Feedback Control System - Lab

Open-Ended Lab Report

Designing Light Intensity Control using PID Controller

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Introduction

This project focuses on developing a hardware-based PID (Proportional-Integral-Derivative) control system to automatically regulate the brightness of a DC filament bulb based on a reference set-point.

The control system is entirely analog, designed using LM741 op-amps, a TIP31 power transistor, and passive components like resistors and capacitors. The feedback mechanism utilizes an LDR (Light Dependent Resistor), whose resistance varies with ambient light levels. By building this control system, we apply theoretical knowledge of analog electronics and control engineering to a real-world automation task.

The project highlights how analog components can be used to achieve feedback control without requiring digital computing platforms. This demonstrates the power and versatility of analog design, particularly in constrained environments or legacy systems where microcontrollers are not viable.

Problem Analysis

The core problem addressed in this project is designing a closed-loop feedback system that adjusts light intensity to match a desired reference. This must be achieved using analog circuitry only, without digital microcontrollers or software assistance.

A user sets a target voltage as a reference, representing desired light intensity. The actual light intensity is sensed using an LDR, and its voltage is compared with the reference using a comparator circuit. The resulting error is passed through proportional, integral, and derivative analog circuits that calculate a control signal. This control signal adjusts the base current of a BJT (TIP31) to vary the power supplied to a DC bulb.

The system must be stable, accurate, and responsive, managing transient behavior while ensuring energy efficiency.

Design Requirements

The primary design requirements for this system include a reference voltage input, a light intensity sensor (LDR), an analog PID control block, and a power output stage to drive a filament bulb.

The system must operate within a ±12V supply and be able to regulate the brightness of a 5V, 500mA DC bulb. The input reference is provided via a potentiometer, while the LDR provides a feedback voltage based on ambient light. The system must compute the error between the reference and feedback voltages and apply PID corrections using three separate analog op-amp blocks. Each PID component (P, I, D) must be fine-tuned using specific resistor-capacitor configurations.

The final output must be sufficient to drive a high-current load via the BJT, and the output should exhibit minimal overshoot and a quick settling time.

Feasibility Analysis

This project is highly feasible both in terms of component availability and time constraints.

All major components such as LM741 op-amps, TIP31 BJTs, resistors, capacitors, and LDRs are readily available in most electronics laboratories.

The total cost is minimal, making the design affordable for academic use.

From a time perspective, the project can be divided into manageable phases: circuit design, simulation, testing, and documentation, all of which can be completed in 3-4 days.

Academic lab equipment like function generators, DC power supplies, and oscilloscopes are sufficient for verification.

The theoretical knowledge required is basic circuit analysis, op-amp applications, and PID control fundamentals, which are typically covered in control systems and analog electronics courses.

Possible Solutions

Various methods exist to regulate light intensity in response to changing environmental conditions:

- A digital solution using microcontrollers and sensors offers programmability and dynamic tuning but is not permitted under the given constraints
- A software-simulated PID would lack real-time feedback and physical response.

The most viable solution is an analog PID controller, which uses op-amp circuits to simulate the P, I, and D control actions

Among analog configurations, using separate op-amp blocks for each component allows easy adjustment and clear debugging

Alternatives such as using only PI or PD control were considered but ultimately discarded because a full PID controller provides better error minimization and dynamic response control, ensuring precise and smooth operation

Preliminary Design

The proposed system is broken down into functional blocks: Reference Input, Light Sensor, Error Computation, PID Controller (Proportional, Integral, Derivative branches), Signal Summation, and Power Control.

- The reference input is generated through a variable resistor.
- The LDR forms a voltage divider with a fixed resistor to provide the feedback signal.
- The comparator circuit computes the difference between reference and feedback voltages.
- This error is then processed by the P, I, and D blocks, each implemented using op-amps.
- The three signals are then added using a summing amplifier.
- The final output is fed to the base of a TIP31 transistor which amplifies the signal to drive the bulb.

Each block is designed with careful consideration of gain, stability, and component values to match control theory with practical circuit behavior.

