

AI-Powered Robotic System for Intelligent Vegetable Sorting and Placement

Submitted in partial fulfillment of the requirements for the award of

Bachelor of Engineering Degree in
Computer Science Engineering

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ABSTRACT

Agricultural automation has emerged as a critical solution to address labor shortages and enhance productivity in modern farming. This project presents an AI-powered robotic system designed for intelligent vegetable sorting and placement, utilizing advanced sensor technology and robotic automation. The system employs a color-detection algorithm integrated with a robotic arm to automatically identify and sort vegetables based on their color characteristics, specifically targeting red vegetables (tomatoes) and purple/blue vegetables (brinjal/eggplant).

The prototype consists of a 3ft x 3ft modular farming setup that simulates a complete agricultural ecosystem. The system incorporates multiple intelligent features including an entry detection mechanism using proximity sensors that alert when objects or vehicles approach the farm area, and an automated lighting system utilizing Light Dependent Resistors (LDR) that activates illumination only during low-light conditions, thereby optimizing energy consumption. Future integration of solar panels is planned to achieve complete energy independence.

The core functionality revolves around the robotic sorting mechanism developed using Robot Operating System (ROS) and programmed in C++. The system utilizes color sensors to identify vegetables placed before it, and through computer vision algorithms, the robotic arm automatically picks and places each vegetable into designated collection baskets based on color classification. This eliminates the manual sorting process, which is traditionally time-consuming and labor-intensive, especially in farms cultivating multiple crop varieties simultaneously.

The sorted vegetables are then transferred to a miniature warehouse within the setup, simulating the complete supply chain from farm to storage. This automation significantly reduces post-harvest handling time, minimizes human error in sorting, and increases overall efficiency in agricultural operations. The system demonstrates practical applications in real-world farming scenarios where multiple vegetable crops are grown together, offering a scalable solution for small to medium-scale farming operations seeking to modernize their harvest processing methods.

The project demonstrates the integration of multiple sensor technologies working in harmony to create a smart farming environment. The proximity sensors ensure security and monitoring of the farm premises, while the light sensors contribute to sustainable energy management. The color-sorting mechanism represents the pinnacle of the system's intelligence, where machine learning algorithms process real-time visual data to make instantaneous sorting decisions. This multi-sensor approach not only automates the sorting process but also establishes a foundation for future enhancements such as quality assessment, ripeness detection, and defect identification. The modular design allows for easy scalability and adaptation to different crop types and farm sizes. By combining robotics, artificial intelligence, and IoT technologies, this system bridges the gap between traditional farming practices and Industry 4.0 standards, paving the way for fully automated smart farms that can operate with minimal human intervention while maximizing productivity and efficiency.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Agriculture has always been the cornerstone of human civilization, serving as the foundation upon which societies have developed, economies have prospered, and populations have thrived. It provides not only food but also raw materials for various industries, employment for millions, and a stable source of livelihood for rural communities. However, in the 21st century, the agricultural sector faces an unprecedented set of challenges driven by rapid population growth, urbanization, and changing consumption patterns.

The increasing global demand for high-quality and safe food products has put immense pressure on farmers and agribusinesses to enhance productivity, efficiency, and consistency across all stages of production.

In response to these challenges, technological innovations such as **automation, robotics, and artificial intelligence (AI)** are revolutionizing agricultural operations. The integration of these intelligent systems has transformed agriculture from a labor-intensive activity into a data-driven, precision-oriented discipline. Among the numerous applications of AI in agriculture—such as crop monitoring, yield prediction, pest control, and irrigation management—post-harvest operations like sorting, grading, and packaging hold special significance. These processes determine not only the visual and physical quality of produce but also its market value and consumer appeal.

Traditional post-harvest practices largely depend on human labor for sorting and grading. While effective on a small scale, these manual methods suffer from several drawbacks such as inconsistency, fatigue-related errors, slow processing speed, and dependence on skilled labor. As labor shortages and rising wages continue to challenge agricultural industries, the need for automation has become increasingly critical. To overcome these barriers, the adoption of **AI-powered robotic systems** has emerged as a promising solution. These systems combine **computer vision, machine learning, and robotic manipulation** to perform complex sorting tasks with superior precision, speed, and reliability.

One of the most important applications of such automation lies in **color-based sorting** of vegetables and fruits. Color is a primary indicator of ripeness, freshness, and overall quality. Consumers naturally associate bright, consistent coloration with superior quality and good taste. Therefore, accurate color sorting is crucial not only for consumer satisfaction but also for maintaining brand reputation and minimizing waste. Manual color sorting, however, becomes inefficient and error-prone when dealing with large quantities of produce.

AI-based color sorting systems, equipped with **color sensors and high-resolution cameras**, can accurately detect subtle variations in hue and brightness, allowing for rapid and objective classification.

An **AI-powered robotic vegetable sorting system** typically integrates multiple sensing technologies—such as **color sensors, proximity sensors, and light sensors**—alongside intelligent algorithms that analyze and interpret visual data. These systems identify vegetables based on color intensity and tone, differentiating, for instance, ripe red tomatoes from green or partially ripened ones, or distinguishing between purple brinjals (eggplants) and green cucumbers. The robotic arm or conveyor-based mechanism then segregates the items into appropriate bins or baskets for packaging or further processing.

Additionally, smart lighting control and automated entry detection mechanisms can optimize energy usage and enhance system performance, making the operation more sustainable.

This project, therefore, aims to design and implement an **automated color-based vegetable sorting system** that operates efficiently with minimal human intervention. Beyond its immediate practical benefits, the project represents a step toward the broader concept of **smart farming**, where AI, sensors, and robotics work collaboratively to achieve precision agriculture. Such innovations can significantly reduce post-harvest losses, ensure uniform product quality, and enhance profitability for farmers and agro-industries.

The **AI-powered vegetable sorting system** has wide-ranging applications across various domains, including:

- **Tomato sorting and grading** based on color and ripeness.
- **Eggplant or brinjal classification** for packaging and export quality control.
- **Mixed vegetable separation** in bulk processing facilities.
- **Quality control in packaging units** to ensure uniformity and compliance with standards.
- **Post-harvest processing** for efficient distribution and storage.
- **Warehouse and inventory management** using sensor-based identification.
- **Research and experimental setups** for advancing agricultural automation technologies.

By merging the interdisciplinary domains of **machine vision, robotics, and artificial intelligence**, this project highlights how modern technology can revolutionize traditional agricultural operations. The adoption of such intelligent systems not only enhances efficiency and reduces labor dependency but also contributes to sustainability through resource optimization and waste reduction.

Ultimately, the **AI-based vegetable sorting system** serves as a key enabler for the next generation of **precision agriculture** and **smart food processing**, paving the way toward a future where agriculture becomes more intelligent, efficient, and environmentally sustainable.

1.2 Literature Survey

A wide range of studies and technological advancements have been undertaken in the field of machine vision and AI-based agricultural automation. Researchers have explored various approaches to color detection, object classification, and sorting mechanisms aimed at improving agricultural productivity. The following literature review highlights significant contributions to this domain:

- 1) **Zhang, B. et al. (2014).** "*Computer vision detection of defective apples using automatic lightness correction and weighted RVM classifier.*"

This study developed a computer vision-based sorting system for apples that incorporated automatic lightness correction and a weighted Relevance Vector Machine (RVM) classifier. The model achieved a classification accuracy of 92.3% under controlled lighting conditions. Although processing time increased slightly with the use of RVM compared to simpler threshold-based methods, it significantly enhanced accuracy and robustness.

- 2) **Patel, K. K. et al. (2012).** "*Machine vision system: A tool for quality inspection of food and agricultural products.*"

This comprehensive review examined over 45 peer-reviewed studies on machine vision applications in agricultural sorting and quality inspection. The authors found that color-based sorting was the most commonly adopted approach, though challenges remained regarding cost, environmental variability, and algorithm standardization. The review concluded that while machine vision technology shows strong potential for automation in agriculture, real-world adoption depends on affordable system design and improved adaptability to field conditions.

- 3) **Naik, S. & Patel, B. (2017).** "*Machine Vision-based Fruit Classification and Grading – A Review.*"

Naik and Patel compared the performance of multiple classification algorithms—k-Nearest Neighbors (k-NN), Support Vector Machine (SVM), and Artificial Neural Networks (ANN)—for color-based fruit sorting. The study concluded that ANN achieved the highest accuracy (95%) among the tested algorithms, followed by SVM (93%) and k-NN (89%). However, increased accuracy was associated with longer processing times.

- 4) **Cubero, S. et al. (2011).** "*Advances in Machine Vision Applications for Automatic Inspection and Quality Evaluation of Fruits and Vegetables.*"

This extensive review analyzed 156 publications related to machine vision applications in food processing between 1990 and 2010. Out of these, 68 studies met inclusion standards for quantitative assessment. Color analysis was the most frequently used feature, applied in approximately 78% of studies. The authors observed that while many prototypes showed high laboratory accuracy, only 15 achieved commercial success.

Summary of Literature:

The reviewed studies consistently highlight several key themes. First, **color-based machine vision** remains one of the most reliable and widely used techniques for fruit and vegetable sorting. Second, **algorithmic performance** varies according to crop type, lighting conditions, and dataset characteristics, underscoring the need for adaptive models. Third, the transition from laboratory prototypes to commercial deployment requires balancing **accuracy, processing speed, and affordability**. Finally, advancements in sensor technology, computer vision algorithms, and embedded systems have made it feasible to develop compact, cost-effective solutions for small and medium-scale agricultural operations. The literature thus provides a strong foundation for the proposed system, which leverages the strengths of **HSV color space, AI-based classification, and sensor integration** to achieve efficient, low-cost vegetable sorting.

1.3 Scope of the Project

The proposed **AI-powered robotic vegetable sorting system** aims to demonstrate a fully automated, intelligent, and scalable solution for post-harvest agricultural operations. The project focuses primarily on **color-based classification**, employing computer vision and embedded control systems to automate the sorting of vegetables such as tomatoes and brinjals.

The system is designed to address several key issues prevalent in agricultural processing:

1. **Labor Shortage and Cost:** Manual sorting requires intensive labor, which is increasingly difficult to obtain in rural and semi-urban regions. Automation reduces dependency on manual labor, lowering long-term costs.
2. **Inconsistency and Human Error:** Human sorters may exhibit variability in decision-making due to fatigue or subjective judgment. An AI system ensures consistent quality and uniform sorting criteria.
3. **Efficiency and Throughput:** Automated systems can operate continuously and process larger quantities of produce within shorter timeframes, increasing productivity.
4. **Energy Optimization:** The system incorporates **automated lighting control**, ensuring that artificial illumination is activated only when necessary, thereby conserving energy.
5. **Scalability and Integration:** The modular design allows the system to be scaled for small farms, medium processing units, or large industrial sorting lines. It can also integrate with warehouse management systems for inventory tracking.
6. **Sustainability:** Reducing wastage, improving grading accuracy, and optimizing energy consumption contribute to environmentally sustainable farming practices.

From a **technical perspective**, the system's architecture combines **color sensors** for object recognition, **microcontrollers** for decision-making, and **servo motors** or robotic arms for mechanical sorting. The embedded AI algorithm processes sensor data in real time, classifies the vegetables based on predefined color thresholds, and directs them to corresponding bins. The inclusion of proximity and light sensors enhances precision, enabling adaptive operation under changing environmental conditions.

The **scope of this project** extends beyond a prototype demonstration. It lays the groundwork for:

- Development of affordable **AI-based sorting modules** suitable for small farmers.
- Integration with **Internet of Things (IoT)** platforms for remote monitoring.
- Expansion into **multi-feature classification**, such as size, shape, and defect detection.
- Real-world deployment in agricultural warehouses and food processing units.

Ultimately, this system exemplifies how modern technologies—AI, robotics, and computer vision—can converge to create intelligent agricultural solutions that are **efficient, cost-effective, and sustainable**. By minimizing human labor and maximizing precision, the system contributes to the long-term goal of **smart agriculture**, ensuring that food production processes keep pace with the needs of a growing population.

1.4 EXISTING SORTING METHODS

MANUAL SORTING

Manual sorting is a traditional method widely utilized by farmers, agricultural workers, and processing facility staff to classify and grade vegetables and fruits based on visual inspection. While manual sorting has been the primary method for centuries, it is not effective for all large-scale agricultural operations due to inherent limitations. Manual sorting may help reduce waste and improve product quality if farmers have access to the following resources:

- Skilled labor force
- Adequate lighting conditions
- Quality control standards
- Sufficient workspace
- Time flexibility
- Training programs
- Supervision systems

Types of Manual Sorting

There are two main types of manual sorting approaches: individual inspection and conveyor belt sorting. Both use human visual perception and decision-making abilities (which function like biological processors) to classify produce. The distinction between the two types of manual sorting is the rate at which workers can process the vegetables.

Individual Inspection Sorting. Individual inspection uses workers examining each piece of produce separately in their hands. The workers carefully observe color, size, shape, and defects in each vegetable, making classification decisions based on predetermined quality standards. This detailed examination encourages accurate sorting by allowing workers to assess multiple quality parameters at the individual produce level.

Conveyor Belt Sorting. Conveyor belt manual sorting uses workers stationed along a moving belt to inspect produce. While this still requires careful visual examination, it additionally allows for higher throughput and systematic workflow in processing facilities. This helps to increase processing speed and production volume, therefore improving operational efficiency.

The type of manual sorting method employed depends on the operation scale. If facilities have small production volumes or specialty crops requiring detailed inspection, individual hand sorting is probably the preferred method. If operations involve high volumes with standardized quality requirements, like in commercial packing houses, conveyor belt sorting systems provide more efficiency.

MECHANICAL SORTING SYSTEMS

Mechanical sorting represents an intermediate automation level that uses physical property-based separation techniques. Mechanical sorting has been a commonly used agricultural processing method since it was initially developed in the mid-twentieth century. However, like other traditional technologies, mechanical sorting results are limited to specific parameters and cannot match intelligent systems' versatility.

Mechanical sorting involves using equipment like roller sorters, vibratory separators, and size grading machines that classify produce based on physical dimensions. These systems are designed with precisely calibrated openings, rollers, or screens. The equipment physically separates vegetables into different size categories as they pass through the sorting mechanism.

Mechanical sorting has been tried in numerous agricultural applications as a pre-processing tool. Mechanical systems may be used for preliminary sorting of:

- Potatoes and root vegetables
- Onions and bulb crops
- Citrus fruits
- Apples and stone fruits
- Tomatoes (size-based only)
- Cucumbers and squash
- Carrots and similar vegetables
- Bell peppers and capsicums

The primary advantage of mechanical sorting is its simplicity and reliability for size-based classification. However, these systems have significant limitations as they cannot assess color, ripeness, surface defects, or internal quality – parameters that are crucial for determining market value and consumer acceptance.

BASIC OPTICAL SORTING

Basic optical sorting represents early automation attempts in agricultural processing facilities. The term "basic" refers to simple photoelectric sensors or single-wavelength detection systems. In basic optical sorting, light beams or simple color sensors are used to detect gross differences in produce appearance. These systems can identify obvious color variations or detect the presence/absence of objects on processing lines.

The detection mechanism of basic optical sorting creates binary decisions (accept/reject) based on predetermined threshold values. Early systems could reach detection speeds of several items per second, making them suitable for high-volume processing lines. While these systems don't apply complex analysis to the produce characteristics, the simple triggering mechanisms allowed facilities to automate the most basic sorting decisions.

Basic optical systems work by positioning produce items in front of light sources and sensors. As light reflects off the vegetable surface, sensors measure intensity or simple color values. When measurements fall outside acceptable ranges, pneumatic ejectors or mechanical diverters remove the item from the main product stream.

The main advantage of basic optical sorting is its ability to operate continuously at high speeds without worker fatigue. These systems can gently process produce with minimal handling damage, allowing

facilities to move products more efficiently through processing lines and participate in higher-volume operations with reduced labor costs.

