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Modification and Improvement of a Coffee Berry Sorting Machine

(FYP 22-22)

Project Proposal

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January 28, 2026

Declaration

We declare that this project proposal is our original work and has not been presented for examination in any other institution.

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Acknowledgment

We would like to express our sincere gratitude to the Department of Mechatronic Engineering, JKUAT, for providing the opportunity to work on this innovative coffee berry sorting machine project and for the necessary facilities and resources that made this research possible.

Our deepest appreciation goes to our supervisors for their invaluable guidance, technical expertise, and continuous support throughout the development of this proposal.

We acknowledge the previous fifth-year students whose work on automated coffee sorting systems provided a foundation and valuable insights that informed the direction of this project.

Special thanks to the coffee farming community and industry stakeholders who shared their experiences and highlighted the practical challenges that this research aims to address.

Finally, we thank our families and friends for their unwavering encouragement and support throughout this endeavor.

Abstract

Automated coffee berry sorting is an essential process for ensuring quality consistency and improving the economic value of coffee produce. Previous student-developed prototypes have demonstrated the feasibility of using image-based detection and air-ejection mechanisms for automated sorting. However, limitations related to motion blur, processing delays, and limited computational capacity have restricted real-time performance and throughput.

This project focuses on the modification and improvement of an existing coffee berry sorting machine model by addressing challenges associated with real-time image acquisition, detection, and classification. The study explores optimized computer vision algorithms, improved frame processing strategies, and alternative processing architectures to enhance system efficiency. A co-processing architecture alongside the Raspberry Pi 3 will be introduced to overcome computational bottlenecks, with task division between high-level control and time-critical processing operations.

Performance evaluation is conducted based on sorting accuracy, processing speed, and overall throughput. The improved model aims to provide a cost-effective, reliable, and scalable solution suitable for small-scale coffee processing applications while contributing to research in embedded vision and agricultural automation.

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1 Introduction

1.1 Background of Study

The global coffee industry remains a significant contributor to the economies of many developing countries, supporting millions of smallholder farmers worldwide. Coffee production involves several critical stages, from cultivation and harvesting to processing and packaging. Among these stages, the sorting of coffee berries is one of the most labor-intensive and quality-sensitive processes. Traditionally, coffee berry sorting has relied heavily on manual visual inspection, where workers separate berries based on ripeness, size, and visible defects. This approach is time-consuming, inconsistent, and costly, often leading to variations in coffee quality and increased operational expenses.

Manual sorting methods are highly susceptible to human error and fatigue, which can result in misclassification of berries and reduced overall product quality. Furthermore, the labor-intensive nature of manual sorting limits scalability and efficiency, particularly during peak harvest periods when labor shortages are common. These challenges highlight the need for automated sorting solutions capable of performing classification tasks with higher accuracy, consistency, and throughput.

Recent advancements in computer vision, machine learning, and embedded systems have enabled the development of automated coffee berry sorting machines that utilize image-based detection and real-time classification techniques. Previous work by fifth-year mechatronics engineering students resulted in the development of an image-based coffee berry sorting machine incorporating a vibrating conveyor system, optical detection, and air-ejection mechanisms controlled by a Raspberry Pi-based processing unit. While the system successfully demonstrated automated sorting, practical challenges were identified during real-time operation, particularly related to motion blur, processing latency, and limited computational throughput.

The visual diversity in harvested coffee berries, including variations in color, size, and



Figure 1.1: Harvested coffee berry variation showing visual diversity in color, size, and surface texture

surface texture, as illustrated in Figure 1.1, presents a significant challenge for accurate automated classification.

This project proposes the modification and improvement of the existing coffee berry sorting machine by addressing the identified limitations in image acquisition, processing speed, and real-time classification performance. By enhancing the vision processing pipeline, optimizing algorithms, and evaluating alternative hardware or processing architectures, the project aims to improve sorting accuracy and throughput while maintaining a cost-effective and scalable design suitable for small- and medium-scale coffee processing applications.

1.2 Problem Statement

The global coffee industry plays a vital role in the economic development of many coffee-producing countries, including Kenya, where coffee farming supports a large population of smallholder farmers. The quality of coffee berries at the processing stage directly de-

termines the final product grade, market value, and competitiveness in both local and international markets. One of the most critical and labor-intensive stages in coffee processing is the sorting of coffee berries based on ripeness, color, size, and the presence of defects.

Traditionally, coffee berry sorting has been carried out manually through visual inspection by human operators. While this method requires minimal capital investment, it is inherently inefficient, inconsistent, and highly dependent on human judgment, which varies due to fatigue, experience, and environmental conditions. As a result, manual sorting often leads to misclassification of berries, reduced product quality, and increased operational costs. These challenges become more pronounced during peak harvest seasons, when large volumes of berries must be processed within limited timeframes.

In response to these limitations, recent final-year mechatronics projects have explored automated coffee berry sorting solutions using machine vision and robotic actuation. One such system employs a vibrating conveyor to ensure consistent berry flow, a chute for alignment, and an image-based detection and tracking system coupled with an air-ejection mechanism for sorting. The system operates under the control of a Raspberry Pi-based processing unit, leveraging computer vision and machine learning techniques to classify individual coffee berries as they move through the sorting process.

Despite the successful demonstration of automated sorting, the existing system exhibits several critical technical limitations that hinder its overall performance and scalability. The natural appearance of harvested coffee berries presents significant visual variability in color, texture, size, and surface defects. These variations, combined with the dynamic motion of berries on the conveyor, introduce challenges such as motion blur, inconsistent illumination, and overlapping objects, which negatively affect image clarity and classification accuracy.

Furthermore, the reliance on real-time image processing using a Raspberry Pi introduces processing bottlenecks. The limited computational capacity of the platform results in delays during frame acquisition, preprocessing, classification, and decision execution. Al-

though the previous implementation attempted to mitigate these issues through optimization techniques such as TensorFlow Lite and multithreading, the system still struggles to achieve higher throughput without compromising accuracy. This limitation directly affects sorting speed and reduces the system's suitability for larger processing volumes.

The core problem, therefore, lies not in the mechanical handling of coffee berries but in the limitations of the vision system, processing architecture, and real-time control strategy used in the existing model. There is a clear need to improve the system's ability to accurately and consistently classify visually diverse coffee berries at higher speeds while maintaining affordability and practicality for small-scale agricultural applications.

This project seeks to address these challenges through the modification and improvement of the existing automated coffee berry sorting system. By enhancing the image acquisition strategy, optimizing or upgrading the processing architecture, and refining the detection-to-actuation pipeline, the project aims to achieve higher throughput, reduced latency, and improved classification accuracy.

1.3 Objectives

1.3.1 Main Objective

To modify and improve an existing automated coffee berry sorting machine

1.3.2 Specific Objectives

1. To analyze the performance limitations of the existing image-based coffee berry sorting system, with emphasis on motion blur, processing latency, and classification accuracy
2. To improve on the sorting mechanism

3. To evaluate alternative or upgraded processing hardware capable of supporting higher frame rates and faster inference

1.4 Justification

Coffee remains one of Kenya's most valuable agricultural exports, and quality grading plays a major role in determining its economic value. Automated coffee berry sorting systems offer a practical solution for improving quality consistency and reducing labor dependency. However, many advanced commercial systems are prohibitively expensive and unsuitable for adoption by small-scale processors and cooperatives.

Improving an existing image-based coffee berry sorting model provides a cost-effective pathway toward practical automation by building upon already validated concepts while addressing observed technical shortcomings. By focusing on real-time processing efficiency, motion-related detection challenges, and system responsiveness, this study aims to bridge the gap between prototype-level demonstrations and deployable solutions.

The proposed improvements contribute to:

1. Enhanced accuracy and throughput in coffee berry sorting
2. Better utilization of affordable embedded vision technologies
3. Increased feasibility of locally developed agri-tech solutions
4. Practical learning and innovation in mechatronics system integration

Furthermore, incorporating real harvested coffee berries into testing and demonstration provides a realistic visual and operational representation of actual field conditions, strengthening the relevance and credibility of the system. The outcomes of this project are expected to support the development of scalable, affordable, and locally adaptable coffee processing technologies aligned with Kenya's agricultural and technological development goals.

2 Literature Review

The global coffee industry plays a critical role in the economies of many developing countries, including Kenya, by providing livelihoods to millions of smallholder farmers. Coffee processing involves several stages, among which sorting of coffee berries is one of the most critical for determining final product quality and market value. The presence of unripe, overripe, damaged, or defective berries significantly affects cup quality, leading to reduced prices and rejection in premium markets.

Traditionally, coffee berry sorting has relied on manual visual inspection, where workers separate berries based on perceived color, size, and visible defects. While this approach has been practiced for decades, numerous studies have demonstrated that manual sorting is labor-intensive, inconsistent, slow, and highly subjective, particularly under fatigue and time pressure (Mugo et al., 2017; Silva & Santos, 2019).



