Design and Implementation of a Closed-Loop Anesthesia Delivery System

Hackathon

TinkerHub 24-Hour Hackathon

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Team Members

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Abstract

Closed-loop anesthesia delivery systems aim to automate drug infusion by continuously monitoring patient vital parameters and adjusting dosage in real time. Conventional anesthesia administration depends heavily on manual intervention, which may lead to delayed responses and human error.

This project presents the design and implementation of a low-cost, embedded closed-loop anesthesia delivery prototype. The system uses physiological parameters such as heart rate (HR), mean arterial pressure (MAP), respiratory rate (RR), and oxygen saturation (SpO_2) as feedback inputs. A microcontroller-based control algorithm dynamically adjusts infusion flow using a servo-controlled drip mechanism.

The proposed system demonstrates stable operation, safety prioritization, and real-time response, making it suitable for academic demonstration and future research extensions.

Chapter 1

Introduction

Anesthesia is a critical component of modern surgery, requiring precise dosing to maintain patient stability. Over- or under-administration can lead to serious complications.

Closed-loop control systems automatically regulate outputs using feedback, minimizing human intervention. By applying control theory to anesthesia delivery, drug dosage can be adjusted continuously based on patient response.

This project demonstrates a simplified closed-loop anesthesia delivery system using embedded hardware, suitable for hackathon demonstration and academic learning.

Chapter 2

Problem Statement

Traditional anesthesia delivery systems rely on manual adjustment by clinicians based on intermittent observation of patient vitals. This approach suffers from:

- Delayed response to physiological changes
- Dependence on operator experience
- Increased risk during long surgical procedures

The challenge is to design a compact, automated system that can continuously monitor vital signs and regulate anesthetic drug infusion in real time while maintaining safety constraints.

Chapter 3

Objectives

- Design a closed-loop anesthesia delivery prototype
- Monitor HR, MAP, RR, and SpO_2
- Implement a real-time control algorithm
- Control infusion rate using a servo-driven mechanism
- Ensure safety using threshold-based overrides

Chapter 4

System Architecture

The system consists of sensing, processing, actuation, and feedback components.

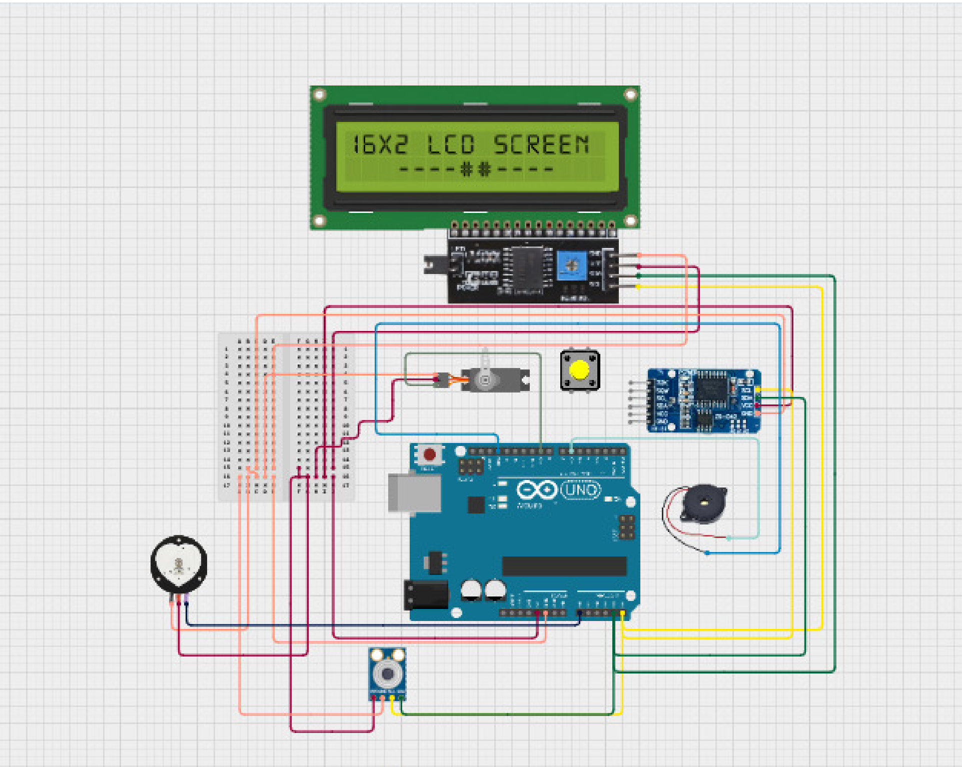

Figure 4.1: Overall System Architecture

`Sensors → Microcontroller → Control Algorithm → Servo Motor → Infusion Control`

Chapter 5

Control Algorithm Design

5.1 Set-Point Definition

$$HR_0 = 80\ bpm, \quad MAP_0 = 70\ mmHg, \quad RR_0 = 14, \quad SpO_{2,0} = 98\%$$

5.2 Normalized Error Calculation

$$e_{HR} = \frac{HR - HR_0}{HR_0}$$

$$e_{MAP} = \frac{MAP_0 - MAP}{MAP_0}$$

$$e_{RR} = \frac{RR - RR_0}{RR_0}$$

$$e_{SpO_2} = \frac{SpO_{2,0} - SpO_2}{SpO_{2,0}}$$

5.3 Weighted Control Signal

$$C = 0.5e_{MAP} + 0.25e_{HR} + 0.15e_{RR} + 0.10e_{SpO_2}$$

5.4 Infusion Rate Calculation

$$F = F_0 + K \times C$$

Where:

- F_0 = baseline infusion rate
- K = controller gain

Chapter 6

Flow Rate to Drop Conversion

Given a drop factor of 20 drops/mL:

$$\text{Drops per minute} = \text{Flow (mL/min)} \times 20$$

This value is mapped to servo angles using calibration.