Basic optical sorting is not limited to just quality control applications. These systems can be used in counting operations where sensors count individual items passing on conveyor belts. Simple presence/absence detection generated by optical sensors can trigger automated bagging systems, helping to portion products into consumer packages. For instance, basic optical counting systems are commonly used for packaging operations in facilities processing uniform products like eggs, small fruits, or standardized vegetable packages.

Basic optical systems can also be programmed to remove foreign objects like leaves, stems, stones, or packaging materials that accidentally enter processing lines. The contrast between unwanted materials and actual produce is often sufficient for simple optical sensors to identify and trigger rejection mechanisms, addressing contamination issues in processing facilities without requiring constant human monitoring.

SEMI-AUTOMATED GRADING SYSTEMS

Semi-automated grading represents a hybrid approach that combines mechanical handling with human decision-making. These systems are a prominent type of sorting solution (different from fully manual or fully automated approaches) that involves transporting produce past inspection stations where workers make grading decisions. The vegetables are conveyed from one point to another past trained operators positioned at strategic locations along the processing line.

Typical semi-automated grading lines operate with multiple inspection stations where 3-5 workers simultaneously evaluate produce quality. Each worker is responsible for specific quality parameters or defect types, creating a division of labor that improves consistency compared to single-worker inspection. These systems typically process 50-200 items per minute depending on produce type, worker skill levels, and quality standards being applied.

Semi-automated systems provide benefits over purely manual sorting by standardizing the presentation of produce to workers. Each item passes the inspector at the same distance, angle, and lighting condition, reducing variability in assessment conditions. The mechanical handling also reduces physical strain on workers by eliminating the need to repeatedly lift and manipulate heavy produce items.

However, semi-automated systems still depend heavily on human judgment and are subject to inconsistencies from worker fatigue, attention lapses, and subjective interpretation of quality standards. Training requirements remain substantial, and labor costs continue to represent a significant operational expense. Throughput is limited by human reaction time and decision-making speed, creating bottlenecks in high-volume operations.

The evolution from manual to semi-automated and finally to fully automated intelligent systems represents the natural progression of agricultural technology. Each generation addresses limitations of previous approaches while introducing new capabilities. Modern AI-powered robotic sorting systems represent the latest advancement, offering consistent, objective, high-speed classification based on multiple parameters simultaneously – capabilities that traditional methods cannot match. These intelligent systems learn from data, adapt to variations, and provide traceability and documentation that manual and mechanical methods cannot offer, making them essential for meeting contemporary agricultural industry demands for efficiency, consistency, and quality assurance.

CHAPTER 2

PROJECT DESCRIPTION

2.1 BLOCK DIAGRAM

The AI-powered robotic system for intelligent vegetable sorting represents a comprehensive integration of multiple subsystems working in harmony to achieve automated agricultural processing. The block diagram illustrates the interconnection between various functional modules that collectively enable the system to detect, classify, and sort vegetables based on their color characteristics while simultaneously managing farm security and energy efficiency.

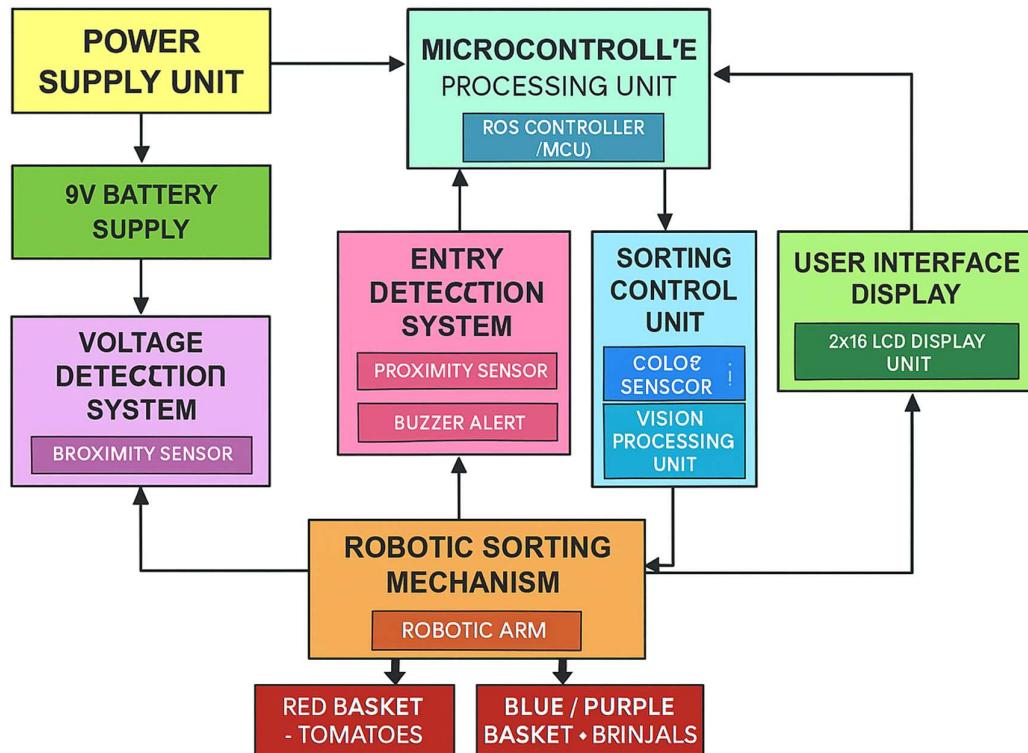


Fig 2.1: Block Diagram of Vegetable Sorting System

The system architecture is divided into five primary functional blocks: the power management unit, the sensing and detection subsystem, the processing and control unit, the actuation mechanism, and the user interface module. Each block performs specific functions that contribute to the overall system operation.

The **Power Management Unit** forms the foundation of the electrical system, converting the 9V battery supply into a regulated 5V DC output required by the microcontroller and peripheral devices. This unit

incorporates a voltage regulator (7805) that ensures stable power delivery to all electronic components regardless of battery voltage variations. The power distribution network branches out to supply individual subsystems including sensors, display unit, processing unit, and actuators. Future enhancement plans include integration of solar panels to achieve energy independence, making the system completely self-sufficient for outdoor agricultural applications.

The **Sensing and Detection Subsystem** comprises three critical sensor modules. The entry detection system utilizes a proximity sensor (HC-SR04 ultrasonic sensor or IR sensor) positioned at the farm entrance to monitor object or vehicle movement. When an object passes through the detection zone, the sensor triggers an alert mechanism through a buzzer, providing security monitoring for the miniature farm setup. This feature simulates real-world farm security systems where unauthorized entry detection is crucial for protecting crops and equipment.

The light sensing module employs a Light Dependent Resistor (LDR) that continuously monitors ambient light levels. The LDR's resistance varies inversely with light intensity - decreasing in bright conditions and increasing in darkness. This analog resistance change is converted to a voltage signal through a voltage divider circuit and fed to the microcontroller's analog input pin. Based on programmable threshold values, the system automatically controls illumination, turning lights ON during low-light conditions and OFF during daylight hours. This intelligent lighting management significantly reduces energy consumption, particularly important for future solar-powered implementations.

The color detection module represents the core sensing component for vegetable sorting operations. A TCS3200 or TCS34725 RGB color sensor is positioned in the sorting area where vegetables are placed for classification. The color sensor incorporates photodiodes with red, green, and blue filters that measure reflected light intensity at each wavelength. The sensor outputs frequency signals or digital values proportional to the intensity of each color component, enabling precise color characterization of the vegetable surface. The microcontroller processes these RGB values through color classification algorithms to determine whether the object is a red vegetable (tomato) or a purple/blue vegetable (brinjal/eggplant).

The **Processing and Control Unit** serves as the system's brain, orchestrating all operations through a microcontroller (ATmega328, Arduino-compatible, or ARM-based processor). The microcontroller executes the control program written in C++ and interfaces with ROS (Robot Operating System) for advanced robotic control capabilities. ROS provides a structured framework for managing sensor data, implementing control algorithms, and coordinating actuator movements. The processing unit continuously performs several tasks in a cyclic manner: reading sensor inputs, processing color data through classification algorithms, making sorting decisions, generating control signals for the robotic arm, updating the display, and monitoring emergency stop conditions.

The control logic implements a state machine architecture with multiple operational states including initialization, standby, detection, classification, sorting, and emergency stop. During initialization, all sensors and actuators are configured and tested. In standby mode, the system monitors sensors while waiting for user input. Upon receiving the start command, the system enters active mode where it continuously scans for vegetables in the detection zone. When a vegetable is detected, the color sensor captures RGB values, and the classification algorithm determines the vegetable type. Based on classification results, appropriate control signals are sent to the robotic arm to pick the vegetable and place it in the corresponding basket.

The **Actuation Mechanism** consists of a robotic arm assembly driven by servo motors. A typical configuration employs three servo motors: a base rotation servo for horizontal positioning, a shoulder/elbow servo for vertical reach adjustment, and a gripper servo for opening and closing the end

effector. The microcontroller generates PWM (Pulse Width Modulation) signals to control servo positions with precise angular accuracy. The robotic arm follows a programmed sequence: moving to the pickup position above the detected vegetable, lowering the gripper, closing to grasp the object, lifting, moving to the appropriate basket location (red basket for tomatoes or blue basket for brinjal), and releasing the vegetable by opening the gripper. After completing the sorting action, the arm returns to its home position, ready for the next cycle.

The sorting baskets are strategically positioned within the robotic arm's workspace. Two collection containers are designated - one for red vegetables and another for purple/blue vegetables. These baskets simulate the collection bins used in commercial sorting facilities where separated produce is collected for subsequent packaging and distribution.

The **User Interface Module** provides system monitoring and control capabilities through a 16x2 character LCD display and push-button inputs. The display shows real-time system status including operational mode, sorting count for each vegetable type, and error messages. Three push buttons provide user control: a mode selection button to configure system parameters, a start/stop button to initiate or pause sorting operations, and an emergency stop button that immediately halts all operations when safety concerns arise. LED indicators provide visual status information with different colors representing various states: green for system ready, yellow for active sorting, and red for emergency stop or error conditions.

The complete system operates as an integrated unit where sensor inputs flow to the processing unit, decisions are made based on programmed algorithms, and actuators respond to control commands. Data flows continuously through the system: the proximity sensor detects entry and triggers alerts, the LDR monitors light levels and controls illumination, the color sensor captures vegetable characteristics and enables classification, the microcontroller processes all inputs and generates appropriate outputs, the robotic arm executes sorting movements, and the display keeps the user informed of system status.

This modular architecture provides several advantages including ease of troubleshooting (each subsystem can be tested independently), scalability (additional sensors or actuators can be integrated), and flexibility (control algorithms can be modified without hardware changes). The block diagram representation clarifies the system hierarchy and information flow, serving as a valuable reference during system development, testing, and documentation.

2.2 CIRCUIT DIAGRAM

The circuit diagram provides detailed electrical connections between all components, showing specific pin assignments, power distribution, and signal routing. This schematic serves as the blueprint for physical implementation, enabling accurate assembly and troubleshooting.

Circuit Diagram of Vegetable Sorting System

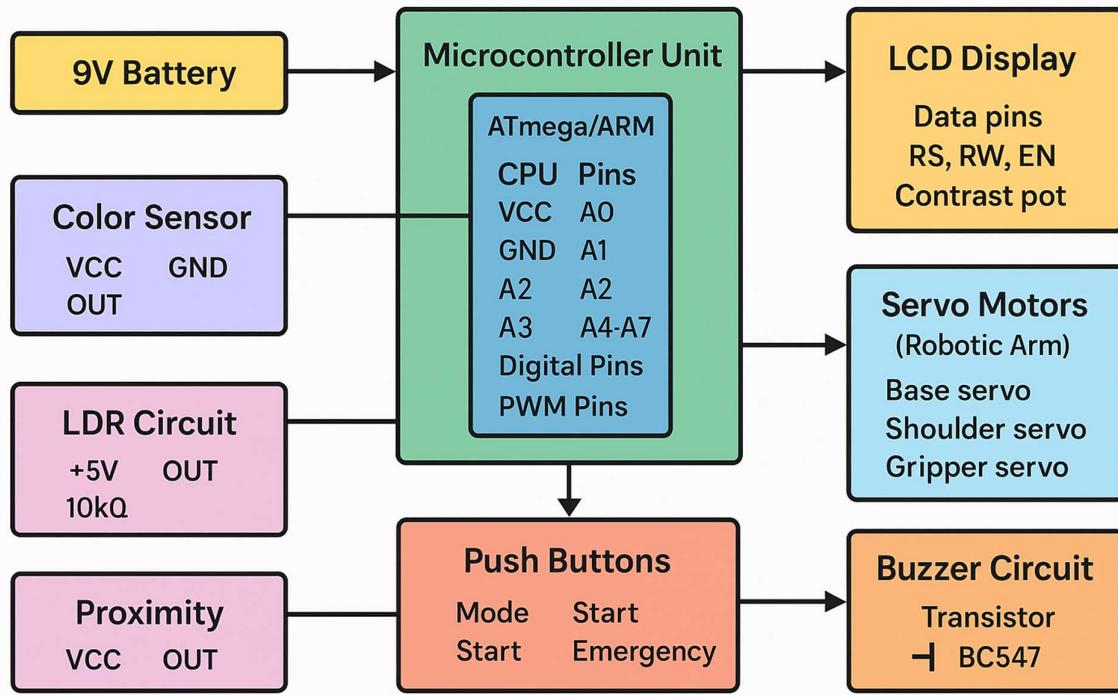


Fig 2.2: Circuit Diagram of Vegetable Sorting System

The power supply section forms the entry point of the circuit. A 9V battery connects to the input terminals of a 7805 voltage regulator IC. The 7805 is a linear voltage regulator that converts the 9V input to a stable 5V output suitable for digital circuits. Input and output capacitors (100 μ F electrolytic and 0.1 μ F ceramic) are connected to ground to filter voltage fluctuations and ensure stable operation. The regulated 5V rail distributes power to all components through a common bus.

The microcontroller occupies the central position in the circuit diagram. An ATmega328P (or equivalent) microcontroller in DIP-28 package connects to various peripherals through its I/O pins. The VCC pin connects to the +5V rail, and GND connects to the ground bus. A 16MHz crystal oscillator connects between XTAL1 and XTAL2 pins with 22pF capacitors to ground, providing the clock signal for microcontroller operation. A 10k Ω pull-up resistor connects the RESET pin to VCC, with a push button to ground enabling manual reset capability.

The color sensor interface shows the TCS3200 color sensor module connections. The sensor's VCC and GND pins connect to the power rails. Four selection pins (S0, S1, S2, S3) connect to digital output pins (D8-D11) of the microcontroller, allowing software control of the sensor's frequency scaling and photodiode selection. The sensor's output pin connects to a digital input pin (D12) configured for frequency measurement. The LED control pin may connect to another digital output for enabling/disabling the sensor's onboard LEDs.

The proximity sensor circuit shows an HC-SR04 ultrasonic sensor or IR sensor module. For HC-SR04, the VCC and GND pins connect to power rails, the TRIGGER pin connects to a digital output (D2), and the ECHO pin connects to a digital input (D3). The microcontroller sends a 10 μ s pulse to the trigger pin

and measures the echo pulse width to determine distance. When an object is detected within the threshold distance, the buzzer is activated.

The LDR (Light Dependent Resistor) circuit forms a voltage divider with a $10\text{k}\Omega$ fixed resistor. One end of the LDR connects to $+5\text{V}$, the junction between LDR and the $10\text{k}\Omega$ resistor connects to an analog input pin (A0), and the other end of the fixed resistor connects to ground. As ambient light changes, the LDR resistance varies, causing voltage at the junction to change proportionally. The microcontroller's ADC (Analog to Digital Converter) reads this voltage and determines whether to activate the lighting system.

The servo motor connections show three servo motors for the robotic arm. Each servo has three wires: red (VCC), brown/black (GND), and orange/yellow (signal). The power wires connect to the $+5\text{V}$ rail (though external power supply may be needed for multiple servos under load), ground wires connect to the common ground, and signal wires connect to PWM-capable digital pins (D9, D10, D11). The microcontroller generates PWM signals with specific pulse widths (typically 1-2ms) to control servo positions.