Figure 2.1: Ripe coffee berries showing color variation from green to deep red

Advances in machine vision, robotics, and embedded computing have enabled the development of automated coffee berry sorting systems capable of performing classification and separation tasks with higher accuracy, speed, and consistency. Automated systems

typically integrate three core subsystems:

- A material handling mechanism (vibrating conveyor or chute)
- A sensing and classification unit (camera and image processing algorithms)
- A separation mechanism (air jets, ejector plates, or diverters)

The 2019 automated coffee berry sorting machine project (reference project) represents a significant academic effort in this domain. The system employed a vibrating conveyor for controlled berry flow, a chute for alignment, image-based detection using a Raspberry Pi 3, and an air ejection mechanism for separation. While the system demonstrated the feasibility of automated sorting, several technical challenges were identified, particularly in real-time image processing and actuation timing, forming the foundation for the present study.

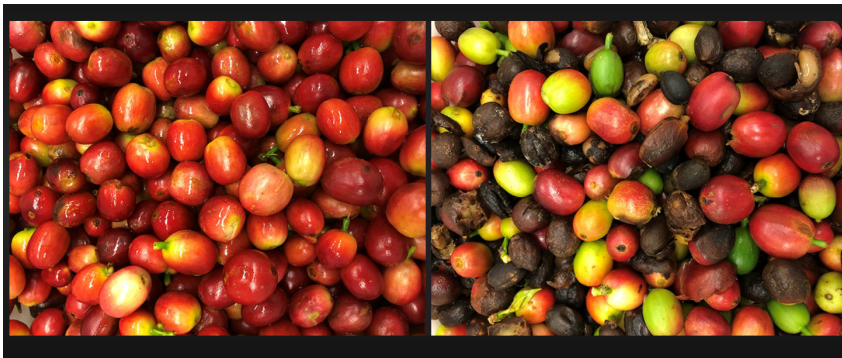


Figure 2.2: Coffee berry samples showing distinct visual differences between ripe (red/purple) and unripe (green/yellow) berries targeted for binary classification

2.1 Challenges of Traditional Sorting Methods

Manual sorting remains prevalent among small-scale farmers due to its low initial cost; however, extensive literature highlights its limitations.

1. Labor Intensity and Fatigue: Manual sorting requires a large workforce to maintain reasonable throughput. Studies show that prolonged visual inspection leads to fatigue, which directly reduces sorting accuracy and consistency [1]. Fatigued workers are more likely to misclassify berries, allowing defective berries to pass through or rejecting acceptable ones.

2. Human Error and Subjectivity: Manual sorting depends heavily on individual judgment, which varies between workers and across time [2]. Significant variability in sorting outcomes has been observed across different shifts, even when standardized grading guidelines were provided. This subjectivity results in inconsistent quality between batches.

3. Limited Throughput: Human sorting speed is inherently constrained. Manual sorting becomes a bottleneck during peak harvest seasons, limiting scalability and increasing processing delays [3]. This inefficiency directly affects farmers' ability to meet market demand.

These challenges have driven research into automated sorting systems capable of overcoming the limitations of manual methods.

2.2 Advantages of Automated Coffee Berry Sorting

Automated coffee berry sorting systems offer several key advantages over manual methods [4]:

1. Increased Efficiency and Throughput: Automated systems can process significantly larger volumes in shorter times compared to manual sorting. Modern optical sorting machines can handle hundreds of kilograms per hour, substantially reducing processing time during peak harvest.

2. Improved Consistency and Accuracy: Machine-based systems apply uniform classification criteria across all berries, eliminating subjective variation. Studies by Perez et al. (2020) demonstrate that automated systems maintain stable accuracy levels exceeding 92%, even during extended operation periods.

- 3. Reduced Labour Costs:** While requiring initial capital investment, automated sorting reduces ongoing labor requirements. Economic analysis by Mashauri et al. (2021) indicates that medium-scale processors can achieve cost recovery within 2–3 seasons through labor savings alone.
- 4. Data Collection and Traceability:** Automated systems enable collection of processing statistics, including throughput rates, defect percentages, and batch-level quality metrics. This data supports quality management systems and provides traceability demanded by premium export markets.

2.3 Separation Methods

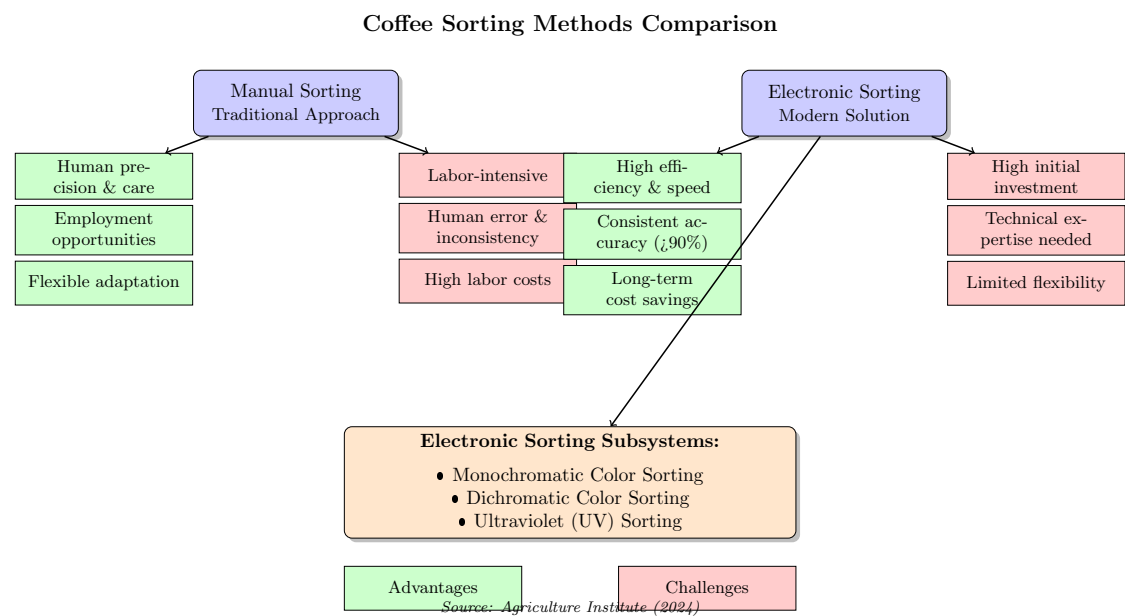


Figure 2.3: Comparison of manual and electronic coffee sorting methods (Source: Agriculture Institute, 2024)

2.3.1 Air Jet System

Air jet separation systems operate on a detect-decide-deflect principle. As berries pass through the imaging zone on a conveyor or chute, a high-speed camera (typically CCD or CMOS sensors) captures images in real time. Some advanced systems incorporate near-infrared (NIR) sensors to detect internal defects not visible in the RGB spectrum. Image processing algorithms classify each berry, and defective berries trigger compressed air jets precisely timed to deflect them into reject chutes while acceptable berries continue along the primary path.

Key advantages include: minimal physical contact reducing berry damage, very high throughput capacity, and adaptability to various berry sizes without mechanical adjustment [5]. However, limitations include requirement for compressed air infrastructure, sensitivity to environmental conditions (wind, dust), and complexity in timing calibration.

2.3.2 Ejector Plates

Ejector plate systems employ mechanical actuation to physically separate undesirable berries. When a defect is detected by upstream sensors, a solenoid or pneumatic actuator extends a small plate or paddle that pushes the target berry into a reject stream. This method ensures positive separation, meaning that once actuated, the berry is definitively moved to the reject pathway.

Advantages include: high reliability in separation (no missed deflections due to air pressure variation), suitability for larger or heavier objects, and lower compressed air consumption. Limitations include: mechanical wear on actuators and contact surfaces, slower response times compared to air jets (20–50 ms), and potential for berry bruising at the contact point.

2.3.3 Diverter Systems

Diverter systems redirect entire groups or batches of berries rather than individual units. When a sensor detects a defective berry, a mechanical gate or diverter flap reroutes the material stream into a reject bin. This approach is typically used in lower-precision, bulk sorting scenarios where strict unit-level separation is not required.

Advantages include: structural simplicity, low maintenance, and suitability for high-volume, low-cost operations. Disadvantages include: lower precision (acceptable berries in the same batch may be rejected), inability to handle single-file streams, and inefficiency when defect rates are low.

