, MA, USA: Addison-Wesley, 2009.