The LCD display interface shows a 16x2 character LCD module connection. The LCD operates in 4-bit mode to conserve microcontroller pins. The VSS pin connects to ground, VDD to $+5\text{V}$, and VO (contrast) to the wiper of a $10\text{k}\Omega$ potentiometer (with fixed ends connected between $+5\text{V}$ and ground). The RS (Register Select) pin connects to D4, RW (Read/Write) to ground (write mode), and E (Enable) to D5. Data pins D4-D7 of the LCD connect to D6-D9 of the microcontroller. Backlight pins (A and K) connect to $+5\text{V}$ and ground respectively through a current-limiting resistor (220Ω).

The buzzer circuit uses a transistor driver for adequate current supply. An NPN transistor (BC547 or 2N2222) has its base connected to a digital output pin (D13) through a $1\text{k}\Omega$ current-limiting resistor. The collector connects to one terminal of a 5V buzzer, with the other buzzer terminal connected to $+5\text{V}$. The emitter connects to ground. A flyback diode (1N4148) connects across the buzzer with cathode to $+5\text{V}$ to protect the transistor from inductive kickback.

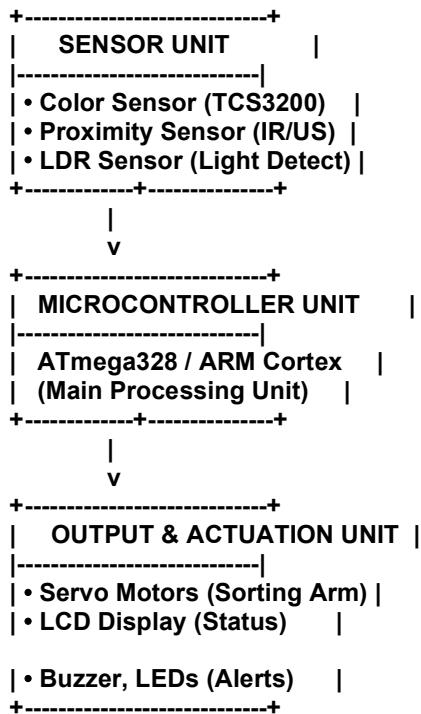
The push button input circuits show three tactile switches for user control. Each button has one terminal connected to a digital input pin (D14-D16 / A1-A3) and the other terminal to ground. Internal or external pull-up resistors ($10\text{k}\Omega$ to $+5\text{V}$) ensure the input reads HIGH when the button is not pressed and LOW when pressed. Software debouncing routines handle contact bounce.

LED indicator circuits show three LEDs (red, green, yellow) with their anodes connected to digital output pins (D17-D19 / A4-A6) through 220Ω current-limiting resistors. The cathodes connect to ground. The microcontroller controls LED states to provide visual feedback about system operation.

All ground connections merge into a common ground bus ensuring a stable reference potential throughout the circuit. Power distribution follows a star topology where possible to minimize voltage drops and noise coupling. Decoupling capacitors ($0.1\mu\text{F}$ ceramic) are placed close to each IC's power pins to filter high-frequency noise.

The circuit diagram includes wire color coding recommendations: red for $+5\text{V}$, black for ground, and various colors for signal wires. Proper wire routing minimizes electromagnetic interference and maintains signal integrity. The complete circuit fits on a standard prototyping board or custom PCB, with components arranged to minimize connection lengths and facilitate troubleshooting.

2.3 COMPONENTS REQUIRED



The implementation of the AI-powered vegetable sorting system requires a comprehensive selection of electronic components, mechanical parts, and structural materials. This section provides detailed specifications for all required components, organized by functional categories.

2.3.1 HARDWARE COMPONENTS

Microcontroller and Processing:

The system employs an ATmega328P microcontroller (as used in Arduino Uno) or a more powerful ARM Cortex-M series processor depending on processing requirements. The ATmega328P offers 32KB flash memory, 2KB SRAM, 1KB EEPROM, and 23 I/O pins sufficient for this application. It operates at 16MHz clock frequency providing adequate processing speed for sensor reading, decision-making, and actuator control. For more complex vision processing or future enhancements, an ARM Cortex-M4 processor or Raspberry Pi can be substituted, offering higher processing power and built-in peripherals.

Color Sensing Module:

The TCS3200 or TCS34725 RGB color sensor serves as the primary vegetable classification component. The TCS3200 is a programmable color light-to-frequency converter that combines configurable silicon photodiodes and a current-to-frequency converter on a single CMOS integrated circuit. It outputs a square wave with frequency proportional to light intensity at the selected color (red, green, or blue). The sensor includes an array of photodiodes, each with either red, green, blue, or clear filters. The TCS34725 is an I₂C-compatible sensor providing digital RGB and clear light data with integrated IR blocking filter,

making it suitable for accurate color measurement. The sensor should be mounted 10-30mm above the vegetable detection zone with consistent ambient lighting or integrated illumination.

Proximity and Distance Sensing:

An HC-SR04 ultrasonic distance sensor provides non-contact entry detection with 2cm to 400cm range and 3mm accuracy. The sensor transmits 40kHz ultrasonic pulses and measures echo return time to calculate distance. Alternatively, an IR (Infrared) obstacle detection sensor using an IR LED transmitter and photodiode receiver offers simpler implementation for presence detection applications. The sensor should be mounted at the farm entrance with appropriate height and angle to detect passing objects or vehicles reliably.

Light Level Sensing:

A standard 5mm LDR (Light Dependent Resistor) photoresistor serves for ambient light detection. The LDR exhibits resistance typically ranging from $1M\Omega$ in darkness to $10k\Omega$ in bright light. Paired with a fixed $10k\Omega$ resistor in a voltage divider configuration, it produces an analog voltage signal proportional to light intensity. The LDR should be positioned to sense ambient environmental lighting without direct exposure to controlled illumination sources.

Servo Motors and Actuation:

Three SG90 micro servo motors provide robotic arm articulation. Each SG90 offers 180-degree rotation range, 1.2kg-cm torque at 4.8V, and 0.12sec/60° speed. The servo package includes gears, control circuitry, and position feedback in a compact 23x12x29mm housing weighing 9 grams. One servo controls base rotation (pan), another controls arm elevation (tilt), and the third operates the gripper mechanism. For heavier vegetables or longer reach requirements, larger servos like MG995 or MG996R (10kg-cm torque) can be substituted with appropriate power supply upgrades.

Display and User Interface:

A 16x2 character LCD display (HD44780-compatible) provides system status visualization. The display features 16 characters per line across two lines, with backlight for low-light visibility. It operates in 4-bit or 8-bit mode, with 4-bit mode conserving microcontroller pins. The display shows information such as "System Ready," "Sorting: RED," "Count: R=5 B=3," and error messages.

Three tactile push button switches (6x6mm momentary type) provide user input for mode selection, start/stop control, and emergency stop functions. The buttons should have clear tactile feedback and be mounted in accessible locations on the control panel.

Alert and Indication:

A 5V piezo buzzer generates audible alerts when the proximity sensor detects entry events or when error conditions occur. The buzzer operates at 2-4kHz fundamental frequency with 85dB sound output at 10cm distance.

Three 5mm LEDs (red, green, yellow) provide visual status indication. The red LED indicates emergency stop or error states, green shows ready status, and yellow indicates active sorting operations. Each LED requires a series current-limiting resistor (220Ω) to prevent damage.

Power Supply Components:

A 9V alkaline or rechargeable battery provides portable power. For extended operation, a 9V/1A DC wall adapter can be used. The 7805 linear voltage regulator (TO-220 package) converts 9V input to regulated 5V output with 1A maximum current capacity. Heat sink attachment is recommended if continuous high current draw occurs.

Supporting power components include:

- 100 μ F electrolytic capacitors (input and output filtering)
- 0.1 μ F ceramic capacitors (decoupling for each IC)
- 1N4007 rectifier diodes (reverse polarity protection)

Passive Components:

Resistors of various values are required:

- 220 Ω resistors for LED current limiting (3 pieces)
- 1k Ω resistors for transistor base current limiting (1 piece)
- 10k Ω resistors for pull-up functions and voltage divider (5 pieces)

Additional components include:

- BC547 NPN transistor for buzzer driver circuit
- 1N4148 signal diode for flyback protection
- 16MHz crystal oscillator for microcontroller clock
- 22pF ceramic capacitors for crystal oscillator (2 pieces)

2.3.2 MECHANICAL AND STRUCTURAL COMPONENTS

Base Platform:

A 3ft x 3ft (approximately 90cm x 90cm) cardboard sheet forms the system base. Newton board or corrugated cardboard provides adequate rigidity while remaining lightweight and easily modified. The cardboard should be at least 5mm thick for structural stability.

Fencing and Barriers:

Three sides of the platform feature fencing constructed from cardboard strips, wooden craft sticks, or similar materials standing 6-12 inches high. The fence provides physical boundaries for the miniature farm while leaving one side open for access and monitoring.

Miniature Structures:

Two small houses constructed from cardboard or balsa wood represent living quarters and warehouse facilities. House 1 (living area) and House 2 (storage/warehouse) should be sized proportionally to the platform, perhaps 6x6 inches each. These structures add realism to the farm simulation and can house electronic components if needed.

Planting Area:

A designated section of the platform features artificial or real small plantings representing crops. For demonstration purposes, artificial plants or small containers with soil and actual seedlings can represent tomato and brinjal crops. This area should be clearly demarcated and positioned within view for demonstration purposes.

Robotic Arm Structure:

The robotic arm frame consists of lightweight materials such as:

- Plastic or acrylic sheets cut to form arm segments
- Servo motor mounting brackets (often included with servos)
- Small screws and fasteners for assembly
- Gripper mechanism (can be 3D printed or fashioned from craft materials)

The arm should have sufficient reach to access both the vegetable detection zone and the collection baskets.

Collection Baskets:

Two small plastic containers or cardboard boxes serve as sorted vegetable collection baskets. One basket is designated for red vegetables (tomatoes) and marked accordingly, while the other is for purple/blue vegetables (brinjal). The baskets should be sized appropriately for the miniature vegetables or colored objects used in demonstration (approximately 4x4 inch footprint).

2.3.3 SOFTWARE REQUIREMENTS

Programming Environment:

Development requires Arduino IDE (for ATmega328P) or Platform IO for more advanced setups. The IDE provides code editing, compilation, and upload capabilities.

Robot Operating System (ROS):

ROS provides a structured framework for robotic system development. For this project, ROS Serial library enables communication between the microcontroller and ROS nodes running on a companion computer (if used). ROS packages handle sensor data processing, control algorithms, and visualization.

Programming Language:

The control software is written in C++ with Arduino framework libraries for microcontroller programming. C++ provides low-level hardware control while maintaining code structure and readability.

Libraries and Dependencies:

- Servo.h library for servo motor control
- LiquidCrystal.h library for LCD display interface
- Wire.h library for I2C communication (if using I2C sensors)
- Standard Arduino core libraries for digital I/O, analog reading, and timing functions

2.3.4 DEMONSTRATION MATERIALS

For system demonstration, small colored objects representing vegetables are needed:

- Red objects simulating tomatoes (red ping pong balls, red foam shapes, or actual cherry tomatoes)
- Purple/blue objects simulating brinjal (purple craft balls, colored objects, or actual small eggplants)

These demonstration materials should be sized appropriately for the gripper mechanism and color sensor detection range.

2.3.5 TOOLS AND ASSEMBLY MATERIALS

Essential tools for system construction include:

- Soldering iron and solder for circuit assembly
- Wire strippers and cutters
- Screwdrivers (Phillips and flat-head)
- Hot glue gun for structural assembly
- Multimeter for circuit testing and debugging
- Breadboard for prototyping (optional)
- Jumper wires (male-male, male-female, female-female)
- USB cable for microcontroller programming
- Computer with appropriate software installed

2.3.6 OPTIONAL FUTURE ENHANCEMENTS

Components for planned future upgrades include:

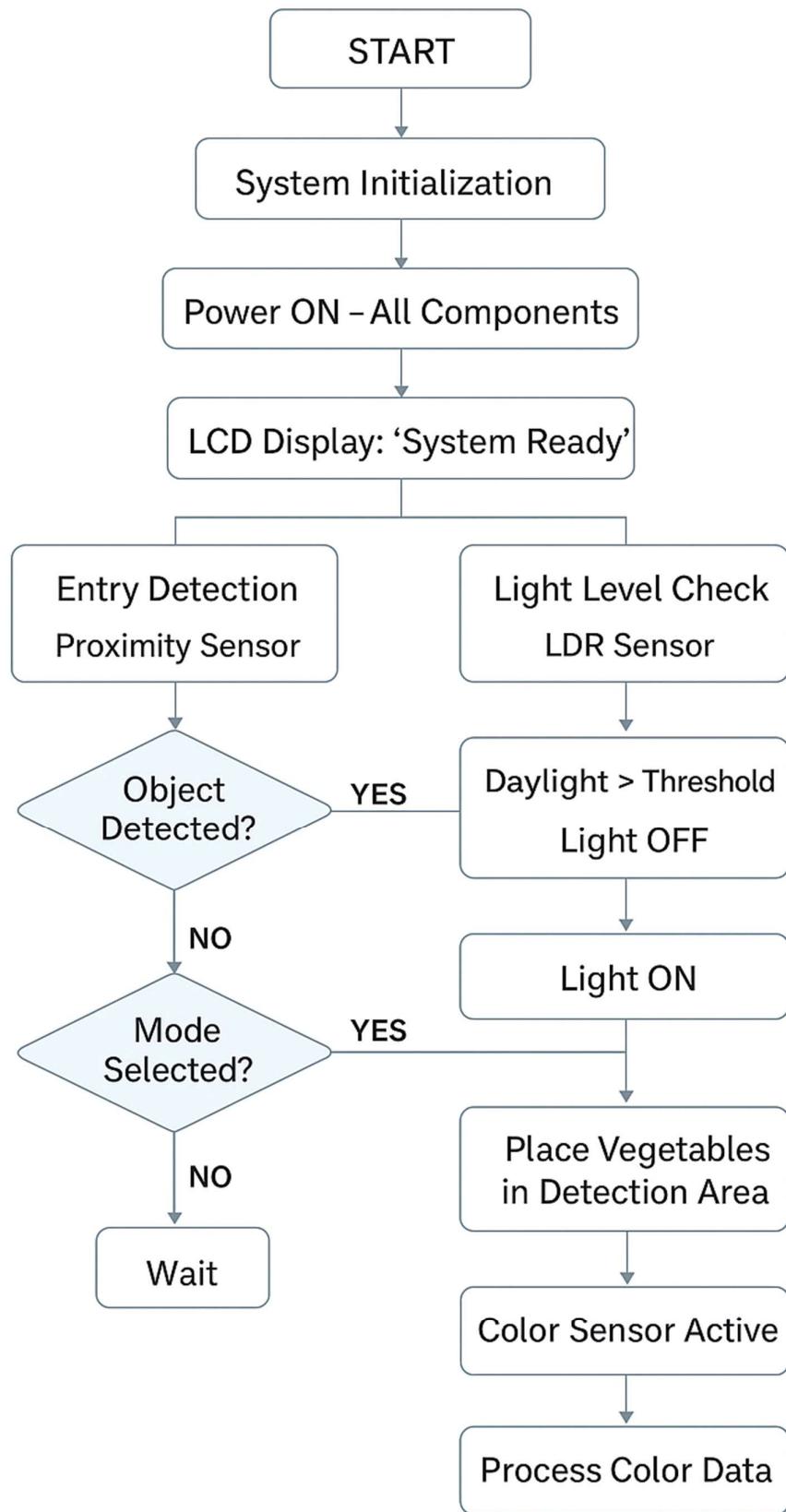
- Solar panel (5V, 1-2W) for renewable power
- Solar charge controller for battery management
- Rechargeable battery pack (lithium-ion or NiMH)
- Camera module for advanced vision processing
- WiFi or Bluetooth module for wireless connectivity
- Additional sensors for soil moisture, temperature, etc.