2.4 Classification Methods

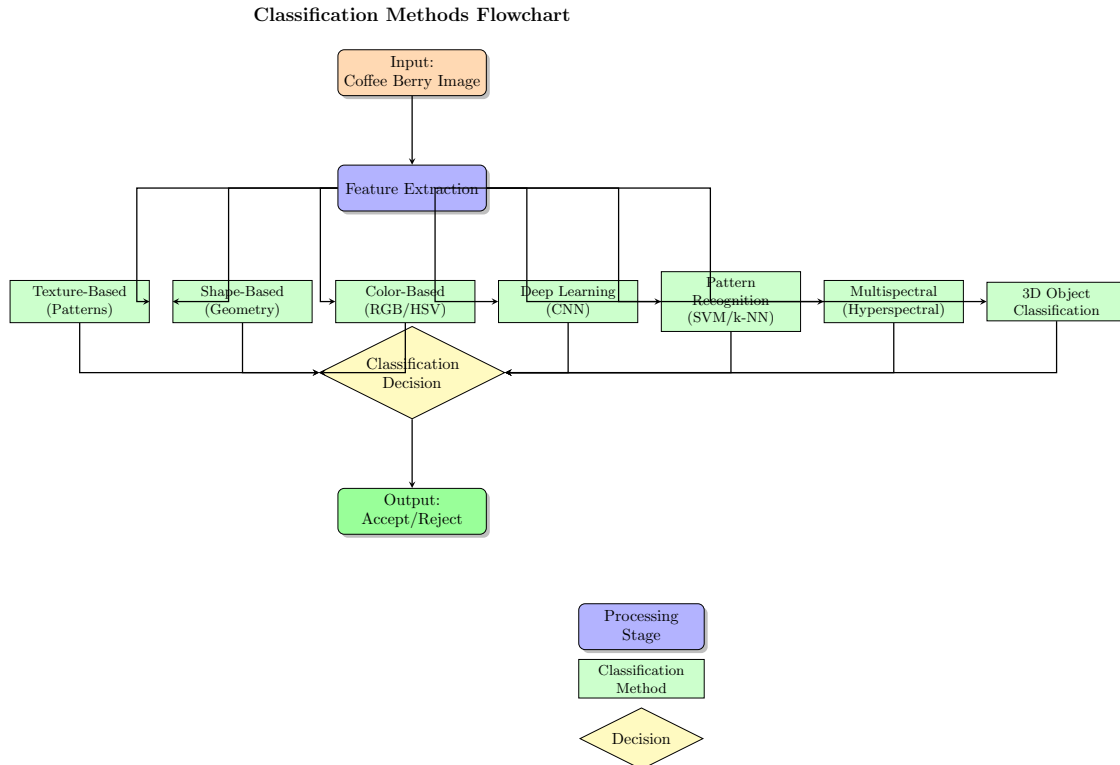


Figure 2.4: Overview of classification methods used in coffee berry sorting systems

2.4.1 Color-Based Classification

Color-based classification is the most widely used method in coffee berry sorting due to its direct correlation with maturity [6]. Ripe coffee berries exhibit deep red or purple hues, while unripe berries appear green or yellow. Systems employ RGB cameras to capture color information, which is then analyzed using color histograms, color space transformations (e.g., HSV, Lab), or simple thresholding.

This method is cost-effective and computationally efficient, making it suitable for real-time processing on embedded platforms. However, it is highly dependent on uniform lighting conditions and can struggle with berries exhibiting intermediate ripeness states or surface discoloration from environmental factors.

2.4.2 Shape-Based Classification

Shape analysis assesses geometric attributes such as size, contour smoothness, aspect ratio, and circularity [7]. Machine vision systems extract berry contours from binary images and calculate shape descriptors to identify malformed, damaged, or insect-infested berries.

This method complements color-based classification by detecting defects that do not manifest as color differences (e.g., physical damage, irregular growth). However, shape analysis requires clear berry separation on the conveyor and consistent camera positioning to ensure measurement accuracy.

2.4.3 Texture-Based Classification

Texture-based methods analyze surface patterns using techniques such as Gray-Level Co-Occurrence Matrix (GLCM), Local Binary Patterns (LBP), or Gabor filters. These approaches can detect surface defects like insect bites, mold growth, or drying-induced wrinkling.

Texture analysis is particularly effective for identifying subtle defects not visible through color or shape alone. However, texture features are more computationally expensive to extract and may require higher-resolution imaging, which can limit real-time throughput on low-cost hardware.

2.4.4 Deep Learning-Based Classification

Deep learning approaches, particularly Convolutional Neural Networks (CNNs), have demonstrated superior classification accuracy by automatically learning discriminative features from labeled training data [8]. Architectures such as MobileNet [9], ResNet, and YOLO (You Only Look Once) [10] enable real-time object detection and classification.

Deep learning models can handle complex, non-linear relationships between visual features and quality categories, achieving accuracies exceeding 95% in controlled conditions. However, these models require substantial computational resources, large labeled datasets for training, and careful optimization to run efficiently on embedded platforms like the Raspberry Pi.

2.4.5 Pattern Recognition-Based Classification

Traditional pattern recognition methods employ supervised learning algorithms such as k-Nearest Neighbors (k-NN), Support Vector Machines (SVMs), or decision trees. These classifiers use hand-crafted features (color, shape, texture) as input and learn decision boundaries from training samples.

Pattern recognition methods offer a balance between performance and computational efficiency. They are less demanding than deep learning approaches and more robust than simple thresholding, making them well-suited for embedded systems with limited processing power.

2.4.6 Multispectral and Hyperspectral Imaging-Based Classification

Multispectral and hyperspectral imaging capture information across multiple wavelengths, including visible and non-visible spectra (e.g., near-infrared, short-wave infrared). This allows detection of internal defects, moisture content variations, and chemical composition differences not visible to standard RGB cameras.

These methods provide the highest classification accuracy and defect detection capability. However, the high cost of specialized cameras, the large data volumes requiring processing, and the complexity of spectral analysis limit their adoption primarily to high-value, large-scale industrial operations.

2.4.7 Three-Dimensional (3D) Object Classification

3D imaging systems use stereo vision, structured light, or time-of-flight sensors to capture depth information alongside 2D images. This enables measurement of berry volume, surface irregularities, and three-dimensional shape descriptors.

3D classification is valuable for detecting internal voids, volume-based sorting, and identifying deformities. However, 3D imaging systems are more expensive, require more complex calibration, and impose higher computational loads compared to 2D methods.

2.5 Gap Analysis

Despite significant advances in automated coffee berry sorting, several critical gaps remain, particularly in the context of cost-effective, scalable solutions suitable for small-to-medium processors and university research environments.

2.5.1 Real-Time Processing and Throughput Limitations

The 5th-year project identified that the Raspberry Pi 3, while cost-effective, struggles to maintain real-time classification performance at higher throughput rates. The system

experienced difficulties processing high frame rates, performing simultaneous object tracking and classification, and maintaining synchronization with real-time actuation signals. Although optimizations such as TensorFlow Lite deployment and multithreading were attempted, performance remained below the levels required for practical deployment.

Current literature predominantly focuses on either high-performance industrial systems using GPUs or field-programmable gate arrays (FPGAs), which are cost-prohibitive, or low-throughput academic prototypes that do not address scalability. There is insufficient exploration of hybrid processing architectures where time-critical tasks are offloaded to co-processors (e.g., ESP32, STM32, or similar microcontrollers), allowing algorithm restructuring and task division between layers to achieve both cost efficiency and acceptable performance.

2.5.2 Motion Blur and Image Degradation at Higher Speeds

As conveyor speeds increase to meet higher throughput demands, image quality degrades due to motion blur, reducing classification accuracy. The 5th-year project explicitly identified motion blur as a major limitation, particularly at speeds exceeding certain thresholds.

Existing solutions typically involve either reducing conveyor speed (sacrificing throughput) or increasing camera shutter speed and lighting intensity (increasing cost and power consumption). However, there is limited research on integrated approaches that combine algorithmic and mechanical mitigation strategies—such as adaptive frame capture triggering, region-of-interest (ROI) selective processing, and timing-aware rejection logic—that could address motion blur without disproportionately sacrificing speed or cost.

2.5.3 Cost-Performance Trade-Off in Hardware Selection

There exists a notable gap in the literature regarding optimal hardware configurations for mid-scale sorting operations. High-performance systems using industrial-grade GPUs or

dedicated vision processors offer excellent performance but are financially inaccessible to smallholder cooperatives and university prototypes. Conversely, ultra-low-cost platforms (e.g., Raspberry Pi alone) demonstrate limited processing speed and reduced scalability.

Few studies systematically investigate cost-optimized improvements that maintain affordability while achieving meaningful performance gains. Strategies such as algorithm restructuring, selective processing pipelines, and intelligent task division between processing layers are underexplored. The current project aims to address this gap by evaluating hybrid processing architectures and system-level optimizations tailored to resource-constrained environments.

