Project Proposal: Robotic Hand with Human Hand Recognition and Imitation

Team #9
Xihe Shao
(xihes2@illinois.edu)
Qihan Shan
(qshan3@illinois.edu)
Jun Liang
(junl6@illinois.edu)
Sizhao Ma
(sizhaom2@illinois.edu)
TA: Leixin Chang

March 14, 2025

Contents

1 Introduction

1.1 Objective and Background

Humans working in hazardous environments, such as those involving toxic materials, high-pressure equipment, or explosives, face life-threatening risks. Current solutions, such as sensor-equipped gloves or pre-programmed robots, suffer from inflexibility, discomfort, high cost, and dependence on physically wearable devices, limiting their usefulness. To address these challenges, this project introduces a vision-based robotic hand system that utilizes camera tracking and 3D-printed components to enable real-time human gesture imitation. The solution moves away from reliance on wearable sensors and prioritizes adaptability. The system aims to redefine safety and accessibility in hazardous operations.

1.2 Goals

Its main goal is to reduce human exposure in hazardous environments by replacing rigid, sensor-dependent solutions with a flexible, vision-driven robotic system that replicates human gestures in real time.

1.3 Functions

The system (1) captures and interprets human hand gestures via cameras, (2) translates them into precise robotic movements using closed-loop feedback, and (3) employs a modular, 3D-printed robotic hand for safe manipulation of hazardous objects.

1.4 Benefits

Consumers gain a non-invasive, low-cost alternative to traditional methods, eliminating the need for restrictive wearables while improving operational safety, adaptability, and ease of deployment in high-risk scenarios.

1.5 Features

Key marketable features include:

- **Camera-driven gesture recognition** (no physical sensors required).
- **Real-time mimicry with closed-loop feedback** for sub-millisecond precision.
- **Affordable 3D-printed construction** (80% cost reduction vs. industrial robots).

1.6 High-Level Requirements List

- The system must achieve **gesture recognition accuracy** $\geq 95\% undervaryinglightingandocclusioncond$ $to-endlatencybetweenhumangestureandroboticresponsemustbe$**200 ms**$toensurereal-$ $timeperformance.$

- The robotic hand system must demonstrate **zero unintended motions** during a **1-hour** stress test under error-inducing conditions (e.g., sensor noise, communication latency, or environmental disturbances).

2 Design and Requirements

2.1 Block Diagram

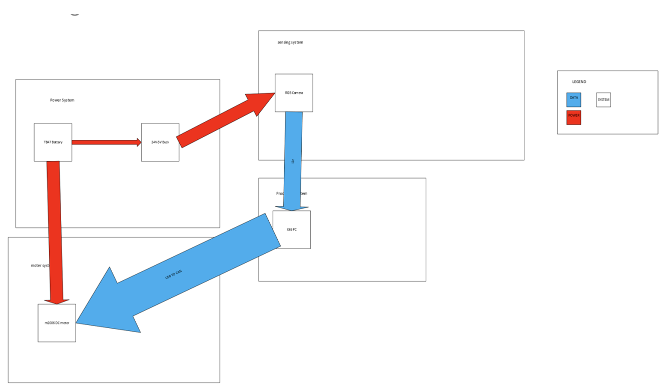

Figure 1: Block diagram of the robotic hand system (Power, Sensing, Processing, Motor subsystems).

2.2 Subsystem Overview

The robotic hand system is divided into four primary subsystems: Power, Sensing, Processing, and Motor. Each subsystem plays a critical role in enabling the robotic hand to recognize and imitate human hand movements.

2.2.1 Power Subsystem

- **Components**: TB47 Lithium-Ion Battery (22.2V, 4.5Ah), Buck Converters (12V, 5V, 3.3V).

- **Function**: Provides stable power to all subsystems. Includes a Battery Management System (BMS) for voltage, current, and temperature monitoring.

2.2.2 Sensing Subsystem

- **Components**: RGB Camera (Logitech C920).
- **Function**: Captures real-time hand movements and extracts skeletal keypoints using MediaPipe Hand Tracking.

2.2.3 Processing Subsystem

- **Components**: X86 Laptop (ROS2), USB-to-CAN module.
- **Function**: Maps hand landmarks to motor control signals via CAN bus at 1Mbps with 50ms latency.

2.2.4 Motor Subsystem

- **Components**: RoboMaster M2006 motors + C610 ESCs.
- **Function**: Drives finger joints via tendon mechanisms with 1 N-m torque and 0.5 sec/joint actuation speed.

2.2.5 Hand Subsystem

- **Components**: 3D-printed fingers (PLA) with spring-loaded knuckles.
- **Function**: Modular design allows safe manipulation of objects with low mechanical force.

2.3 Subsystem Requirements

Subsystem	**Requirements**
Power	12V ±0.1V (2A) for motors; 5V ±0.1V (500mA) for camera.
Sensing	RGB camera: 30 FPS at 1080p resolution.
Processing	Latency 50ms; CAN bus communication at 1Mbps.
Motor	Actuation speed: 0.5 sec/joint; torque sharing for coupled fingers.