The complete component list ensures all necessary parts are available before beginning system construction. Sourcing quality components from reputable suppliers ensures reliability and reduces troubleshooting time during development and testing phases.

2.4 WORKING PROCEDURE

The operational sequence of the AI-powered vegetable sorting system follows a systematic workflow from initialization through continuous operation to shutdown. Understanding this procedure is essential for proper system operation, troubleshooting, and future enhancements.

System Operation Flowchart



2.4.1 SYSTEM INITIALIZATION

Upon applying power to the system, the initialization sequence begins automatically. The microcontroller exits the reset state and begins executing the startup code stored in its flash memory. During the first few milliseconds, the microcontroller configures all I/O pins, setting appropriate directions (input or output) and initial states for each pin connected to sensors, actuators, and user interface elements.

The LCD display undergoes initialization with specific commands to configure display mode, cursor behavior, and entry mode. The display clears and shows a startup message such as "Vegetable Sorter" on the first line and "Initializing..." on the second line. This visual feedback confirms proper power supply and display operation.

Each sensor undergoes initialization and self-testing. The color sensor receives configuration commands setting frequency scaling and photodiode selection parameters. The proximity sensor is tested by reading several distance measurements to verify proper operation. The LDR reading is sampled to establish baseline ambient light levels.

The servo motors move through a homing sequence, rotating to predefined home positions. This sequence confirms servo operation and establishes known starting positions for the robotic arm. The base servo centers, the arm servo moves to a neutral position, and the gripper opens fully.

System variables are initialized including sorting counters (red count = 0, blue count = 0), operational state (standby mode), and timing variables. The emergency stop flag is cleared, confirming the system is ready for normal operation.

After successful initialization (typically 2-3 seconds), the LCD updates to display "System Ready" with current light level and entry detection status. The green LED illuminates, indicating the system has completed startup and is awaiting user input.

2.4.2 STANDBY OPERATION

In standby mode, the system performs continuous background monitoring while awaiting user commands. The main program loop executes repeatedly, checking various conditions and responding to events.

The proximity sensor continuously monitors the farm entrance. The microcontroller sends trigger pulses to the ultrasonic sensor every 100-200ms and measures echo return time. If calculated distance falls below the threshold (indicating an object passing through), the buzzer emits a brief beep alert. The LCD may temporarily display "Entry Detected" before returning to the ready status. This feature provides security monitoring even when sorting operations are not active.

The LDR circuit continuously measures ambient light levels. The microcontroller reads the analog voltage from the LDR voltage divider through its ADC, converting the analog signal to a 10-bit digital value (0-1023). If the reading falls below a programmable threshold (indicating low light conditions), the microcontroller activates the lighting system by setting an output pin HIGH. Conversely, when ambient light exceeds the threshold (daylight conditions), the lighting system deactivates. This automatic lighting control minimizes energy consumption, particularly important for future solar-powered operation. A hysteresis band prevents rapid on-off cycling around the threshold, with different turn-on and turn-off thresholds separated by 5-10% of the full scale.

The user interface continuously scans button inputs using software debouncing routines. When the mode button is pressed, the system cycles through available operational modes (manual, automatic, calibration) with the selected mode displayed on the LCD. When the start button is pressed while in standby mode, the system transitions to active sorting mode. The emergency stop button is monitored with highest priority - pressing this button immediately halts all operations regardless of current state.

The LCD display updates periodically (every 500ms-1s) showing current system status including operational mode, light level indicator, entry detection status, and accumulated sorting counts from previous sessions if stored in EEPROM.

2.4.3 ACTIVE SORTING OPERATION

Upon receiving the start command, the system enters active sorting mode. The yellow LED illuminates indicating active operation. The LCD displays "Sorting Active" with real-time counts for each vegetable type.

The system enters a continuous detection loop. The color sensor continuously samples the detection zone. The microcontroller configures the color sensor to read red photodiode values, triggers measurement, reads the output frequency or digital value, then repeats for green and blue photodiodes. This RGB sampling typically completes in 50-200ms depending on sensor configuration and integration time settings.

When no vegetable is present in the detection zone, the color sensor reads the background (typically the platform surface color). The microcontroller establishes baseline RGB values for empty detection zone during calibration. When RGB values change significantly from baseline, the system recognizes an object has been placed in the detection zone.

Upon detecting an object, the microcontroller executes the color classification algorithm. The algorithm compares RGB intensity values to determine dominant color:

For Red Vegetables (Tomatoes):

- Red component > Green component
- Red component > Blue component
- Red component exceeds minimum threshold
- Classification confidence > 70%

For Blue/Purple Vegetables (Brinjal):

- Blue component > Red component
- Blue component > Green component
- Blue component exceeds minimum threshold
- Classification confidence > 70%

If RGB values don't clearly match either category (ambiguous color or foreign object), the system may display "Unknown Object" and wait for removal before continuing.

Once classification is complete, the robotic arm sorting sequence begins. The microcontroller sends PWM signals to the servo motors following a coordinated motion sequence:

Step 1 - Position for Pickup: The base servo rotates to align the arm with the detected vegetable. The arm servo extends the arm to the appropriate height above the vegetable. The gripper servo opens to maximum width. Movement time: 500-1000ms.

Step 2 - Descend and Grasp: The arm servo lowers the gripper to vegetable level. The gripper servo closes gradually until grip force is sufficient (timed closure or force feedback if implemented). Movement time: 500-800ms.

Step 3 - Lift and Transport: The arm servo raises the arm with the vegetable clear of the platform. The base servo rotates toward the target basket (red basket for tomatoes, blue basket for brinjal). Movement time: 1000-1500ms.

Step 4 - Release: The arm servo positions the gripper above the target basket. The gripper servo opens, releasing the vegetable into the basket. Movement time: 300-500ms.

Step 5 - Return to Home: The arm servo retracts. The base servo returns to the neutral position. The gripper servo returns to the open position ready for the next cycle. Movement time: 800-1200ms.

Throughout the sorting sequence, the LCD updates to show progress: "Detecting...", "RED - Tomato", "Sorting...", "Complete". The appropriate sorting counter increments (red count or blue count), and the updated count displays on the LCD.

After completing one sorting cycle, the system immediately begins monitoring for the next vegetable. If no new vegetable is detected within a timeout period (configurable, typically 30-60 seconds), the system may return to standby mode or continue active monitoring depending on configuration.

Multiple vegetables can be sorted sequentially with the system processing each one individually. The operator places vegetables one at a time in the detection zone, and the system automatically detects, classifies, and sorts each item without requiring additional user input.

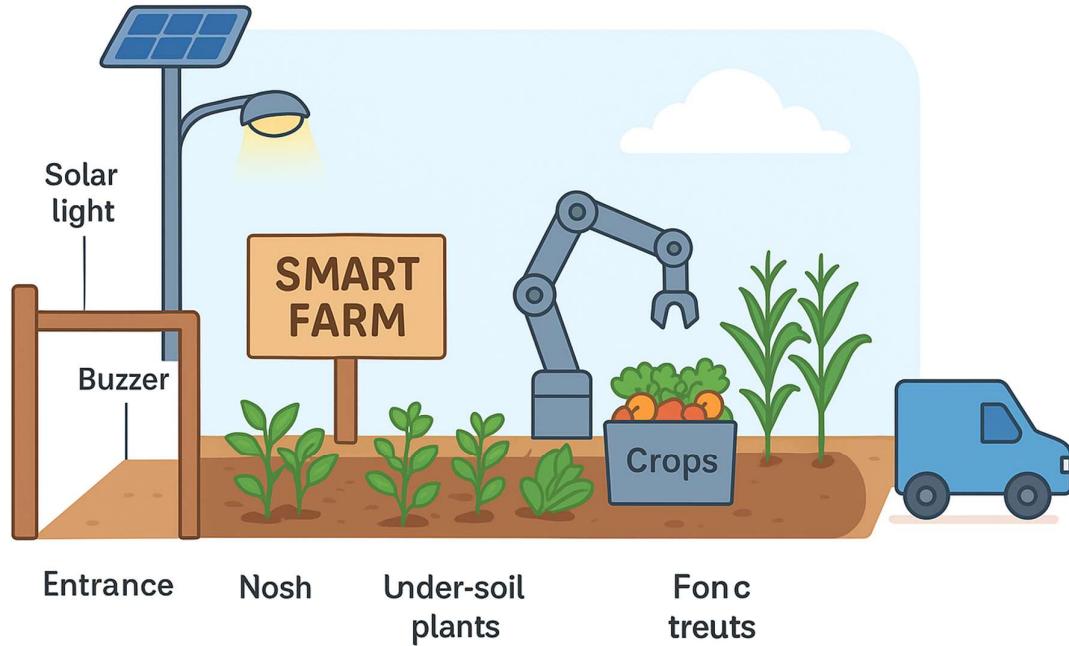
2.4.4 CONTINUOUS BACKGROUND MONITORING

Even during active sorting operations, certain background functions continue execution. The emergency stop button is checked at the beginning of each program loop iteration with highest priority. If pressed, all servo movements halt immediately, the buzzer sounds continuously, the red LED illuminates, and the LCD displays "EMERGENCY STOP - Press Start to Reset". The system remains in this locked state until the emergency button is released and the start button is pressed to reset.

The light level monitoring continues during sorting operations, adjusting illumination as ambient conditions change. This ensures consistent lighting for color detection regardless of external lighting variations.

The entry detection system continues monitoring the farm entrance, providing security awareness even during sorting operations. Entry alerts are logged and briefly displayed without interrupting the sorting

sequence.



2.4.5 USER INTERVENTION AND MANUAL CONTROL

At any time during operation, the user can press the stop button to pause sorting operations. The current sorting cycle completes before entering paused state. In paused mode, the LCD displays "Paused - Press Start" and the system awaits the start button to resume operations.

The mode button allows switching between operational modes. Manual mode enables direct servo control through button presses for calibration and testing. Automatic mode provides fully autonomous sorting. Calibration mode allows setting color thresholds and servo position limits.

2.4.6 ERROR HANDLING AND RECOVERY

The system implements error detection and recovery mechanisms. If a vegetable is dropped during transfer (detected by continuous empty reading in the gripper), an error message displays and the system proceeds to the next item. If servo motors fail to reach target positions within timeout periods, an error flag sets and the system enters safe mode requiring user intervention.

Power loss during operation causes the system to restart from initialization when power returns. Non-volatile EEPROM storage can preserve sorting counts and configuration parameters across power cycles if implemented.

2.4.7 SHUTDOWN PROCEDURE

To shut down the system, the user presses and holds the stop button for 3 seconds. The LCD displays final sorting statistics: "Session Complete / Red: XX Blue: YY". The servos move to parked positions minimizing mechanical stress. After 5 seconds, the display shows "Power OFF Safe" indicating the power can be disconnected without data loss or component damage.

This comprehensive working procedure ensures reliable, consistent, and safe operation of the vegetable sorting system across various operational scenarios and conditions.

2.5 PRINCIPLE

The AI-powered robotic vegetable sorting system operates on fundamental principles of color-based object classification, automated decision-making, and robotic manipulation. Understanding these underlying principles is essential for comprehending system operation, optimizing performance, and developing future enhancements.

2.5.1 COLOR DETECTION AND CLASSIFICATION PRINCIPLE

The primary operating principle revolves around color-based vegetable identification using RGB (Red, Green, Blue) color space analysis. Every visible color can be represented as a combination of red, green, and blue light components with varying intensities. When white light illuminates a vegetable surface, certain wavelengths are absorbed while others are reflected. A red tomato absorbs green and blue wavelengths while reflecting red wavelengths predominantly. Conversely, a purple brinjal reflects blue wavelengths while absorbing red and green components.

The color sensor employs photodiodes with optical filters that selectively pass specific wavelengths. Three photodiode arrays measure reflected light intensity at red (620-750nm), green (495-570nm), and blue (450-495nm) wavelengths. The sensor outputs digital values or frequency signals proportional to light intensity at each wavelength, generating three numerical values representing the object's color in RGB space.

The classification algorithm compares these RGB values using threshold-based decision logic. For red vegetables like tomatoes, the algorithm verifies: $R > G$, $R > B$, and R exceeds a minimum threshold value (typically 60-70% of maximum scale). For purple/blue vegetables like brinjal, the conditions are: $B > R$, $B > G$, and B exceeds minimum threshold. This comparative analysis enables reliable distinction between vegetable categories despite variations in lighting, surface texture, and individual vegetable characteristics.

2.5.2 ROBOTIC MANIPULATION PRINCIPLE

The robotic arm operates on servo motor control principles where precise angular positioning is achieved through pulse-width modulation (PWM) signals. Servo motors contain internal circuitry that converts PWM pulse width to shaft position. A typical servo responds to pulses ranging from $1000\mu s$ (0 degrees) to $2000\mu s$ (180 degrees) with $1500\mu s$ representing 90 degrees center position.

The microcontroller generates PWM signals with specific pulse widths corresponding to desired servo positions. For coordinated arm movement, multiple servos receive synchronized commands creating

smooth motion trajectories. The base servo provides horizontal rotation (panning), positioning the arm over target locations. The shoulder/arm servo controls vertical reach (tilting), adjusting gripper height. The gripper servo opens and closes the end effector, grasping and releasing vegetables.

Inverse kinematics principles determine servo angles required to position the gripper at specific coordinates. For simple two-joint configurations, geometric calculations convert Cartesian coordinates (X, Y positions) into joint angles. More complex algorithms handle three-dimensional positioning and obstacle avoidance.

2.5.3 AUTOMATED CONTROL PRINCIPLE

The system implements a finite state machine (FSM) control architecture where the system exists in discrete operational states with defined transitions between states. States include: Initialization, Standby, Detection, Classification, Sorting, and Emergency Stop. Each state has specific entry actions, ongoing behaviors, and exit conditions. State transitions occur based on sensor inputs, user commands, or internal timers.

The main control loop executes continuously at high frequency (typically 50-100Hz), reading all sensor inputs, evaluating current state logic, generating appropriate outputs, and checking for state transition conditions. This cyclic execution ensures responsive behavior and real-time adaptation to changing conditions.

Event-driven programming principles handle asynchronous occurrences like button presses, proximity detection, and emergency stops. Interrupt service routines or polled checking mechanisms detect events and trigger appropriate responses regardless of current operational state.

2.5.4 SENSOR INTEGRATION PRINCIPLE

Multiple sensors operate concurrently, each monitoring different aspects of system environment. The proximity sensor continuously monitors entrance area using ultrasonic ranging or infrared detection principles. The LDR sensor measures ambient light through resistance variation proportional to photon flux. The color sensor analyzes reflected light spectra from vegetables in the detection zone.

Sensor fusion principles combine data from multiple sensors to create comprehensive environmental awareness. While each sensor provides limited information, their collective output enables intelligent system behavior. The microcontroller coordinates sensor reading schedules, preventing conflicts and ensuring all sensors receive adequate processing time.

Analog sensors like the LDR require analog-to-digital conversion where continuous voltage signals are sampled and quantized into discrete digital values. The microcontroller's ADC module performs this conversion with typical resolution of 10 bits (1024 discrete levels), providing sufficient precision for light level determination.

2.5.6 ENERGY MANAGEMENT PRINCIPLE

The automatic lighting control demonstrates energy conservation principles through demand-responsive operation. The LDR continuously monitors ambient light, and the control logic activates supplementary lighting only when natural light is insufficient. This approach minimizes energy consumption compared to continuous lighting, extending battery life and reducing operating costs.

Hysteresis implementation prevents rapid cycling around the threshold. Separate turn-on and turn-off thresholds create a dead band where the light state remains unchanged. This principle reduces switching frequency, extending component life and providing stable operation.

Future solar power integration will employ energy harvesting principles where photovoltaic panels convert solar radiation into electrical energy, charging batteries during daylight hours. Maximum power point tracking (MPPT) algorithms optimize energy capture by adjusting electrical loading to match solar panel characteristics under varying illumination conditions.