3 Research Design and Methodology

This study will adopt an experimental and design-based research approach. The research will involve the modification and improvement of an existing image-based coffee berry sorting machine through systematic redesign of its mechanical, electrical, and software subsystems. A functional prototype will be developed and evaluated to determine improvements in sorting accuracy, processing speed, and system reliability. The research design will be iterative, where system performance will be evaluated at each stage, and necessary refinements will be implemented to address identified limitations such as motion blur, processing delays, and ejection timing inaccuracies observed in the previous model.

3.1 System Overview

The proposed coffee berry sorting machine will consist of three main modules:

- **Mechanical Module** – Responsible for controlled berry feeding, alignment, and physical support
- **Electrical and Electronic Module** – Responsible for sensing, actuation, power distribution, and processing
- **Software Module** – Responsible for image acquisition, processing, classification, tracking, and ejection control

Each module will be designed to work in synchronization to enable real-time detection, classification, and rejection of unwanted coffee berries.

3.2 Mechanical Module Design

The mechanical module will be designed to ensure consistent berry flow, minimal vibration-induced image distortion, accurate alignment, and precise ejection positioning.

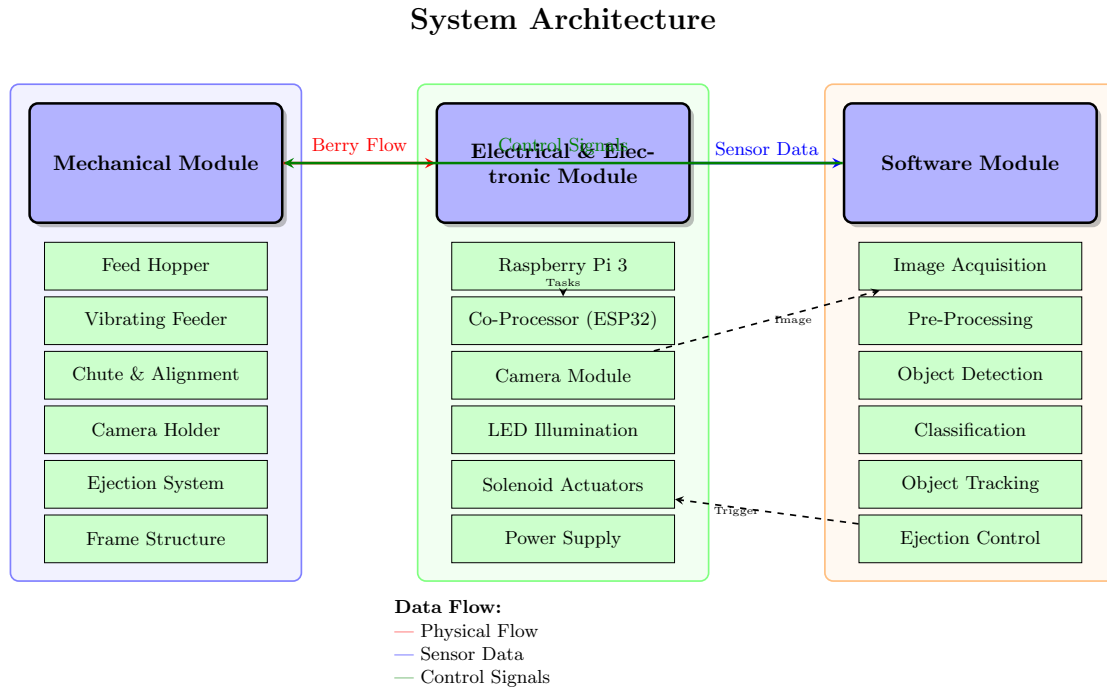


Figure 3.1: Overall system architecture of the improved coffee berry sorting machine

3.2.1 Hopper

The hopper will be used to store harvested coffee berries before sorting. It will be designed with sloped walls to allow gravity-assisted flow while preventing clogging and bridging of berries.

Material Selection: Mild steel sheet or food-grade aluminium will be used due to: structural strength, ease of fabrication, resistance to wear, and suitability for agricultural products. The hopper will feed berries uniformly onto the vibrating feeder.

3.2.2 Linear Vibrating Feeder

A linear vibrating feeder will be employed to regulate the flow rate of coffee berries and prevent overlapping during image capture. Controlled vibration will ensure berries are spread into a near-single-file arrangement.

Justification: Reduces berry overlap, improves image clarity, minimizes motion blur, and enhances object tracking accuracy.

Material Selection: Stainless steel or aluminium tray to reduce corrosion and contamination. Rubber vibration isolators to reduce transmission of vibration to the camera holder.

3.2.3 Chute

The chute will guide berries from the feeder to the imaging zone while maintaining alignment and spacing.

Design Considerations: Inclination angle optimized for gravity flow, smooth surface finish to reduce friction, fixed berry trajectory for predictable motion.

Material Selection: Acrylic or aluminium sheet chosen for smoothness, light weight, and ease of modification.

3.2.4 Camera Holder

The camera holder will support the Raspberry Pi camera directly above the imaging zone. It will be mechanically isolated from vibrations originating from the feeder.

Design Improvements: Use of rubber dampers to reduce vibration transmission, rigid frame mounting to maintain fixed focal distance, adjustable height mechanism for calibration.

Material Selection: Aluminium profile or 3D-printed ABS selected for rigidity and lightweight properties.

3.2.5 Ejection Holder

The ejection holder will house the air ejectors responsible for rejecting unwanted berries.

Design Considerations: Precise alignment with berry trajectory, fixed distance from detection zone to allow accurate ejection scheduling, modular design for easy adjustment.

Material Selection: Aluminium brackets resistant to vibration and compressed air forces.

3.2.6 Frame Structure

The frame will support all mechanical and electrical components.

Material Selection: Mild steel angle bars or aluminium extrusion selected for strength, stability, and ease of assembly.

3.3 Proposed Electrical and Control Module

The proposed electrical and control module will be designed to support high-speed image acquisition, real-time processing, and precise actuation required for accurate coffee berry sorting. To address the processing bottlenecks identified in the previous system, a co-processing architecture will be introduced.

3.3.1 Central Processing and Co-Processing Architecture

The system will employ a Raspberry Pi 3 as the main processing unit responsible for computationally intensive tasks. The Raspberry Pi will handle image acquisition, image processing, classification using machine learning models, and object tracking across frames. These operations require significant computational resources and are best suited to the Raspberry Pi's processing capabilities.

To improve system responsiveness and reduce latency in real-time control operations, an ESP32 microcontroller will be introduced as a co-processing unit. This secondary processor will handle motor control for the vibrating feeder, timing calculations for ejection

scheduling, direct interfacing with solenoid actuators, and sensor signal conditioning. By offloading these real-time control tasks from the Raspberry Pi, the system achieves better parallel processing and enhanced real-time performance.