Chapter 7

Hardware Components

- Arduino microcontroller
- Servo motor
- OLED display (SSD1306)
- Buzzer for alarms
- Power supply
- IV drip setup (simulated)

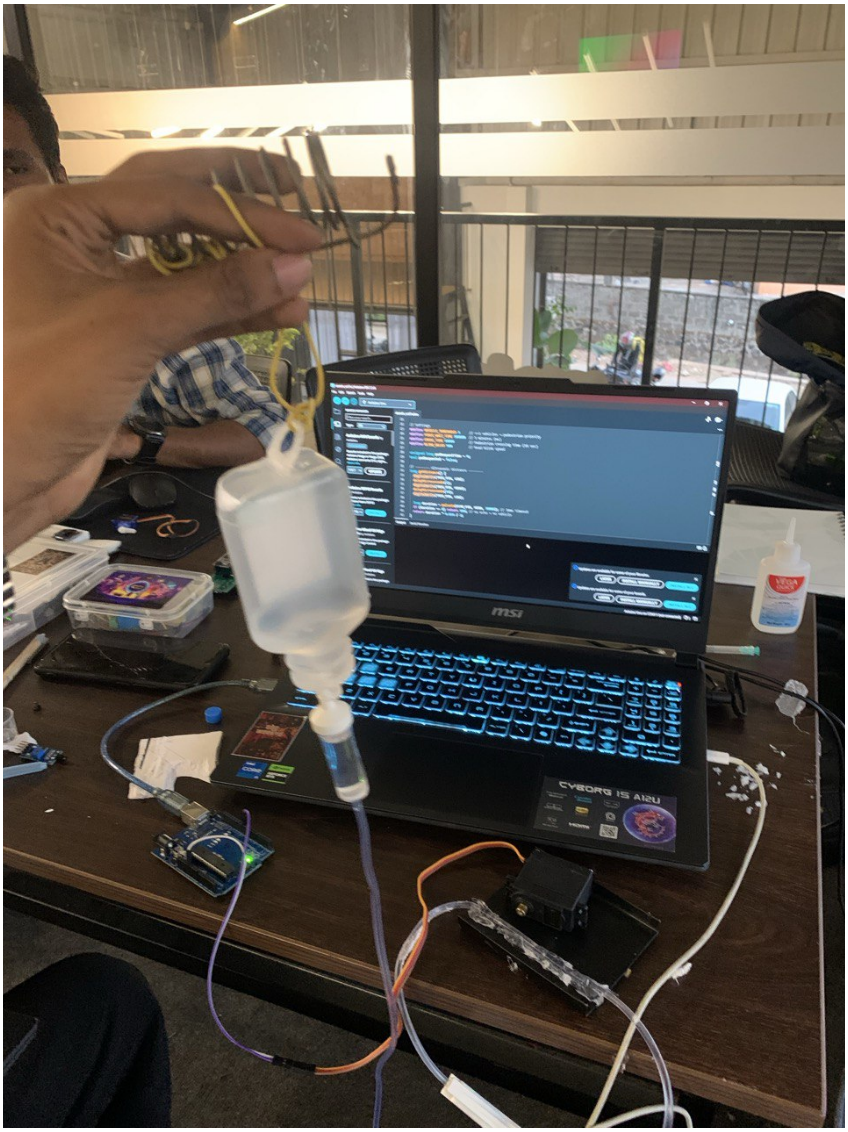

Figure 7.1: Hardware Integration

Chapter 8

Software Implementation

The system is programmed using Embedded C. Serial input simulates real-time vital signs. The control loop runs periodically and updates the servo angle and alarm status.

Key features:

- Priority-based control logic
- Real-time safety overrides
- OLED visualization
- Audible alarms

Chapter 9

Challenges and Solutions

- **Serial data instability**: Solved using structured parsing and validation
- **Servo response conflicts**: Solved using priority-based logic
- **Safety enforcement**: Implemented hard thresholds for SpO_2 and MAP

Chapter 10

Results and Discussion

The prototype successfully:

- Adjusted infusion rate based on physiological changes
- Triggered alarms under unsafe conditions
- Maintained stable operation during continuous testing

Input Condition	Servo Angle	Buzzer
Normal	65°	OFF
Low BP	55°	Beep
Low SpO_2	47°	Continuous

Table 10.1: System Response Summary

Chapter 11

Conclusion

This project demonstrates a functional closed-loop anesthesia delivery prototype using embedded systems and control theory. While simplified, the system highlights the feasibility of automated drug delivery using real-time physiological feedback.

Chapter 12

Future Scope

- Integration of real biomedical sensors
- PID or adaptive control algorithms
- Wireless monitoring dashboard
- Machine learning-based patient modeling