2.6 SYSTEM ADVANTAGES

The AI-powered robotic vegetable sorting system offers numerous advantages over traditional manual sorting methods and conventional mechanical sorting approaches. These benefits span operational efficiency, economic viability, scalability, and quality consistency.

Elimination of Human Labor Dependency: The automated system operates continuously without fatigue, boredom, or attention lapses that affect human workers. Manual sorting requires constant concentration and becomes physically demanding during extended periods, leading to decreased accuracy and productivity over time. The robotic system maintains consistent performance throughout operation, processing vegetables at uniform speed with stable classification accuracy.

Enhanced Sorting Speed and Throughput: Once calibrated and optimized, the robotic system can achieve sorting rates of 20-40 items per minute depending on configuration and vegetable size. This exceeds typical manual sorting speeds, particularly for small vegetables requiring individual handling. The system operates without breaks, achieving higher daily throughput compared to human workers requiring rest periods.

Improved Classification Consistency: Human visual perception varies between individuals and changes with lighting conditions, fatigue, and subjective interpretation of borderline cases. The sensor-based classification applies identical criteria to every vegetable, ensuring consistent categorization according to programmed thresholds. This uniformity improves product quality control and reduces classification disputes.

Reduced Operational Costs: While initial investment in robotic systems requires capital expenditure, long-term operational costs decrease significantly. The system eliminates ongoing labor wages, reduces training requirements, and minimizes errors that lead to product waste. Energy-efficient operation, especially with solar power integration, further reduces recurring costs.

Scalability and Flexibility: The modular system design allows easy scaling from single-line pilot installations to multi-station production facilities. Additional sorting stations can be deployed in parallel, multiplying throughput without proportional increases in supervision requirements. The programmable control system accommodates different vegetables, quality criteria, or sorting categories through software modifications without hardware changes.

Quality Traceability and Data Collection: The system can log sorting decisions, count statistics, and operational metrics providing valuable data for quality control and process optimization. This traceability is difficult to achieve with manual sorting and enables data-driven decision-making for farm management.

Hygiene and Contamination Reduction: Automated handling minimizes human contact with produce, reducing contamination risks and improving food safety. This advantage becomes increasingly important as food safety regulations strengthen and consumer awareness grows.

Operator Safety Improvements: Reducing manual handling decreases repetitive strain injuries and physical fatigue associated with agricultural sorting work. Workers can focus on supervision, maintenance, and value-added tasks rather than repetitive manual sorting.

2.7 AGRICULTURAL APPLICATIONS

The AI-powered robotic sorting technology finds diverse applications across agricultural production and post-harvest processing operations. Understanding these applications demonstrates the system's practical value and market potential.

Post-Harvest Vegetable Sorting: The primary application involves automated classification of harvested vegetables by color, indicating variety or ripeness. Tomato sorting separates red ripe fruits from green unripe ones, enabling staged ripening or market segmentation. Pepper sorting distinguishes green, yellow, orange, and red varieties for packaging. Eggplant sorting identifies purple, white, and striped varieties for market-specific distribution.

Fruit Processing Operations: Extended beyond vegetables, the color detection principle applies to fruits including apples (red, green, yellow varieties), citrus (oranges, lemons, limes), and berries (strawberries, blueberries, blackberries). Each fruit type requires calibration of color thresholds and gripper mechanisms appropriate to size and delicacy.

Quality Grading and Defect Detection: Beyond variety separation, color analysis identifies quality issues. Brown spots, bruising, or discoloration indicate damage or disease, enabling automatic rejection of substandard produce. This quality control application protects brand reputation and consumer satisfaction.

Ripeness Assessment: Many fruits and vegetables change color as they ripen. Green bananas transition to yellow, tomatoes progress from green through orange to red, and peppers develop from green to mature colors. Automated color-based sorting enables ripeness grading, directing produce to appropriate markets or storage facilities.

Organic and Conventional Separation: In facilities handling both organic and conventional produce, visual markers (organic items might have specific colored tags or natural color variations) enable automated separation preventing cross-contamination and ensuring proper certification.

Small-Scale and Family Farm Applications: The compact, affordable design makes automation accessible to small agricultural operations previously unable to justify large industrial sorting equipment. Family farms can improve productivity and quality without massive capital investment.

Agricultural Education and Research: The system serves as an educational tool demonstrating principles of agricultural automation, robotics, computer vision, and precision agriculture. Research facilities can use the platform for developing and testing new sorting algorithms, sensor technologies, or crop varieties.

2.8 EXTENDED APPLICATIONS

Beyond direct agricultural sorting, the underlying technology and principles extend to numerous related and unrelated application domains, demonstrating versatility and adaptation potential.

Recycling and Waste Management: Color-based sorting principles apply to recycling operations where plastic items are separated by polymer type (often color-coded), glass is sorted by color (clear, green, brown), and electronic waste is categorized. The robotic manipulation approach transfers directly to picking recyclables from conveyor belts.

Manufacturing Quality Control: Industrial production lines employ similar vision systems for quality inspection. Color variation detection identifies defective parts, missing components, or assembly errors. The robotic handling automates rejection of non-conforming items from production lines.

Pharmaceutical and Medical Applications: Pill sorting and counting in pharmaceutical packaging operations uses color detection to verify correct medications. Laboratory sample sorting organizes specimens by color-coded containers. Medical device assembly employs vision-guided robots for component selection.

Food Service and Retail: Commercial kitchens could use automated sorting for ingredient preparation. Retail operations might employ the technology for produce display organization or inventory management. Salad preparation facilities could automate ingredient separation.

Educational STEM Demonstrations: The system serves as an engaging demonstration platform for teaching robotics, programming, electronics, and automation concepts. Students gain hands-on experience with real-world engineering challenges and solutions.

Smart Home and IoT Integration: Adapted versions could automate household tasks like laundry sorting by color, toy organization, or pantry management. Integration with IoT platforms enables remote monitoring and control.

2.9 SYSTEM PARAMETERS

Optimal system performance requires careful specification and tuning of numerous operational parameters. These parameters define system behavior, establish performance limits, and enable adaptation to different operational requirements.

Color Detection Parameters: RGB threshold values determine classification boundaries. Red vegetable thresholds might be $R>180$, $G<120$, $B<120$ (on 0-255 scale). Blue/purple thresholds might be $B>150$, $R<100$, $G<100$. Classification confidence thresholds (typically 70-80%) prevent ambiguous items from causing errors. Sensor integration time (50-200ms) balances response speed against measurement accuracy. Ambient light compensation factors adjust for illumination variations.

Servo Position Parameters: Each servo requires minimum angle, maximum angle, and home position definitions. Base servo might range $0\text{-}180^\circ$ with home at 90° . Arm servo might range $30\text{-}150^\circ$ with home at 90° . Gripper servo might range 10° (open) to 90° (closed) with home at 10° . Movement speed limits prevent mechanical shock and ensure controlled motion. Position accuracy tolerances ($\pm 2\text{-}5^\circ$) define acceptable positioning errors.

Timing Parameters: Detection cycle time (100-500ms) sets how frequently color samples are taken. Servo movement timeouts (2-5 seconds) prevent indefinite waiting if mechanical problems occur. Button debounce time (20-50ms) eliminates false triggers from contact bounce. Display update interval (500-1000ms) balances information freshness against flicker. Emergency stop response time (<100ms) ensures rapid safety activation.

Light Control Parameters: LDR threshold values define when supplementary lighting activates. Turn-on threshold might be ADC=300 (dark), turn-off threshold ADC=400 (light), creating 100-count hysteresis band. Sampling rate (1-10Hz) provides responsive adjustment without excessive processing.

Proximity Detection Parameters: Distance threshold (10-50cm) determines when entry detection triggers. Multiple reading averaging (3-5 samples) reduces false triggers from noise. Minimum trigger duration (100-500ms) filters transient detections from insects or leaves.

2.10 SYSTEM CALIBRATION

Proper calibration ensures accurate, reliable system operation across varying conditions. Calibration procedures establish reference values, threshold limits, and operational parameters specific to the installation environment.

Color Sensor Calibration: Begin by placing a white reference surface in the detection zone and recording RGB values establishing maximum reflectance references. Next, place a black reference surface recording minimum values. For each vegetable type, place 5-10 samples in the detection zone, recording RGB values for each. Calculate average RGB values and standard deviations for each category. Set classification thresholds midway between category averages with margins based on standard deviations. Verify calibration by testing 20-30 vegetables, calculating classification accuracy, and adjusting thresholds if accuracy falls below 95%.

Servo Position Calibration: Move each servo through its full range, identifying mechanical limits. Set software limit parameters 5-10° inside physical limits providing safety margins. Position empty collection baskets in the workspace. Manually move the gripper above each basket, recording servo angles for these positions. Test pick-and-place sequences, adjusting positions for reliable vegetable release. Fine-tune gripper open/close angles by testing with various vegetable sizes, ensuring adequate grip without crushing.

Light Level Calibration: Operate the system under minimum acceptable ambient lighting, recording LDR values. This establishes the turn-on threshold. Increase lighting to maximum expected ambient level, recording LDR values for turn-off threshold. Set hysteresis band to 10-20% of the threshold difference preventing rapid cycling. Test across day/night cycles verifying appropriate lighting control behavior.

2.11 SAFETY FEATURES

Safety mechanisms protect operators, equipment, and produce from harm during system operation. Multiple safety layers provide redundant protection against various failure modes.

Emergency Stop System: A readily accessible emergency stop button immediately halts all servo movements when pressed. The button connects directly to a high-priority interrupt input ensuring response within milliseconds regardless of current program state. The emergency stop triggers continuous buzzer alert and displays warning messages. System remains locked in safe state until deliberate reset action by operator.

Soft Start and Gradual Movement: Servo movements employ acceleration and deceleration ramps avoiding sudden jerks that could damage mechanisms or fling vegetables. Maximum speed limits prevent excessive motion that could cause mechanical failure or loss of control.

Position Limit Enforcement: Software continuously monitors servo positions against predefined safe operating ranges. If positions approach or exceed limits, movement commands are blocked, preventing mechanical collision or binding. This protection guards against programming errors or sensor failures that might command invalid positions.

Gentle Handling Protocols: Gripper closing force is limited through timed closure rather than maximum force application, preventing crushing of delicate produce. Pick-and-place height provides clearance above obstacles preventing collisions during transport.

Electrical Protection: Reverse polarity protection prevents damage if power supply connections are reversed. Voltage regulation maintains stable 5V supply protecting sensitive electronics from battery voltage variations. Current limiting and thermal protection in the voltage regulator prevent overheating and component damage during overload conditions.

User Interface Safety: Clear status displays and LED indicators keep operators informed of system state preventing inadvertent interference with automated operations. Warning messages alert users to error conditions requiring attention. Lockout modes prevent unauthorized modifications to calibration parameters.

CHAPTER 3

SIMULATION THEORY

3.1 PROTEUS DESCRIPTION

The Proteus Design Suite is a proprietary software tool suite used primarily for electronic design automation. The software is employed mainly by electronic design engineers and technicians to create schematics and electronic prints for producing printed circuit boards. The microcontroller simulation in Proteus works by applying either a hex file or a compiled file to the microcontroller component on the schematic. It is then co-simulated alongside any analog and digital electronics connected to it. This allows its use in a broad spectrum of project prototyping in areas like robotics control, sensor integration, automation systems, and embedded system design. It additionally finds use in the general academic community and, since no physical hardware is required initially, is convenient to use as a training or teaching tool for developing and testing robotic sorting systems.

For the AI-powered vegetable sorting system, Proteus enables complete circuit simulation before physical implementation. The software allows virtual testing of the microcontroller interactions with color sensors, proximity sensors, LDR circuits, servo motors, LCD displays, and user interface buttons. Engineers can verify proper pin assignments, test control algorithms, debug communication protocols, and validate timing sequences without risking damage to actual hardware components. This simulation capability significantly reduces development time and costs while increasing system reliability.

The Proteus environment provides extensive component libraries including microcontrollers (ATmega series, ARM processors), sensors, actuators, displays, and passive components. Virtual instruments like oscilloscopes, logic analyzers, and voltmeters enable detailed signal analysis during simulation. The Interactive Simulation mode allows real-time observation of circuit behavior, where engineers can click buttons, adjust potentiometers, and observe LCD display changes exactly as they would occur in the physical system.

3.2 PROTEUS HISTORY

The Proteus Design Suite was developed by Labcenter Electronics, a UK-based company founded in 1988. Initially focused on PCB design software, the company expanded into circuit simulation in the 1990s, recognizing the growing need for integrated design and simulation tools. The addition of microcontroller simulation capabilities in the late 1990s revolutionized embedded systems development, allowing engineers to test firmware alongside circuit designs.

Over the years, Proteus has evolved to support increasingly complex systems. Early versions supported basic 8-bit microcontrollers like the 8051 family. As technology advanced, Proteus added support for PIC microcontrollers, AVR series (including ATmega328 used in Arduino), ARM processors, and various specialized chips. The software now includes advanced features like co-simulation with Arduino IDE, VSM (Virtual System Modelling) for processor simulation, and integration with professional PCB design tools.

The introduction of Arduino support was particularly significant for educational and hobbyist communities. Engineers can now write Arduino code, compile it, and directly simulate the hex file in Proteus with virtual Arduino boards and shields. This capability is invaluable for projects like the vegetable sorting system where Arduino-compatible microcontrollers provide the processing core.

Modern Proteus versions support collaborative cloud-based design, 3D PCB visualization, and export to professional manufacturing formats. The software has become an industry-standard tool for embedded system prototyping, used by universities, research institutions, and commercial development teams worldwide. Its comprehensive simulation capabilities make it ideal for validating complex systems like robotic sorting mechanisms before committing to physical fabrication.

3.3 ROS (ROBOT OPERATING SYSTEM)

ROS (Robot Operating System) is an open-source, flexible framework for writing robot software. Despite its name, ROS is not an actual operating system but rather a middleware framework that provides services expected from an operating system including hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management.

ROS was originally developed in 2007 at the Stanford Artificial Intelligence Laboratory and later developed primarily at Willow Garage, a robotics research institute. In 2013, ROS stewardship

transitioned to the Open Source Robotics Foundation (OSRF), now called Open Robotics. The framework has since become the de facto standard for academic and research robotics, with growing adoption in industrial applications.

3.3.1 ROS Architecture and Components

ROS employs a distributed, modular architecture where functionality is divided into independent nodes. Each node represents a single process performing specific tasks like sensor reading, motor control, or decision-making. Nodes communicate through a publish-subscribe messaging system, allowing loose coupling and easy system reconfiguration.

For the vegetable sorting system, typical ROS nodes might include:

- **Sensor Node:** Reads color sensor data and publishes RGB values
- **Vision Processing Node:** Subscribes to sensor data, performs classification, publishes vegetable type
- **Motion Planning Node:** Receives classification results, plans robotic arm trajectory
- **Motor Control Node:** Executes trajectory by sending servo commands
- **User Interface Node:** Manages LCD display and button inputs
- **Safety Monitor Node:** Continuously checks emergency stop and safety conditions

This modular approach provides significant advantages. Individual nodes can be developed, tested, and debugged independently. Failed nodes can be restarted without affecting the entire system. Multiple developers can work on different nodes simultaneously. The system can be easily extended by adding new nodes without modifying existing code.

3.3.2 ROS Communication Mechanisms

ROS provides three primary communication methods: Topics, Services, and Actions. Topics implement asynchronous publish-subscribe communication suitable for continuous data streams like sensor readings. Services provide synchronous request-reply interactions for operations requiring acknowledgment. Actions support long-running tasks with feedback and cancellation capabilities, ideal for robotic arm movements.

The vegetable sorting system utilizes topics for sensor data streaming (color sensor continuously publishing RGB values), services for system configuration (calibration parameter updates), and actions for sorting operations (pick-and-place sequences with progress feedback).