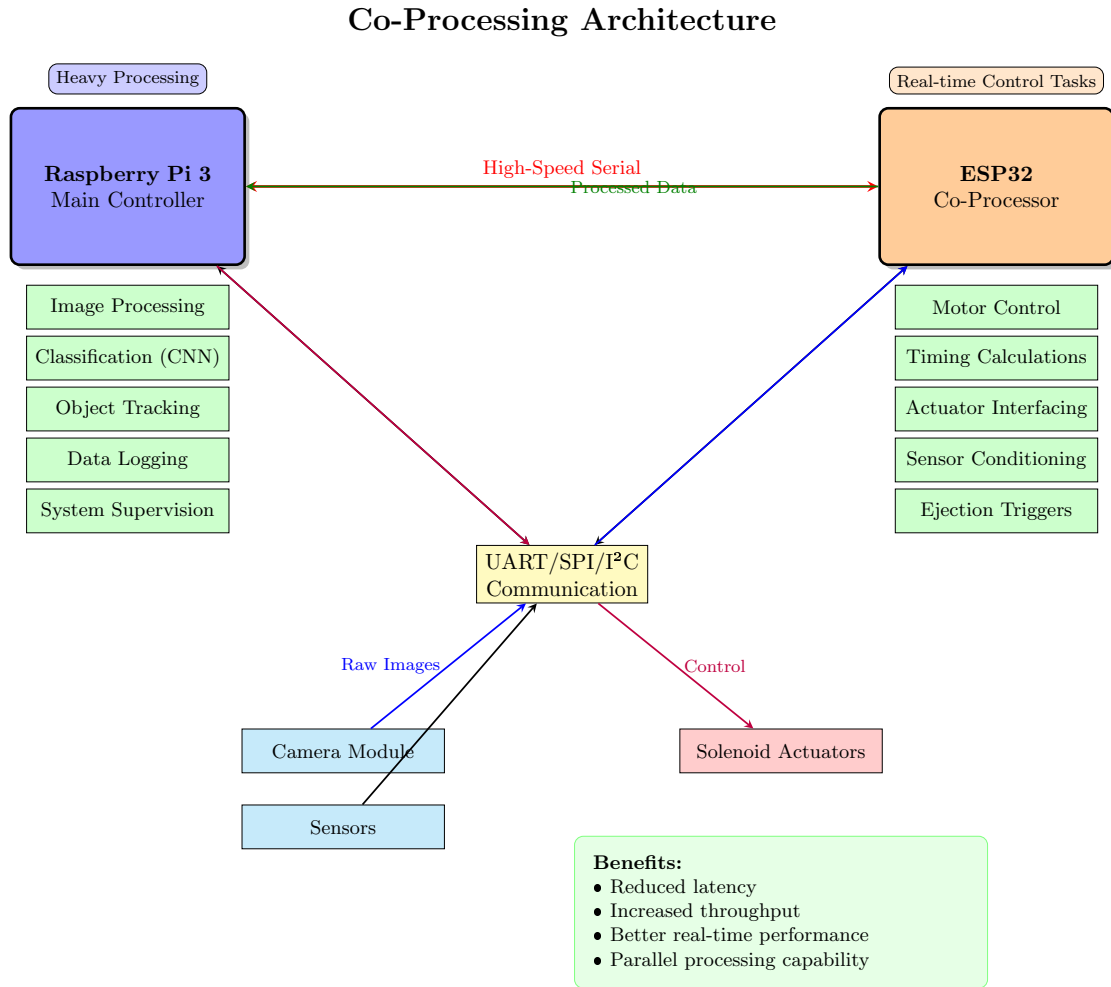


Figure 3.2: Co-processing architecture showing task distribution: Raspberry Pi handles image processing, classification, and tracking; ESP32 handles motor control, actuator interfacing, and timing

The division of tasks will be implemented as follows: The Raspberry Pi will execute all image processing operations including pre-processing, feature extraction, CNN-based classification, and multi-frame object tracking. The ESP32 co-processor will manage

motor speed control for the vibrating feeder, calculate precise timing for ejection based on berry position data received from the Raspberry Pi, directly trigger solenoid actuators, and condition sensor signals before transmission.

Communication between the Raspberry Pi and the ESP32 will be achieved through high-speed UART serial communication, ensuring minimal data transfer delay. The Raspberry Pi will transmit classification results and position data to the ESP32, which will then execute the corresponding actuation commands.

3.3.2 Image Acquisition System

A Raspberry Pi Camera Module will be mounted above the chute using a rigid camera holder to capture high-resolution images of coffee berries in motion. The camera will operate at an optimized frame rate to balance image clarity and processing speed while minimizing motion blur.

Controlled LED lighting modules will be installed around the imaging zone to provide uniform illumination, reduce shadows, and ensure consistent image quality regardless of ambient lighting conditions.

3.3.3 Air Ejection and Actuation System

The berry rejection mechanism will consist of: high-speed air ejectors (solenoid-controlled air nozzles) positioned along the chute, and a compressed air supply system, including a compact air compressor and pressure regulation unit.

The Raspberry Pi will perform real-time classification and tracking of berries, computing their positions and velocities. This information will be transmitted to the ESP32, which will calculate precise ejection timing and directly trigger the solenoid actuators. This distributed approach ensures accurate rejection of defective or unripe berries without affecting accepted berries.

3.3.4 Motor Control and Power Supply

Electric motors used in the linear vibrating feeder will be selected based on vibration frequency requirements, durability, and power efficiency. The ESP32 will control motor drivers to enable precise adjustment of feed rate, ensuring optimal berry spacing for image capture.

The system will utilize: a regulated 5V DC supply for logic-level electronics (Raspberry Pi, ESP32, camera), and a 12V DC supply for actuators, air solenoids, and motors.

Power isolation and protection mechanisms will be incorporated to prevent electrical noise from affecting sensitive processing units.

3.3.5 System Overview

Figure 3.3 provides a high-level overview of the complete system architecture, showing the processor hierarchy, communication links, power distribution, and all actuator outputs.

3.3.6 Electrical Wiring and Pin Assignment

Figure 3.4 illustrates the electrical system architecture and power distribution. All signal lines operate at 3.3V logic levels between the Raspberry Pi and ESP32. The 12V solenoid and motor supplies are isolated with a common ground return to all control electronics.

Figure 3.5 shows the physical breadboard implementation of the control circuit, with the Raspberry Pi 3, ESP32 microcontroller, relay module, and all peripheral connections clearly wired according to the specifications in Table 3.1.

Each ejector solenoid circuit includes a gate drive resistor (220Ohm) for current limiting and a 100kOhm pull-down resistor to GND to prevent false solenoid firing during power-up. A flyback diode (1N4007, cathode to +12V) is connected across each solenoid to suppress inductive transient kickback when the MOSFET switches off. These protection measures ensure reliable and safe operation of the ejection system.

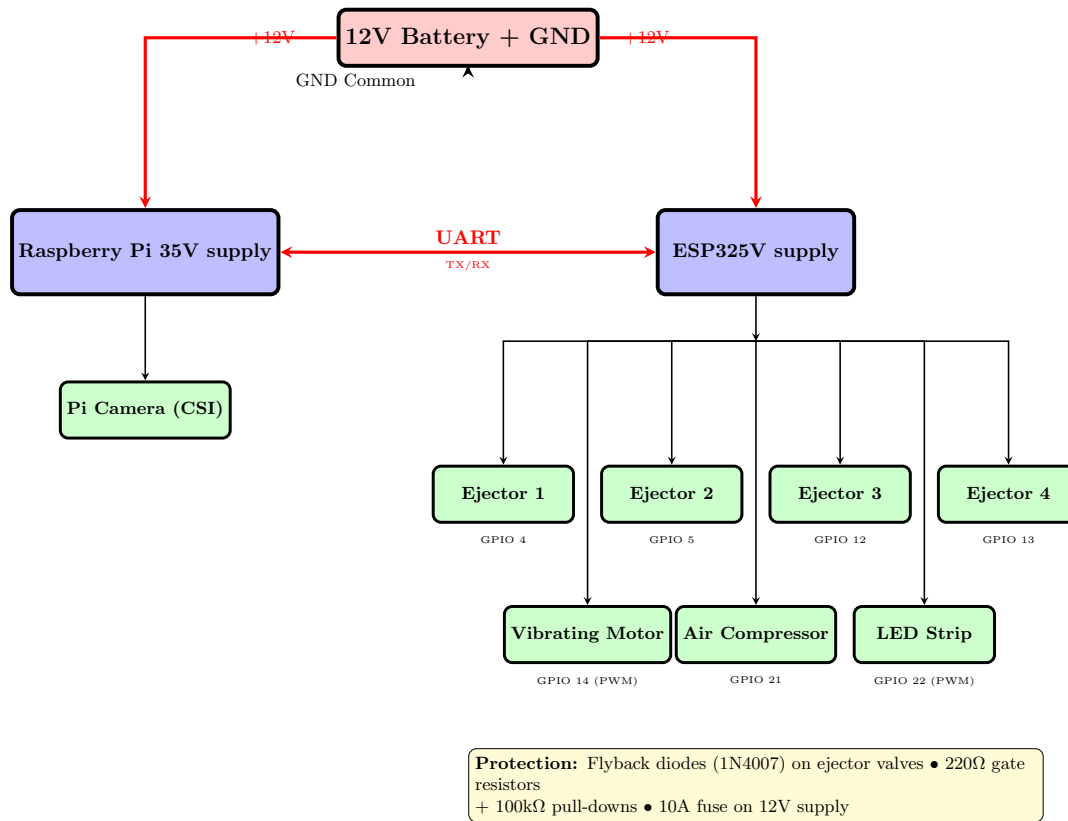


Figure 3.3: System block diagram showing processor hierarchy, communication links, and actuator outputs with power distribution

3.3.7 Actuator Control Circuits

Vibrating Motor (GPIO 14 - PWM Control): The vibrating motor is controlled via pulse-width modulation (PWM) on GPIO 14. An N-channel MOSFET driver circuit amplifies the 3.3V GPIO signal to drive the 12V motor coil. A 220Ω gate resistor limits current to the MOSFET gate, and a flyback diode (1N4007) suppresses inductive kickback when the MOSFET switches off. The PWM frequency allows variable speed control of the vibrating feeder mechanism, enabling adjustment of berry flow rate through the sorting chamber.