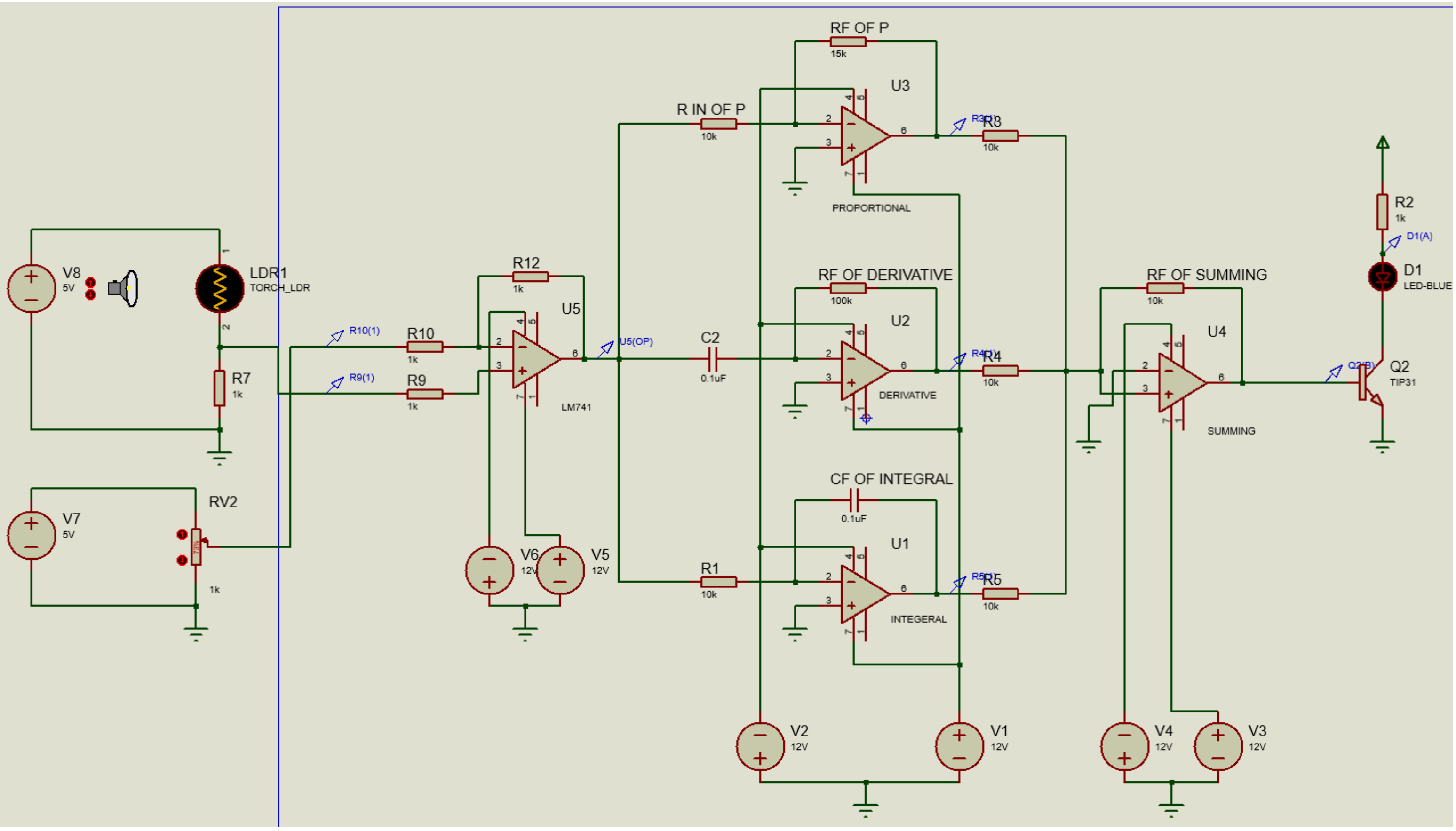
Design Description

The full circuit is composed of five primary op-amp stages and one BJT driver.

- The comparator stage uses an op-amp configured for differential input to compute the error between the reference and LDR voltages.
- The proportional stage amplifies this error directly through a non-inverting amplifier configuration.
- The integral stage, made from an op-amp integrator circuit with a resistor-capacitor feedback loop, accounts for accumulated error over time.
- The derivative stage uses a high-pass filter configuration to anticipate future error trends.
- These three signals are combined in a summing amplifier, which drives the base of a TIP31 BJT transistor.
- The transistor acts as a current amplifier, allowing the low-power control signal to adjust a high-current bulb.

All resistor and capacitor values are selected to balance response time, accuracy, and noise tolerance.

Software Simulation



Experimental Results

During simulation, the system responded effectively to changes in the reference voltage.

Increasing the reference caused a rise in the brightness of the bulb, confirming the proportional control's effectiveness.

Over time, the integral action minimized any offset between actual and desired light levels.

When a sudden change was introduced in the reference or ambient light, the derivative stage responded by adjusting the output to mitigate overshoot.

These results demonstrate the successful functioning of the PID loop and confirm that analog components can provide stable, dynamic control in feedback systems when designed correctly.

Performance Analysis

The analog PID controller performed reliably in simulation, demonstrating key control system characteristics.
The proportional gain ensured that any deviation from the set-point was immediately addressed.
The integral component reduced steady-state error, ensuring accuracy over time.
The derivative element helped to stabilize the system, preventing oscillations or overshoot in response to sudden changes.
The circuit maintained a smooth output signal to the bulb, avoiding abrupt jumps or instability.
Performance metrics such as rise time, settling time, and damping ratio were observed to be within acceptable bounds.
Overall, the PID system achieved a good balance between responsiveness and stability, verifying the effectiveness of analog control in practical applications.

Conclusion

This project successfully achieved the implementation of a fully analog PID controller to regulate light intensity.

Through the use of op-amps and passive components, the controller was able to process real-time feedback from an LDR and control the brightness of a DC bulb to match a reference voltage.

The system performed predictably and reliably under various conditions

The simulation results confirmed the stability and responsiveness of the control loop.

The experience gained from this project enhanced understanding of feedback systems, analog electronics, and control engineering.

It demonstrated that even with basic components, sophisticated control tasks can be performed effectively.

This approach also lays the groundwork for future development of more complex or integrated analog systems.