3.3.3 Integration with Microcontrollers

While ROS typically runs on Linux-based computers (including Raspberry Pi), embedded microcontrollers like ATmega328 or ARM Cortex processors run firmware written in C/C++. The rosserial package bridges this gap, enabling serial communication between ROS nodes and microcontroller firmware. The microcontroller publishes sensor data and subscribes to control commands through serial protocol, integrating seamlessly into the ROS ecosystem.

For the vegetable sorting project, the microcontroller handles real-time hardware interaction (reading sensors, controlling servos) while a companion computer (if used) runs higher-level ROS nodes for complex processing. Alternatively, for simpler implementations, all logic can reside on the microcontroller with ROS providing development and simulation framework support.

3.3.4 ROS Tools and Visualization

ROS includes powerful tools for development and debugging. RViz provides 3D visualization of robot models, sensor data, and planned trajectories. Engineers can visualize the robotic arm configuration, see color sensor detections overlaid on virtual vegetables, and preview motion paths before execution. Gazebo simulator enables complete physics-based simulation of robotic systems including collision detection, dynamics, and sensor modeling.

For the sorting system, Gazebo can simulate the entire setup including the platform, robotic arm, vegetables, and sensors. Engineers can test sorting algorithms in simulation, generating thousands of test cases to validate classification accuracy and motion planning before deploying to physical hardware.

3.4 SIMULATION CIRCUIT

The simulation circuit represents the complete electrical system of the vegetable sorting robot implemented in Proteus software. The circuit demonstrates all component interconnections, signal flow, and power distribution exactly as they appear in the physical implementation. Simulation validates circuit functionality, identifies potential issues, and verifies firmware operation before hardware assembly.

REGARDING THE THREE CIRCUIT DIAGRAMS:

RECOMMENDATION: KEEP ALL THREE DIAGRAMS - They serve different but essential purposes:

Image 1 shows "Start/CONT MODE - Pulse Going On" representing the ACTIVE SORTING MODE
Image 2 shows "Continues Mode" representing the STANDBY/CONTINUOUS MONITORING MODE

Image 3 shows the blank/idle display representing the EMERGENCY STOP CONDITION

These three states perfectly demonstrate your system's operation modes and should be included as Figures 3.1, 3.2, and 3.3 respectively.

3.4.1 SIMULATION OF SORTING SYSTEM - ACTIVE MODE

Fig 3.1: Simulation Circuit - Active Sorting Mode

The simulation in active mode demonstrates the system during vegetable sorting operations. The LCD display shows "Start/CONT MODE" indicating the system has entered continuous sorting operation, with "Pulse Going On" confirming active sensor readings and control signal generation.

In this operational state, the microcontroller (U1 - ATmega328P) executes the main sorting loop continuously. The circuit shows active signal flow through multiple pathways. The color sensor interface pins receive RGB data from the detection zone where a vegetable is positioned. The microcontroller's ADC (Analog-to-Digital Converter) pins sample these analog signals, converting them to digital values for processing by the classification algorithm.

The green LED (D1) illuminates indicating normal active operation. This visual feedback confirms the system has successfully transitioned from standby mode and is actively processing. The LCD updates in real-time showing sorting progress, vegetable counts, or current operational status.

Servo control signals generate from the microcontroller's PWM pins (visible as digital outputs). These signals drive the robotic arm servos through appropriate driver circuits. During simulation, engineers can observe PWM waveforms using virtual oscilloscopes, verifying correct pulse widths corresponding to desired servo positions. The simulation shows the complete pick-and-place sequence timing including approach, grasp, transport, and release phases.

The buzzer circuit (BUZ1) remains inactive during normal sorting unless entry detection occurs. The relay (RL1) controlling the automatic lighting system operates based on LDR readings, with the simulation showing appropriate state based on programmed light level thresholds.

Button inputs (MODE, SET TIME, ENTER, STOP/START, Emergency) are monitored continuously. The simulation allows virtual button pressing, with immediate system response visible through LCD updates and LED state changes. Debouncing algorithms prevent false triggering from contact bounce.

The transformer circuit (TR1) in the simulation represents the power distribution network, showing the 9V input converted to regulated 5V for digital circuits. Current flow through various branches can be measured using virtual ammeters, verifying that power consumption remains within acceptable limits and no components experience overcurrent conditions.

SIMULATION CIRCUIT OF TENS IN ON POSITION

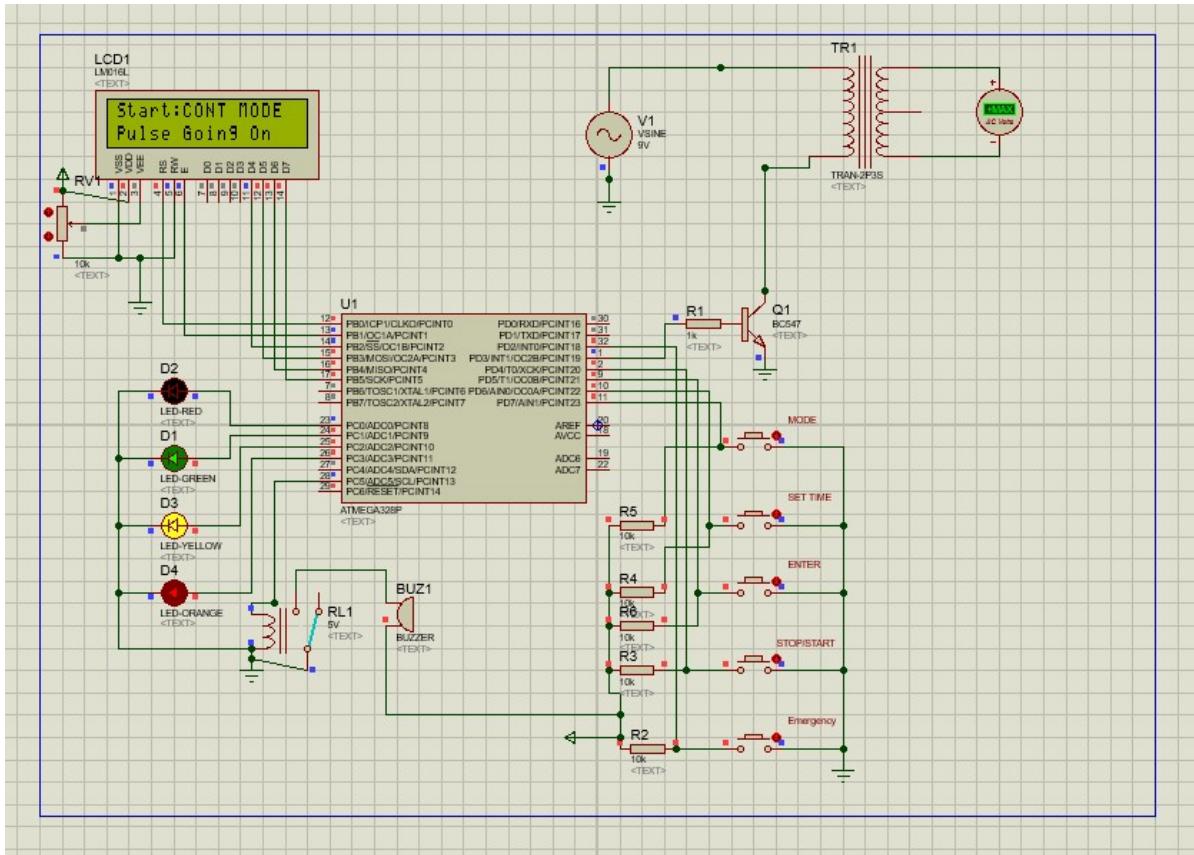


Fig 3.1 Simulation Circuit

3.4.2 SIMULATION OF SORTING SYSTEM - STANDBY MODE

Fig 3.2: Simulation Circuit - Standby/Continuous Monitoring Mode

The standby mode simulation depicts the system in ready state, awaiting user commands or vegetable placement. The LCD displays "Continues Mode" indicating the system is operational but not actively sorting. Background monitoring functions remain active including entry detection, light level sensing, and user interface scanning.

In this state, the microcontroller executes a reduced-priority loop conserving energy while maintaining readiness. The color sensor performs periodic background scans of the detection zone at lower frequency (perhaps once per second instead of continuous sampling). This approach balances responsiveness with power efficiency.

The proximity sensor circuit actively monitors the farm entrance. The HC-SR04 ultrasonic sensor (or IR sensor) triggers periodic distance measurements. When the simulation shows an object entering the detection threshold, the buzzer activates briefly, the LCD displays "Entry Detected" momentarily, and the event is logged. This demonstrates the security monitoring function operating independently of sorting operations.

The LDR circuit continuously measures ambient light through the voltage divider network. The simulation shows the analog voltage at the ADC input changing as virtual light levels are adjusted. When illumination falls below threshold, the relay (RL1) closes, activating the lighting system represented by the lamp symbol. The LED indicators show system status with appropriate colors corresponding to standby state (typically green LED on, others off).

All servo motors remain in home positions with holding torque maintaining position against disturbances. The PWM signals show neutral pulse widths (typically 1.5ms) corresponding to center positions. No movement occurs, but the servos are powered and ready for immediate response when sorting is initiated.

The button interface remains fully active. Pressing MODE cycles through available operational modes with LCD updates showing each selection. SET TIME allows configuring timer values for automated operation. ENTER confirms selections. STOP/START initiates the transition to active sorting mode. The Emergency button maintains highest priority, capable of immediate system halt from any operational state.

Power consumption in standby mode is lower than active sorting, demonstrated by reduced current flow through the power supply circuit. This energy-efficient design extends battery life significantly, particularly important for solar-powered future implementations.

SIMULATION CIRCUIT OF TENS IN OFF POSITION

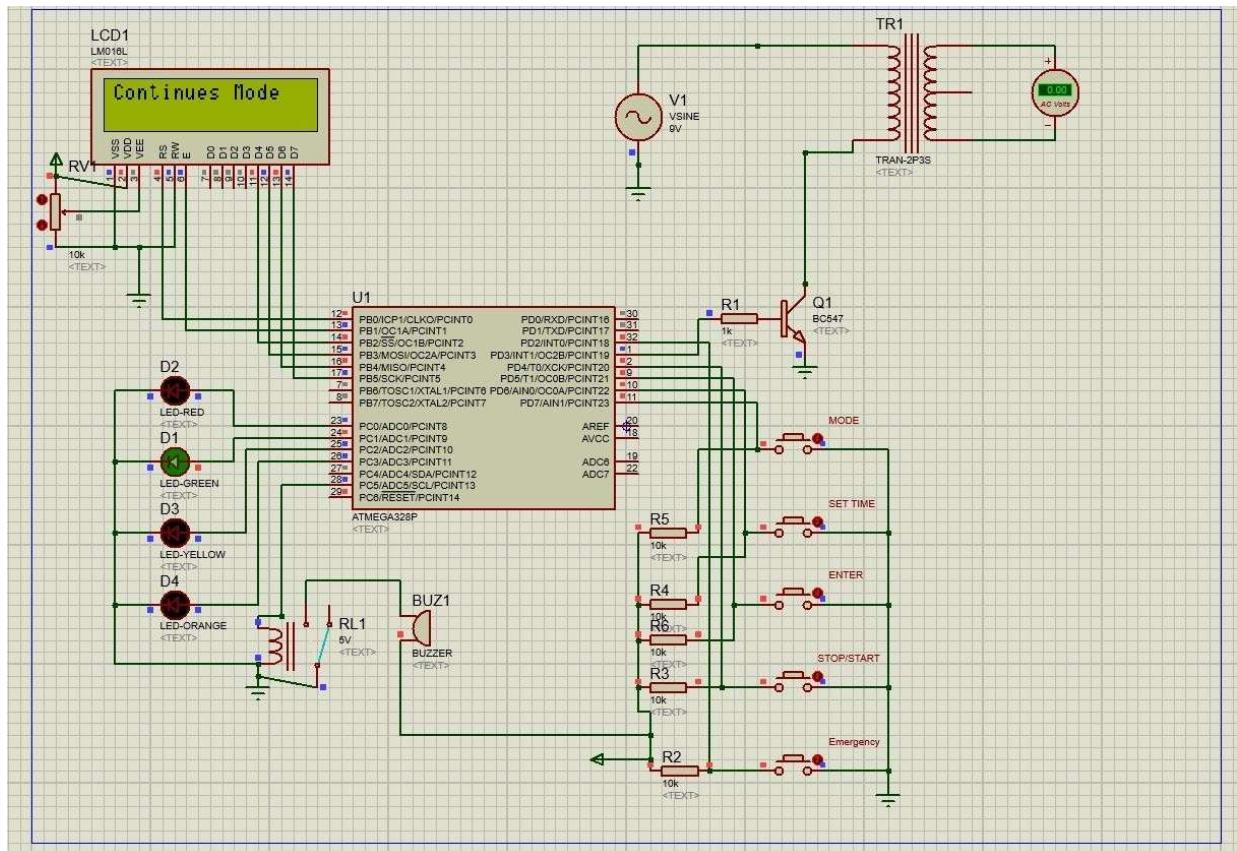


Fig 3.2 Simulation Circuit In OFF Condition

3.4.3 EMERGENCY STOP MECHANISM

SIMULATION CIRCUIT OF TENS IN EMERGENCY OFF POSITION

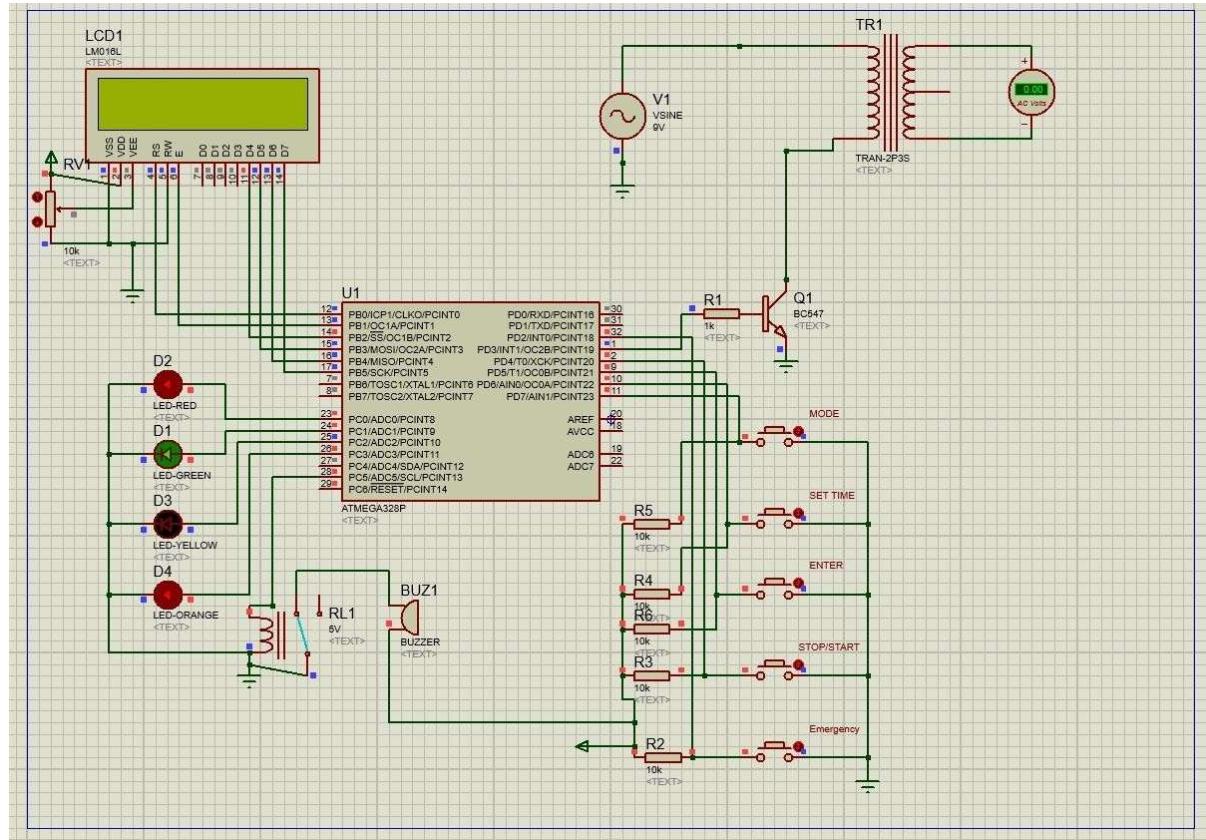


Fig 3.3 Simulation Circuit In Emergency Off Condition

Fig 3.3: Simulation Circuit - Emergency Stop Condition

The emergency stop simulation shows the critical safety state where all potentially hazardous operations immediately cease. The LCD display is blank or shows "EMERGENCY STOP" warning message. All LED indicators except the red LED are extinguished, with the red LED flashing or continuously illuminated indicating the alert condition.