Pneumatic Compressor (GPIO 21 - Relay Control): The air compressor is con-

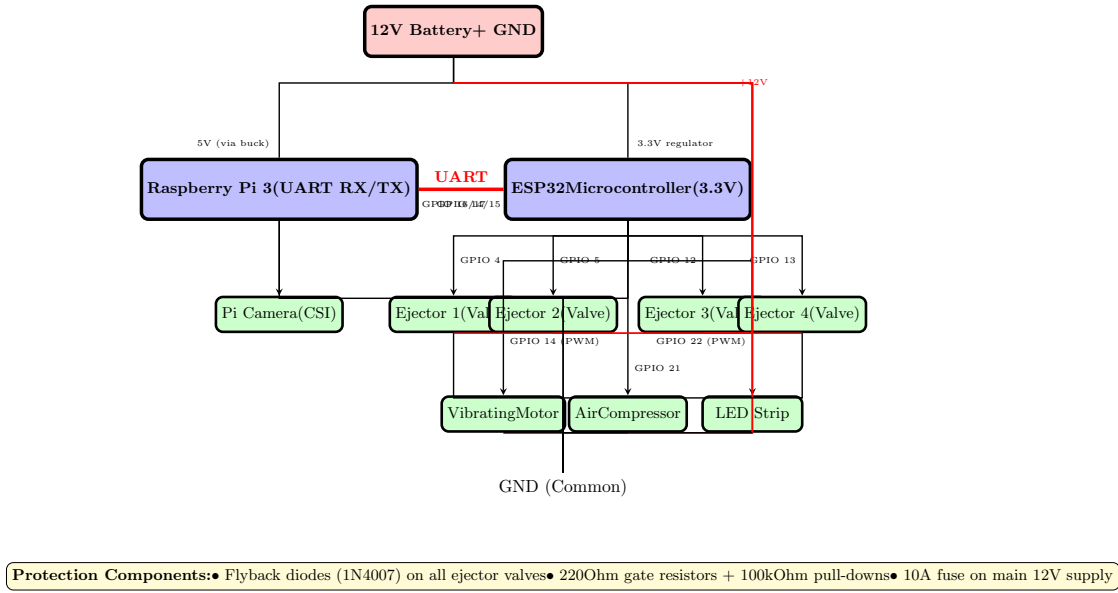


Figure 3.4: Electrical schematic showing power distribution, processor connections, actuator outputs, and communication links

trolled via a relay driver circuit on GPIO 21. Unlike the PWM-controlled motor, the compressor uses simple on/off relay switching since it operates at discrete on/full-power states. The relay coil is driven by a low-current transistor circuit, isolating the low-power GPIO signal from the high-current compressor load. A protection diode across the relay coil prevents voltage spikes when the relay switches off. The compressor supplies pressurized air to the ejector pneumatic circuits.

LED Status Indicator Strip (GPIO 22 - PWM Control): An RGB or monochromatic LED strip provides visual status indication and system feedback. GPIO 22 provides PWM control to a MOSFET driver circuit similar to the motor driver, enabling brightness modulation from 0% to 100%. The LED strip displays system state (operational, ready, error, sorting status) and aids in real-time system monitoring and debugging.

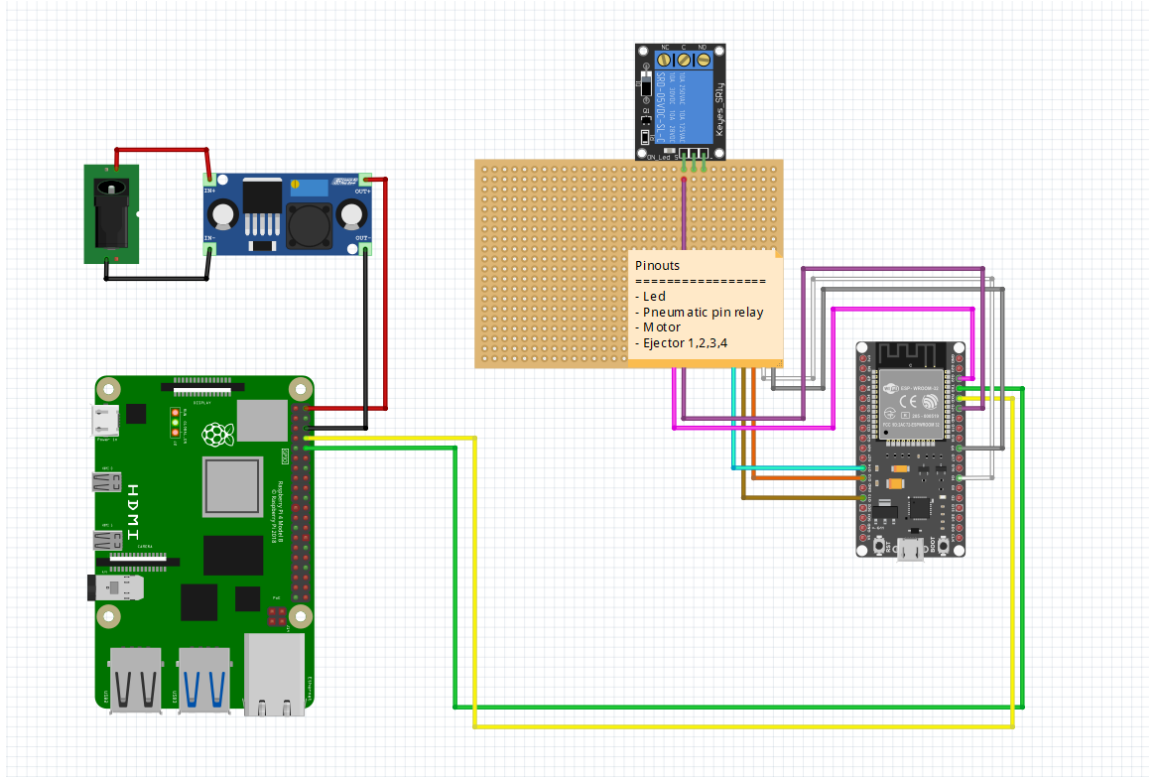


Figure 3.5: Physical breadboard circuit implementation showing Raspberry Pi 3, ESP32 co-processor, relay module, and all peripheral connections (LED, motor, pneumatic compressor, ejector valves)

3.4 Software Architecture and Control Logic

The software system will be modular and executed in stages as outlined below:

3.4.1 System Startup

Upon power-up, the Raspberry Pi will initialize system peripherals, establish UART communication with the ESP32, and perform system diagnostics.

3.4.2 Image Acquisition and Processing

The Raspberry Pi Camera Module will capture images of berries in motion. Captured images will undergo pre-processing on the Raspberry Pi, including grayscale conversion, noise filtering, normalization, and contrast enhancement.

3.4.3 Object Detection and Classification

Coffee berries will be detected using contour-based methods executed on the Raspberry Pi. The classification system will employ a binary classifier (ripe vs. unripe) using a lightweight CNN model optimized with TensorFlow Lite, running on the Raspberry Pi.

3.4.4 Object Tracking

The Raspberry Pi will track detected berries across successive frames to determine velocity and trajectory. Tracking data will be used to compute berry positions and predict ejection points.

3.4.5 Control and Ejection

Based on classification and tracking results, the Raspberry Pi will transmit berry position and classification data to the ESP32 via UART. The ESP32 will calculate optimal actuation timing and trigger the appropriate air ejectors to reject unwanted berries.

The binary classification model (ripe vs. unripe) will be trained using MobileNetV2 architecture, optimized with TensorFlow Lite for efficient deployment on the Raspberry Pi. The model will be trained with data augmentation techniques and quantized to maintain classification accuracy above 90% while minimizing inference time.

3.4.6 System Flow Control

The Raspberry Pi will supervise the entire operation, adjusting system parameters, handling exceptions, and logging performance metrics. Figure 3.6 shows the overall control flow, while Figure 3.7 illustrates the image processing pipeline.

3.4.7 Inter-Processor Communication Protocol

The Raspberry Pi and ESP32 communicate via UART serial connection at 115,200 baud. Figure 3.8 illustrates the data flow and connection between the two processors. The Raspberry Pi sends motor control and ejection commands to the ESP32, which processes these commands in real-time to trigger the appropriate actuators. The ESP32 responds with acknowledgments to confirm command receipt and execution.