2.4 Tolerance (Risk) Analysis

- **Risk 1: MediaPipe Tracking Accuracy**
  Issue: Poor lighting/occlusions reduce accuracy.
  Mitigation: Kalman filtering and controlled lighting.
- **Risk 2: Motor Overload**
  Issue: Overload risk in Motors 2 & 3.
  Mitigation: Torque limits + mechanical slip clutch.
- **Risk 3: Battery Safety**
  Issue: LiPo fire risk.
  Mitigation: BMS with voltage cutoff and fuse protection.

3 Ethics and Safety

3.1 Ethical Considerations

3.1.1 Adherence to IEEE Code of Ethics

This project aligns with the IEEE Code of Ethics by:

- **Prioritizing public safety and well-being**: The primary goal is to reduce risks for workers handling hazardous materials, ensuring a safer alternative to direct human involvement.
- **Ensuring privacy and security**: The camera-based tracking system must handle human motion data responsibly, preventing potential misuse.
- **Maintaining integrity and accuracy**: Real-time mimicry must be reliable to avoid errors that could compromise safety in high-risk environments.

3.1.2 Ethical Concerns Related to This Project

- **Privacy and Data Protection**: Since the system relies on vision-based tracking, it must ensure that user data is handled securely. Potential concerns include:
  - Unauthorized data collection or storage.
  - Risk of surveillance or misuse of visual data.
  - Measures such as local processing, encryption, or anonymization should be implemented to mitigate these risks.
- **Reliability and Safety in Hazardous Environments**:
  - Errors in real-time mimicry could result in dangerous situations, such as mishandling toxic materials or explosives.
  - Fail-safe mechanisms and rigorous testing are necessary to prevent malfunctions that could endanger workers.

3.1.3 Human and Animal Testing Considerations

- **Human Testing (IRB Approval)**:
  - If human subjects are involved in testing the gesture recognition system, Institutional Review Board (IRB) approval may be required.
  - Participants must give informed consent, understanding how their data will be used.
  - The study should ensure no harm or discomfort to participants during testing.
- **Animal Testing (IACUC Approval)**:

  - This project does not involve animal testing, and therefore, Institutional Animal Care and Use Committee (IACUC) approval is not required.

3.2 Safety Considerations

Our project follows **ECE 445 Safety Guidelines** to ensure a safe working environment for both developers and end-users. Below, we address potential safety concerns related to **electrical, mechanical, and lab safety** while justifying areas with minimal safety risks.

3.2.1 Electrical Safety

- Our system primarily uses low-voltage electronics for gesture tracking and robotic hand control. Since it does not involve high voltage, the risk of electrical hazards is minimal.
- If modifications introduce high-voltage components in the future, we will complete the required high-voltage safety training and follow safe electrical handling procedures.
- The system does not involve direct electrical contact with human users, eliminating risks related to electric current exposure.

3.2.2 Mechanical Safety

- The robotic hand is 3D-printed and designed to operate with low force and torque, minimizing the risk of injury.
- Moving parts could pose a pinching hazard during testing. To mitigate this:
  - Team members will keep hands away from moving parts during testing and use tools for assembly or adjustments.

3.2.3 Lab Safety

- **Lab Presence Requirement**: At least two team members will be present in the lab at all times when working on the project.
- **Mandatory Safety Training**: All team members will complete the online safety training and submit certificates on Blackboard before starting lab work.

3.2.4 End-User Safety

- The robotic hand system is designed for remote teleoperation in hazardous environments, reducing risks to human workers.

- Software reliability is crucial to prevent misinterpretation of gestures, which could lead to incorrect robotic actions. To address this:
  - We will implement closed-loop feedback mechanisms to ensure accurate mimicry.
  - Thorough testing will be conducted before deployment in real-world hazardous environments.

3.2.5 Safety Plan

- **Prevention**: Strict hardware and software testing to identify failure points.
- **Fail-Safe Mechanisms**: Emergency stop features to halt movement in case of errors.
- **Protective Measures**: Ensure non-harmful force output from robotic movements.
- **Training & Documentation**: Team members will review safety protocols before operation.

3.2.6 Justification for Minimal Safety Concerns

- The project does **not** involve hazardous chemicals, explosive materials, or biological risks.
- It operates at **low voltage** and does not require **direct human-electrical contact**.
- The robotic hand has **low mechanical force**, and risks such as pinching are mitigated through design and controlled movement.

4 References

- TB47 MSDS (Amperex Technology). https://www.amperextechnology.com/tb47-msds
- RoboMaster M2006 & C610 ESC Manuals (DJI). https://www.dji.com/robomaster-m2006
- MediaPipe Hand Tracking Documentation. https://google.github.io/mediapipe/solutions/hand_tracking
- IEEE Code of Ethics. https://www.ieee.org/about/corporate/governance/p7-8.html