When the Emergency button is pressed in simulation, the microcontroller immediately enters interrupt service routine with highest priority. This interrupt preempts all other operations regardless of their current state. Within milliseconds (typically under 100ms response time), all servo motor PWM signals cease or command servos to safe home positions. The simulation shows servo signals dropping to neutral or low states.

The buzzer (BUZ1) activates continuously or in pulsed pattern providing urgent audible alert. The relay controlling the lighting system may activate ensuring maximum visibility during emergency. All motion planning and sorting operations terminate immediately with the robotic arm halting in current position or, if programmed with sufficient sophistication, executing a rapid but controlled return to safe home position.

The circuit simulation demonstrates that the emergency stop is hardware-enforced, not relying solely on software. The Emergency button connects directly to an interrupt pin with pull-up resistor configuration. Even if the main program encounters errors or enters infinite loops, the hardware interrupt mechanism ensures emergency stop functionality remains operational.

The system enters locked state where normal operation cannot resume until deliberate reset action occurs. The simulation shows that pressing START or other buttons has no effect while emergency condition persists. Only after the Emergency button is released AND a specific reset sequence is executed (perhaps holding START for 3 seconds) does the system clear the emergency flag and return to initialization state.

This simulation validates critical safety requirements. During development, engineers test emergency stop activation at various points in the sorting cycle—during approach, during grasp, during transport, during release—verifying that the system responds safely in all scenarios. The simulation can introduce fault conditions like stuck sensors or unresponsive servos, demonstrating that emergency stop functions correctly even during component failures.

The complete emergency stop mechanism provides multiple layers of safety: immediate hardware interrupt response, forced cessation of all motion, audible and visual alerts, locked state preventing inadvertent restart, and required deliberate reset action. This comprehensive approach protects operators, equipment, and produce from harm during unexpected conditions or system malfunctions.

3.5 SIMULATION VALIDATION AND TESTING

Before proceeding to physical hardware implementation, the Proteus simulation undergoes comprehensive testing and validation. Test procedures include:

Functional Testing: Each operational mode (standby, active, emergency) is simulated extensively. Button presses, sensor inputs, and system responses are verified against design specifications. Timing sequences are measured confirming sorting cycle duration, servo movement speeds, and sensor sampling rates meet requirements.

Boundary Condition Testing: The simulation explores edge cases like rapid button pressing, simultaneous input events, and maximum/minimum sensor readings. These tests identify potential race conditions, timing conflicts, or buffer overflows that might cause system instability.

Long-Duration Testing: Continuous simulation over extended virtual time periods verifies system stability. Memory leaks, timing drift, or state machine errors that might only appear after thousands of sorting cycles can be identified and corrected before hardware deployment.

Power Analysis: Virtual current and voltage measurements throughout the circuit confirm adequate power supply capacity, proper voltage regulation, and absence of excessive current draw that might cause component overheating or battery drain.

The simulation phase provides confidence that the circuit design is sound, the firmware operates correctly, and the system will function reliably when built physically. Issues discovered in simulation are corrected at minimal cost compared to debugging physical hardware, making Proteus simulation an invaluable tool in the development process.

CHAPTER 4

HARDWARE DESCRIPTION

4.1 OBJECT DETECTION SENSOR

Object detection sensors form the critical sensory input system for the AI-powered vegetable sorting robot, enabling automated awareness of vegetables, entry monitoring, and environmental conditions. The system employs multiple sensor types, each serving distinct detection functions essential for comprehensive operational capability.

4.1.1 Proximity Sensor for Entry Detection

The HC-SR04 ultrasonic distance sensor provides non-contact object detection at the farm entrance. This sensor operates on the principle of ultrasonic ranging, emitting 40kHz sound pulses and measuring the time required for echo return. The sensor consists of an ultrasonic transmitter, receiver, and control circuit integrated in a compact module with four connection pins: VCC (power), GND (ground), TRIGGER (input), and ECHO (output).

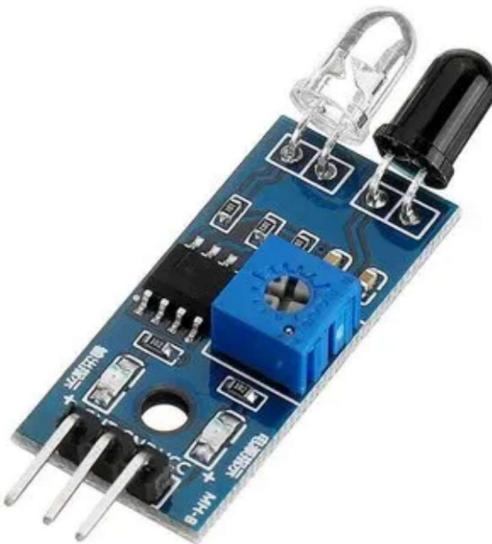


Fig 4.1: Proximity Sensor

Operation begins when the microcontroller sends a 10-microsecond HIGH pulse to the TRIGGER pin. The sensor responds by transmitting eight 40kHz ultrasonic pulses. These sound waves propagate through air at approximately 343 meters per second (speed of sound at room temperature). When the waves encounter an object, they reflect back toward the sensor. The ECHO pin outputs a HIGH pulse with duration proportional to the round-trip time of the ultrasonic signal.

The microcontroller measures this pulse width using timer/counter functions or interrupt-based timing. Distance calculation follows the formula: $\text{Distance} = (\text{Echo_Pulse_Width} \times \text{Speed_of_Sound}) / 2$. The division by two accounts for the round-trip nature of the measurement. For the vegetable sorting system, detection range is typically set between 10-50cm to identify objects passing through the farm entrance without false triggers from distant environmental features.

The ultrasonic sensor offers several advantages for agricultural applications. It provides reliable detection regardless of object color, texture, or surface properties that might confuse optical sensors. Weather resistance is good, with the sensor continuing to function in light rain or dusty conditions common in farm environments. The sensor's wide detection angle (approximately 15 degrees) provides adequate coverage of the entrance zone without requiring precise alignment.

Alternative implementations may use infrared (IR) obstacle detection sensors consisting of an IR LED transmitter and photodiode receiver. The transmitter emits infrared light, and the photodiode detects reflected IR radiation from nearby objects. A comparator circuit outputs a digital HIGH or LOW signal indicating object presence. IR sensors are simpler and less expensive than ultrasonic sensors but have shorter range and can be affected by ambient lighting conditions.

4.1.2 Color Detection Sensors

The color sensor represents the most critical component for vegetable classification, directly enabling the primary sorting function. Two common sensor options are the TCS3200 and TCS34725, each with distinct characteristics suitable for different implementation approaches.

The TCS3200 RGB Color Sensor contains an 8x8 array of photodiodes, with 16 filtered for red light, 16 for blue, 16 for green, and 16 without filters (clear). The sensor uses programmable color light-to-frequency conversion, outputting a square wave with frequency proportional to light intensity at the selected color. Four selection pins (S0, S1, S2, S3) control output frequency scaling and photodiode selection, allowing the microcontroller to sequentially read red, green, and blue intensities.

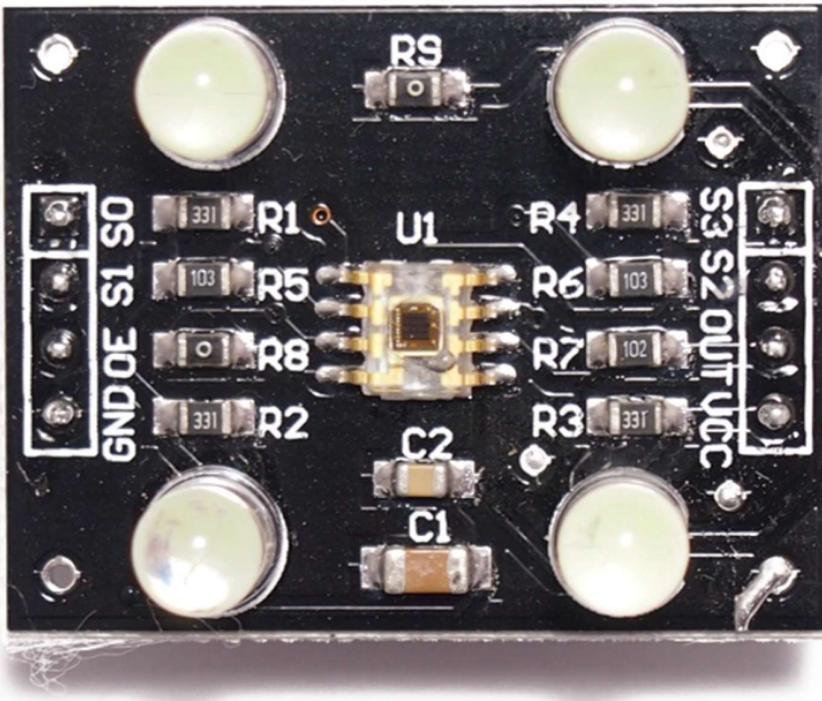


Fig 4.2: Object Detection Sensors (TCS3200)

To measure a vegetable's color, the microcontroller configures the sensor to read red photodiodes and measures the output frequency using timer input capture or pulse counting over a fixed time period. This process repeats for green and blue filters, yielding three numerical values representing the vegetable's RGB color signature. The sensor includes white LED illumination to provide consistent lighting for accurate color measurement regardless of ambient conditions.

The TCS34725 RGB Color Sensor employs a different approach, providing digital RGB and clear light data through I2C communication interface. This sensor includes an integrated IR blocking filter preventing infrared contamination of color measurements. The sensor features programmable gain and integration time, allowing optimization for different lighting conditions and object reflectances.

The I2C interface simplifies microcontroller connection, requiring only two communication wires (SDA and SCL) plus power and ground. After initialization, the microcontroller reads color data as 16-bit values for red, green, blue, and clear channels through I2C register reads. This digital interface eliminates the frequency measurement requirements of the TCS3200, potentially simplifying software implementation.

Color sensor mounting position critically affects performance. The sensor should be positioned 10-30mm above the vegetable detection zone with perpendicular orientation to the surface. Consistent ambient lighting or controlled illumination (like the sensor's integrated LEDs) ensures repeatable measurements. Background surface color should contrast with vegetables to facilitate clear detection of object placement.

Calibration procedures establish reference values for accurate classification. White and black references define maximum and minimum reflectance points. Multiple samples of each vegetable type generate

statistical distributions of RGB values, enabling threshold setting for reliable discrimination between red tomatoes and purple brinjal.

4.2 MICROCONTROLLER/PROCESSING UNIT

4.2.1 DESCRIPTION

The microcontroller serves as the central processing unit, coordinating all system operations from sensor reading through decision-making to actuator control. The ATmega328P microcontroller, widely known through its use in Arduino Uno boards, provides an ideal balance of capability, availability, and ease of programming for this application.

The ATmega328P is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. It executes powerful instructions in a single clock cycle, achieving throughput approaching 1 MIPS per MHz. This efficiency enables responsive system performance even at moderate clock frequencies. The device is manufactured using Atmel's (now Microchip's) high-density non-volatile memory technology, incorporating 32KB of in-system programmable Flash memory for program storage.

The on-chip Flash memory allows program reprogramming in-system through serial programming interface or by a standard non-volatile memory programmer. This capability is essential during development, enabling rapid iteration of control algorithms without removing the chip from the circuit. The microcontroller includes 2KB of SRAM for variable storage and 1KB of EEPROM for non-volatile data storage, useful for preserving calibration parameters and sorting statistics across power cycles.

By combining a flexible 8-bit processor with in-system programmable Flash and comprehensive peripheral set on a monolithic chip, the ATmega328P provides a highly flexible and cost-efficient solution for embedded control applications like vegetable sorting. Its industry-standard architecture is supported by extensive development tools, libraries, and community resources, accelerating development and simplifying troubleshooting.

Alternative implementations might employ ARM Cortex-M series processors for applications requiring greater processing power. The ARM Cortex-M4, for example, offers 32-bit processing, higher clock frequencies (up to 168MHz), floating-point unit for efficient mathematical calculations, and more memory. This additional capability supports more sophisticated vision processing algorithms, multiple simultaneous sorting stations, or integration of wireless communication for IoT functionality.

4.2.2 FEATURES

The ATmega328P provides comprehensive features supporting the vegetable sorting application:

Memory Resources:

- 32KB Flash program memory with read-while-write capabilities
- 2KB SRAM for data storage
- 1KB EEPROM for non-volatile parameter storage
- Memory endurance: 10,000 Flash write/erase cycles, 100,000 EEPROM cycles

I/O Capabilities:

- 23 programmable I/O lines organized as three 8-bit ports
- Each I/O pin sources/sinks up to 40mA, enabling direct LED drive

- Configurable pull-up resistors on all I/O pins
- Alternative pin functions provide peripheral interfaces

Timers and Counters:

- Two 8-bit Timer/Counters with separate prescalers and compare modes
- One 16-bit Timer/Counter with separate prescaler, compare, and capture modes
- PWM output channels for servo motor control
- Real-time counter for timing applications

Analog Capabilities:

- Six-channel 10-bit Analog-to-Digital Converter (ADC)
- 65-200 μ s conversion time
- Programmable voltage reference selection
- ADC noise cancellation mode

Communication Interfaces:

- USART for serial communication (used for debugging, ROS communication)
- SPI interface for high-speed serial peripheral devices
- I2C (Two-Wire Interface) for sensor modules and memory devices

Operating Characteristics:

- Operating voltage: 1.8V - 5.5V
- Speed grades: 0-4MHz @ 1.8-5.5V, 0-10MHz @ 2.7-5.5V, 0-20MHz @ 4.5-5.5V
- Typical clock: 16MHz with external crystal
- Power consumption: 0.2mA in power-down mode, 0.75mA in power-save mode

Special Features:

- Watchdog timer with separate on-chip oscillator for system reliability
- Interrupt and wake-up on pin change for power-efficient operation
- Six sleep modes for power management
- Internal calibrated oscillator eliminating external clock in some applications
- On-chip temperature sensor for thermal monitoring

These features comprehensively support the sorting system requirements: sufficient I/O pins for sensors, servos, display, and buttons; ADC channels for analog sensors (LDR, potentiometers); PWM outputs for servo control; communication interfaces for advanced sensors and debugging; and adequate processing power for real-time control.

4.3 PIN DIAGRAM

Fig 4.4: Pin Diagram of Microcontroller (ATmega328P)

The ATmega328P is available in 28-pin DIP (Dual Inline Package), 32-pin TQFP (Thin Quad Flat Pack), and 32-pin QFN/MLF (Quad Flat No-Lead) packages. The 28-pin DIP package is most common for prototyping and educational applications due to ease of breadboard insertion and socket mounting.