Table 3.1: Raspberry Pi 3, ESP32, and Peripheral Wiring Assignment

Function	Device	Pin/Port	Notes
UART Communication (Pi 3 & ESP32)			
UART TX	Raspberry Pi	GPIO 14 (TXD)	3.3V, transmit to ESP32 RX
UART RX	Raspberry Pi	GPIO 15 (RXD)	3.3V, receive from ESP32 TX
UART RX	ESP32	GPIO 16	Receive from Pi TXD
UART TX	ESP32	GPIO 17	Transmit to Pi RXD
Baud Rate	Both	115200 bps, 8N1	Serial protocol parameters
Ejector Solenoid Control (ESP32)			
Ejector 1	ESP32	GPIO 4	MOSFET gate + 220Ohm series resistor
Ejector 2	ESP32	GPIO 5	Flyback diode across solenoid
Ejector 3	ESP32	GPIO 12	1N4007 or 1N5819 (cathode to +12V)
Ejector 4	ESP32	GPIO 13	100kOhm pull-down for safety
Vibrating Motor (ESP32)			
Motor PWM	ESP32	GPIO 14 (PWM)	MOSFET gate driver with 220Ohm resistor
Motor Supply	Battery	+12V, GND	12V rail with flyback diode protection
Pneumatic Compressor (ESP32)			
Compressor Control	ESP32	GPIO 21 (relay)	Relay driver circuit for on/off switching
Compressor Supply	Battery	+12V, GND	12V rail with relay coil protection
LED Status Strip (ESP32)			
LED PWM	ESP32	GPIO 22 (PWM)	MOSFET gate driver with 220Ohm resistor
LED Supply	Battery	+12V, GND	12V rail with flyback diode protection
Power Supply			
Logic Supply	5V Buck	Raspberry Pi (5V)	3A+ recommended
Logic Supply	5V Buck	ESP32 (5V VIN)	2A+ recommended, onboard 3.3V regulator
Motor Supply	12V Battery	Main fused supply	10A main fuse recommended
Common GND	All devices	Star ground point	All GND returns tied together

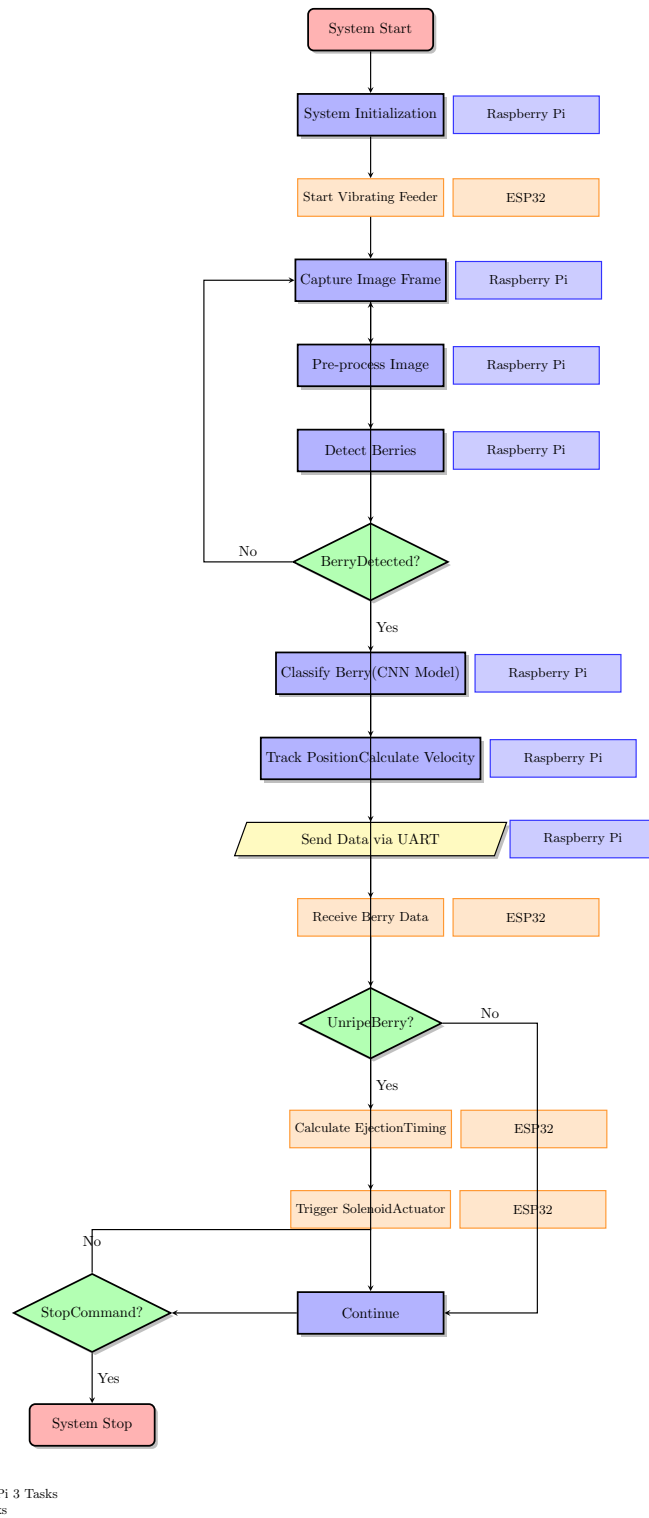
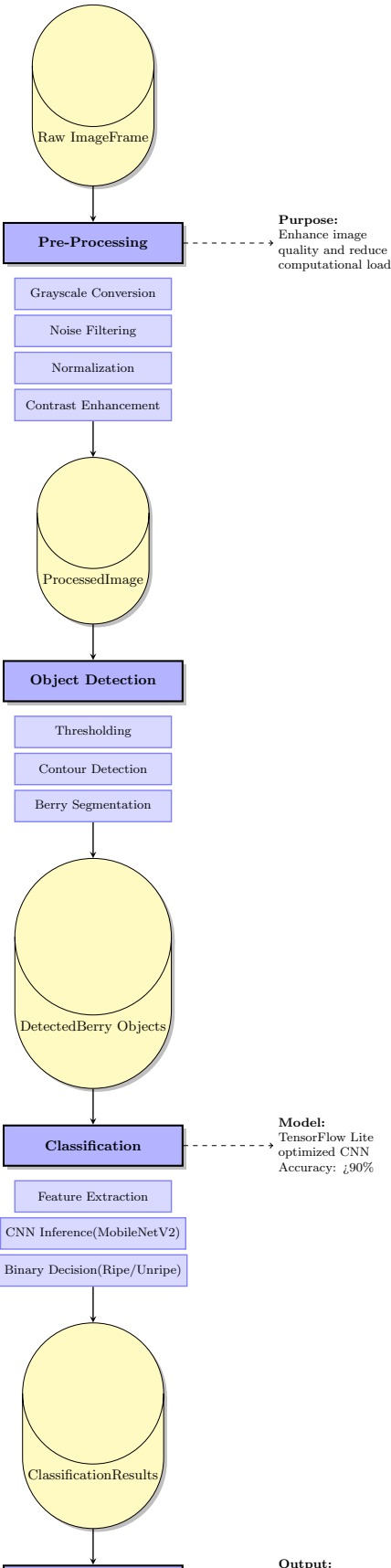


Figure 3.6: System control flow showing task distribution between Raspberry Pi 3 (image processing, classification, tracking) and ESP32 (motor control, timing, actuation)

Image Processing Pipeline (Raspberry Pi 3)



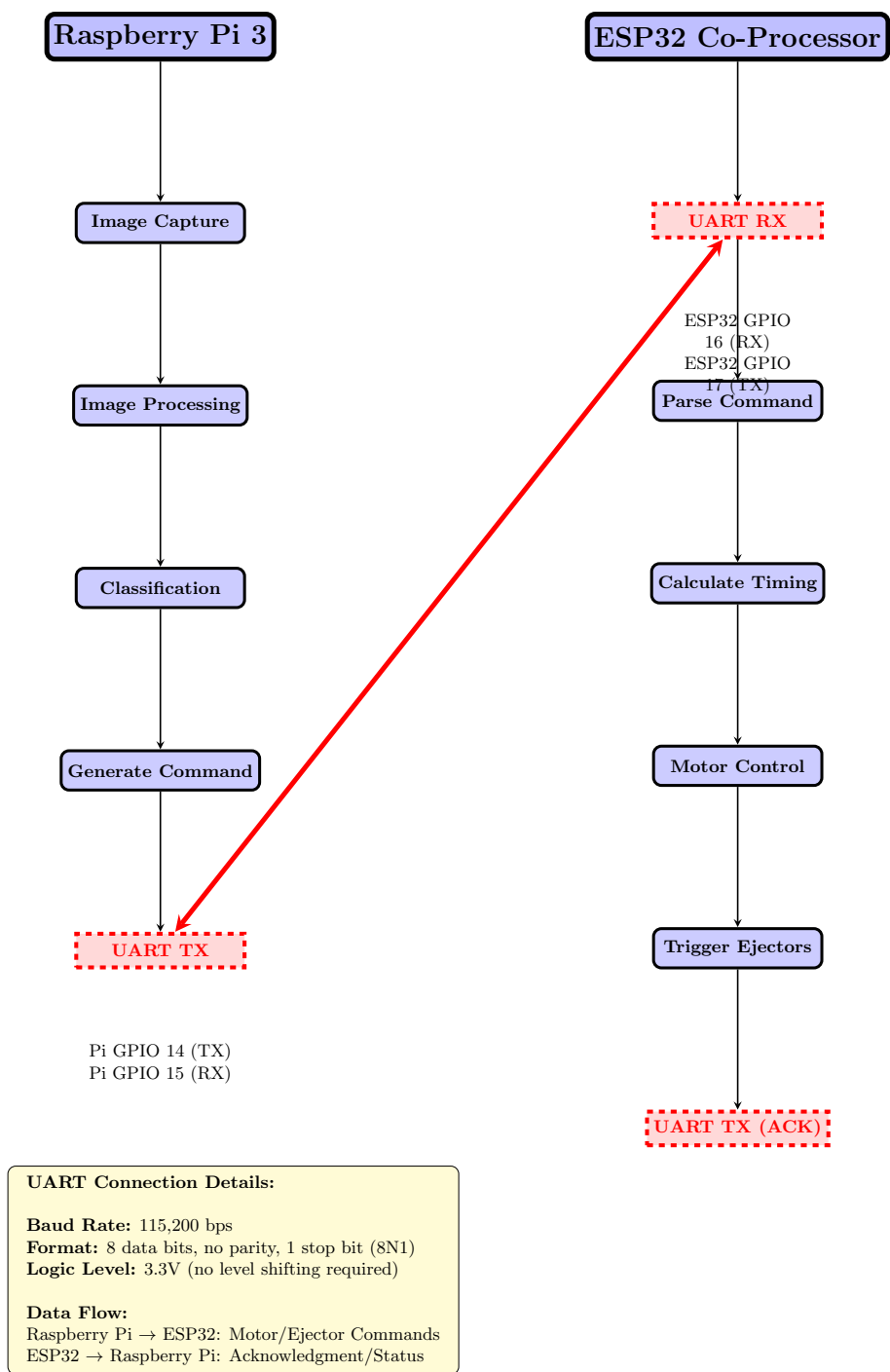


Figure 3.8: UART communication and data flow between Raspberry Pi 3 and ESP32 co-processor showing GPIO pin assignments and connection protocol

4 Expected Outcomes

4.1 An Improved Coffee Berry Sorting Machine Model

The outcome of this project will be a modified and improved coffee berry sorting machine that builds upon the existing prototype architecture. The improvements made will address identified limitations in image clarity, processing throughput, and system reliability.

4.2 Enhanced Real-Time Detection and Classification Performance

The proposed modifications will reduce motion blur and processing delays through an optimized camera configuration, improved lighting, refined image pre-processing methods, and timing-aware ejection scheduling. These enhancements will support classification and sorting at higher throughput levels without compromising accuracy.

The improved system will employ an efficient sorting algorithm that uses color, shape, and surface quality parameters to categorize coffee berries as acceptable or defective, thereby minimizing misclassification rates and improving overall sorting quality.

4.3 Optimized Ejection Timing and Synchronization

By integrating object tracking into the control logic, the system will achieve better alignment between detection, classification, and actuation. This integration will minimize the occurrence of missed ejections, false rejections, and actuation timing errors, resulting in a more reliable sorting process.

4.4 Improved System Stability and Reliability

The refinement of the mechanical and electrical modules will contribute to enhanced system stability. The improved machine will be able to operate continuously without frequent interruptions, contributing to consistent throughput and reduced maintenance downtime.

4.5 A Scalable and Cost-Conscious Design Framework

The project will demonstrate that it is possible to optimize the use of existing Raspberry Pi 3 resources through strategic task distribution and the introduction of low-cost co-processing elements. This framework will provide pathways for future scalability, whether through hardware upgrades or algorithmic improvements.

4.6 Contribution to Agricultural Automation Research

This project will contribute to the ongoing development of low-cost, image-based automated sorting systems in agricultural contexts. It will provide a practical case study on how cost-effective embedded systems can be adapted to meet the real-time processing demands of sorting applications in small-scale Kenyan agricultural settings.

5 Conclusion

This proposal has outlined a structured approach to modifying and improving an existing automated coffee berry sorting machine. Through the introduction of a co-processing architecture alongside the Raspberry Pi 3, the proposed design seeks to overcome the computational and throughput limitations experienced in the current system. The improved mechanical, electrical, and software modules will enhance real-time image processing, classification performance, and ejection timing, thereby supporting more reliable and efficient sorting operations.

The project emphasizes a balance between technological advancement and cost-effectiveness, ensuring that the improvements remain suitable for small-scale agricultural applications. By demonstrating how affordable embedded hardware platforms can be optimized through strategic task distribution and algorithmic refinement, this work aims to contribute to the feasibility of high-performance automated agricultural sorting systems using cost-effective resources.

References

- [1] T. Brosnan and D. W. Sun, “Improving quality inspection of food products by computer vision: A review,” *Journal of Food Engineering*, vol. 61, no. 1, pp. 3–16, 2004.
- [2] J. Blasco, N. Aleixos, and E. Moltó, “Machine vision system for automatic quality grading of fruit,” *Biosystems Engineering*, vol. 85, no. 4, pp. 415–423, 2003.
- [3] R. Kumar and G. S. Mittal, “Classification of food grains using machine vision and neural networks,” *Journal of Food Engineering*, vol. 97, no. 2, pp. 272–279, 2010.
- [4] S. Cubero, N. Aleixos, E. Moltó, J. Gómez-Sanchis, and J. Blasco, “Advances in machine vision applications for automatic inspection and quality evaluation of fruits and vegetables,” *Food and Bioprocess Technology*, vol. 4, no. 4, pp. 487–504, 2011.
- [5] A. Mahmood and M. Khan, “Design of air-jet based sorting mechanisms for agricultural produce,” *International Journal of Agricultural Engineering*, vol. 12, no. 3, pp. 145–152, 2019.
- [6] R. C. Gonzalez and R. E. Woods, *Digital Image Processing*, 4th ed. Pearson Education, 2018.
- [7] R. Szeliski, *Computer Vision: Algorithms and Applications*. Springer, 2011.
- [8] Y. Zhang, L. Wu, and J. Li, “Real-time fruit detection and classification using deep learning techniques,” *Computers and Electronics in Agriculture*, vol. 147, pp. 1–9, 2018.
- [9] A. G. Howard, M. Zhu, B. Chen *et al.*, “Mobilenets: Efficient convolutional neural networks for mobile vision applications,” arXiv preprint arXiv:1704.04861, 2017.
- [10] J. Redmon and A. Farhadi, “Yolov3: An incremental improvement,” arXiv preprint arXiv:1804.02767, 2018.

A Project Budget

Component	Quantity	Price
Raspberry Pi 3	1	5500
Arduino 2560 Micro controller	1	3500
Camera	1	1500
Power Supply	1	3000
Air Ejectors	3	2500
Vibrating Motor	12v 200W (1)	1500
Relay	1	100
Miscellaneous		2000
TOTAL		19,600

Figure A.1: Budget Breakdown

B Project Timeline

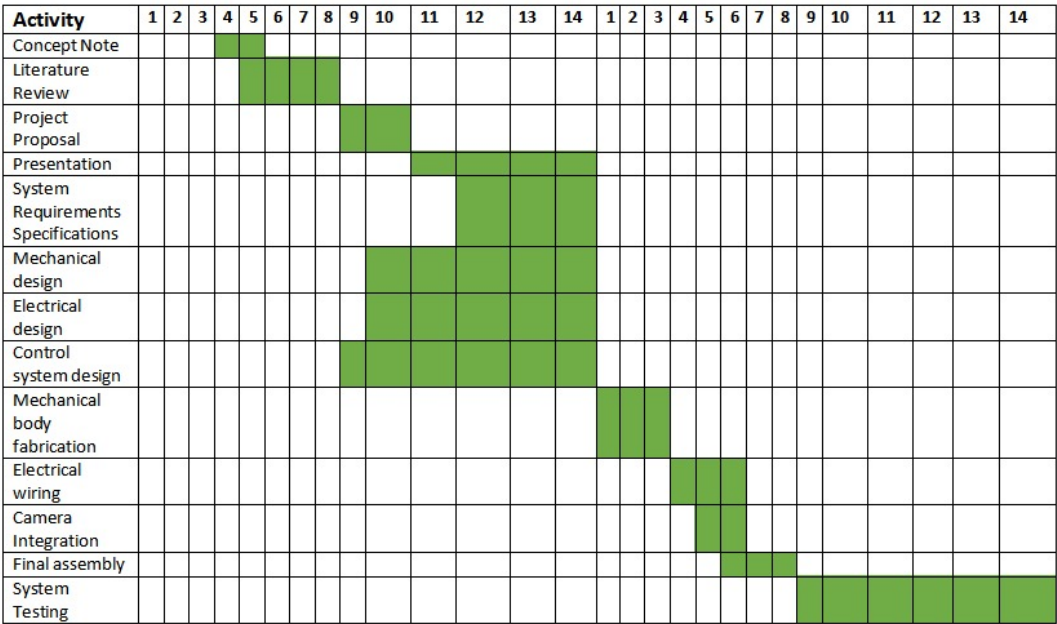


Figure B.1: Implementation Schedule (16 Weeks)