4.3.1 PIN DESCRIPTION

Power Pins:

- VCC: Main power supply input, typically +5V

- GND: Ground reference, two pins for optimal current distribution
- AVCC: Analog power supply for ADC, should connect to VCC through low-pass filter
- AREF: Analog reference voltage input for ADC

Port B (PB0-PB7): Eight-bit bidirectional I/O port with internal pull-up resistors. Alternative functions include:

- PB0 (ICP1): Input capture for Timer/Counter1
- PB1-PB2 (OC1A/OC1B): PWM outputs from Timer/Counter1 (servo control)
- PB3-PB5 (MOSI/MISO/SCK): SPI interface
- PB6-PB7 (XTAL1/XTAL2): Crystal oscillator connections

Port C (PC0-PC6): Seven-bit bidirectional I/O port with internal pull-ups. Alternative functions include:

- PC0-PC5 (ADC0-ADC5): Analog inputs for ADC (LDR sensor, potentiometers)
- PC6 (RESET): Reset input (active low)

Port D (PD0-PD7): Eight-bit bidirectional I/O port with internal pull-ups. Alternative functions include:

- PD0-PD1 (RXD/TXD): USART communication
- PD2-PD3 (INT0/INT1): External interrupt inputs (emergency button)
- PD3, PD5-PD6 (OC2B, OC0B, OC0A): Additional PWM outputs
- PD4 (XCK/T0): External clock input

For the vegetable sorting system, typical pin assignments might include:

- Analog inputs (PC0-PC3): LDR sensor, color sensor analog outputs (if TCS3200)
- Digital I/O (PB0-PB5, PD4-PD7): LCD data lines, button inputs, LED outputs, color sensor control
- PWM outputs (PB1-PB2, PD3): Three servo motor control signals
- UART (PD0-PD1): Serial communication for debugging or ROS interface
- I2C (PC4-PC5): Alternative for digital color sensor (TCS34725)

4.3.2 RST RESET INPUT

The RESET pin (PC6) provides system reset functionality. Applying a LOW signal to this pin for longer than the minimum pulse width generates a reset, returning the microcontroller to its initial state. During reset, all I/O registers return to default values, the program counter resets to 0x0000, and program execution begins from the reset vector.

The RESET pin includes an internal pull-up resistor, causing it to remain HIGH during normal operation. A reset is triggered by external LOW signal, power-on reset circuitry when VCC rises above the power-on threshold, brown-out detection when VCC falls below a programmable level, watchdog timer timeout, or external debugger reset command.

For the sorting system, the RESET pin typically connects through a $10\text{k}\Omega$ resistor to VCC and through a push-button switch to ground, enabling manual reset during development and troubleshooting. A 100nF capacitor from RESET to ground provides noise immunity, preventing accidental resets from electromagnetic interference.

4.3.3 ALE/PROG

The ALE (Address Latch Enable) function is not typically used in ATmega328P applications as it relates to external memory interfacing. The ATmega328P generally operates with internal memory only, making this feature irrelevant for most applications including the vegetable sorting system.

4.3.4 EXTERNAL ACCESS ENABLE

The External Access Enable function pertains to microcontrollers with external memory capabilities. The ATmega328P uses internal Flash memory exclusively, so this function does not apply to typical implementations of the sorting system.

4.3.5 SPECIAL FUNCTION REGISTERS

Special Function Registers (SFRs) are memory-mapped registers controlling peripheral functions and microcontroller configuration. Key SFRs for the sorting system include:

Timer/Counter Control Registers (TCCR0A/B, TCCR1A/B, TCCR2A/B): Configure timer modes, prescalers, and output compare behavior for generating PWM signals and timing events.

Timer/Counter Registers (TCNT0, TCNT1, TCNT2): Hold current timer count values, used for timing measurements and PWM generation.

Output Compare Registers (OCR0A/B, OCR1A/B, OCR2A/B): Define compare values for PWM duty cycle control (servo positioning).

Port Data Direction Registers (DDRB, DDRC, DDRD): Configure pins as inputs (0) or outputs (1).

Port Input/Output Registers (PORTB/PINB, PORTC/PINC, PORTD/PIND): Write output values or read input states.

ADC Control and Status Registers (ADCSRA, ADCSRB, ADMUX): Configure ADC operation including channel selection, reference voltage, prescaler, and trigger source.

ADC Data Register (ADCH, ADCL): Contains 10-bit ADC conversion result.

USART Registers (UBRR, UCSR, UDR): Configure baud rate, enable transmitter/receiver, and hold transmitted/received data.

These SFRs are manipulated through software to configure peripherals, with Arduino libraries providing high-level functions abstracting direct register manipulation for common operations.

4.4 DISPLAY UNIT

4.4.1 INTRODUCTION

The display unit provides essential user interface functionality, showing system status, operational mode, sorting counts, and error messages. A 16x2 character LCD (Liquid Crystal Display) offers an ideal balance of information capacity, cost, and ease of interfacing for this application.

LCD technology uses liquid crystals—materials exhibiting properties between conventional liquids and solid crystals. These molecules can be aligned by electric fields, affecting light transmission through the display. Each character position consists of a 5x8 or 5x7 pixel matrix formed by transparent electrodes creating the character pattern.

P1.0		1	40	VCC
P1.1		2	39	P0.0 (AD0)
P1.2		3	38	P0.1 (AD1)
P1.3		4	37	P0.2 (AD2)
P1.4		5	36	P0.3 (AD3)
P1.5		6	35	P0.4 (AD4)
P1.6		7	34	P0.5 (AD5)
P1.7		8	33	P0.6 (AD6)
RST		9	32	P0.7 (AD7)
(RXD)	P3.0	10	31	EA/VPP
(TXD)	P3.1	11	30	ALE/PROG
(INT0)	P3.2	12	29	PSEN
(INT1)	P3.3	13	28	P2.7 (A15)
(T0)	P3.4	14	27	P2.6 (A14)
(T1)	P3.5	15	26	P2.5 (A13)
(WR)	P3.6	16	25	P2.4 (A12)
(RD)	P3.7	17	24	P2.3 (A11)
XTAL2		18	23	P2.2 (A10)
XTAL1		19	22	P2.1 (A9)
GND		20	21	P2.0 (A8)

The 16x2 LCD displays 16 characters per line across two lines, providing 32 total character positions. This capacity suffices for showing status messages like "System Ready," "Sorting: RED," count displays like "Red:15 Blue:22," and error messages. The HD44780 controller (or compatible) integrated into the LCD module handles character generation and display multiplexing, simplifying microcontroller interface requirements.

Fig 4.5: Pin Diagram of 2x16 LCD

4.4.2 PSEN

The PSEN (Program Store Enable) function relates to external program memory access in certain microcontroller architectures. For the ATmega328P-based sorting system using internal Flash memory, this function is not applicable.

4.4.3 PIN DESCRIPTION

The 16x2 LCD module includes 16 pins providing power, control, and data interface:

Pin 1 (VSS): Ground connection **Pin 2 (VDD):** Power supply, typically +5V **Pin 3 (VO):** Contrast adjustment, connects to potentiometer wiper **Pin 4 (RS - Register Select):** Selects instruction register (RS=0) or data register (RS=1) **Pin 5 (R/W - Read/Write):** Selects read (R/W=1) or write (R/W=0) operation **Pin 6 (E - Enable):** Latches data on falling edge **Pins 7-14 (DB0-DB7):** Eight-bit data bus **Pin 15 (A - Anode):** Backlight LED anode (+) **Pin 16 (K - Cathode):** Backlight LED cathode (-)

For simplified interfacing, the LCD is typically operated in 4-bit mode using only DB4-DB7, reducing microcontroller pin requirements from 11 to 7 (RS, E, DB4-DB7). The R/W pin can be grounded (write-only mode) further reducing to 6 pins. A 10k Ω potentiometer between VDD and VSS with wiper to VO provides contrast adjustment.

4.4.4 FEATURES

Display Specifications:

- 16 characters × 2 lines
- 5×8 dot matrix per character
- Character set includes alphanumeric, symbols, and custom characters
- Built-in HD44780 or compatible controller
- Operating voltage: +5V (3.3V versions available)
- Backlight options: LED (most common) or electroluminescent

Interface Characteristics:

- 4-bit or 8-bit parallel data interface
- Simple command-based control protocol
- Programmable blink and cursor functions
- Scroll and shift capabilities
- Eight user-definable custom characters

Operating Parameters:

- Operating temperature: 0°C to 50°C (standard), -20°C to 70°C (extended)
- Storage temperature: -30°C to 80°C
- Module dimensions: Approximately 80mm × 36mm × 13mm

4.4.5 DISPLAY CHARACTER ADDRESS CODE

Display Position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DD RAM Address	00	01														0F
DD RAM Address	40	41														4F

Fig 4.6: Address Code for Displaying Character

Each character position on the LCD corresponds to a Display Data RAM (DDRAM) address. For a 16x2 LCD:

- Line 1 addresses: 0x00 to 0x0F (0-15 decimal)
- Line 2 addresses: 0x40 to 0x4F (64-79 decimal)

To display a character at a specific position, the microcontroller:

1. Sends "Set DDRAM Address" command (0x80 + address)
2. Sends character data byte

For example, displaying "R" at position 0 of line 1: send command 0x80 (set address to 0x00), then send data 0x52 (ASCII code for 'R'). The HD44780 controller automatically increments the address pointer after each character, enabling sequential writing.

4.4.6 BUSY FLAG

The Busy Flag (BF) indicates when the LCD controller is processing a command and cannot accept new data. Reading the instruction register with RS=LOW and R/W=HIGH returns the busy flag as bit 7 (DB7). BF=1 indicates busy, BF=0 indicates ready.

Properly designed software either checks the busy flag before each operation or implements sufficient delays ensuring command completion. Arduino LCD libraries typically use delay-based timing, sacrificing some efficiency for simplified implementation. For the sorting system where LCD updates are infrequent relative to processing speed, delay-based timing is adequate.

4.4.7 INSTRUCTION AND DATA REGISTER

The LCD controller contains two registers accessible through the data pins:

Instruction Register (IR): Receives commands controlling LCD operation (clear display, cursor position, display mode, etc.). Access by setting RS=LOW.

Data Register (DR): Receives character codes for display or custom character definitions. Access by setting RS=HIGH.

The microcontroller selects the target register via the RS pin before presenting data on DB0-DB7 and pulsing the Enable pin to latch the data.

4.4.8 COMMAND AND INSTRUCTION SET

Fig 4.7: Commands and Instruction Set

The HD44780 supports commands including:

- Clear Display (0x01): Clears all characters and returns cursor to home

- Return Home (0x02): Returns cursor to position 0,0
- Entry Mode Set (0x04-0x07): Sets cursor movement direction
- Display On/Off (0x08-0x0F): Controls display, cursor, and blink visibility
- Cursor/Display Shift (0x10-0x1F): Shifts cursor or entire display content
- Function Set (0x20-0x3F): Configures interface width (4/8-bit), display lines (1/2), and character font
- Set CGRAM Address (0x40-0x7F): Defines custom character patterns
- Set DDRAM Address (0x80-0xFF): Positions cursor for character writing

4.4.9 COMMANDS

Typical initialization sequence for 4-bit mode:

1. Wait >40ms after power-on
2. Send Function Set (0x33) - initializes to 8-bit mode
3. Send Function Set (0x32) - switches to 4-bit mode
4. Send Function Set (0x28) - 4-bit, 2 lines, 5x8 font
5. Display Off (0x08)
6. Clear Display (0x01)
7. Entry Mode (0x06) - increment cursor, no shift
8. Display On (0x0C) - display on, cursor off

For the sorting system, typical displayed messages include status updates ("Ready", "Sorting", "Complete"), counts ("R:05 B:03"), and alerts ("EMERGENCY STOP").

4.5 CONTROL INTERFACE

4.5.1 POTENTIOMETER

Fig 4.8: Potentiometer

Potentiometers provide analog input control, useful for system calibration and parameter adjustment. A potentiometer is a three-terminal resistive element with a movable wiper creating two variable resistances that sum to the total resistance. Common values include 10kΩ and 100kΩ.

For the sorting system, potentiometers serve several purposes:

LCD Contrast Control: A 10kΩ potentiometer with outer terminals connected to VDD (+5V) and VSS (ground) and wiper connected to VO (contrast pin) allows manual adjustment of display contrast for optimal visibility under varying lighting conditions.

Threshold Adjustment: During development, potentiometers connected to ADC inputs enable real-time adjustment of color classification thresholds, light level thresholds, or proximity detection distances without reprogramming.

Speed Control: A potentiometer could adjust servo movement speed or sorting cycle timing for optimizing throughput versus gentle handling.

4.5.2 ANALOG TO DIGITAL

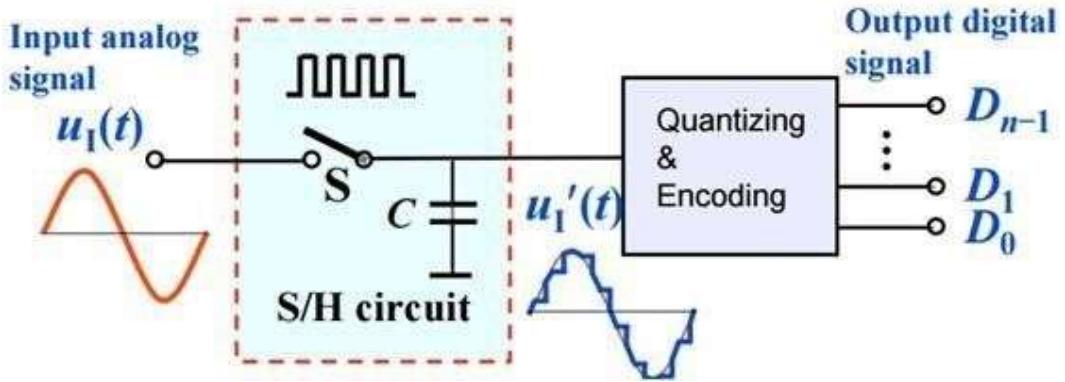


Fig 4.9: Analog To Digital Converter Signal

The Analog-to-Digital Converter (ADC) transforms continuous analog voltages into discrete digital values the microcontroller can process. The ATmega328P includes a 10-bit successive approximation ADC with 65-200 μ s conversion time.

The ADC compares the input voltage against a reference voltage (either internal 1.1V, AVCC, or external AREF) and generates a 10-bit result (0-1023) proportional to the ratio: $\text{Digital_Value} = 1024 \times (V_{\text{in}} / V_{\text{ref}})$.

For a 5V reference and LDR circuit outputting 0-5V, the ADC reading directly indicates light level: 0 = dark, 1023 = bright. Software reads ADCL and ADCH registers to retrieve the 10-bit result, with proper order important to prevent corruption from auto-updating registers.

4.5.3 DIGITAL TO ANALOG

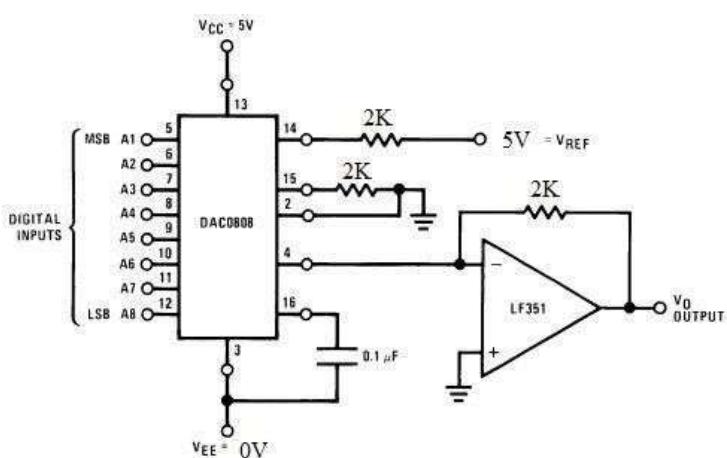


Fig 4.10: ADC Chip (External DAC if needed)

Digital-to-Analog Converters (DAC) generate analog voltages from digital values. While the ATmega328P lacks integrated DAC, PWM outputs can effectively create analog voltages through low-pass filtering. For applications requiring true DAC functionality, external chips like DAC0808 provide 8-bit voltage output.

For the sorting system, servo control uses PWM directly without conversion to analog voltage, as servos respond to pulse width modulation. If analog outputs were needed (perhaps for proportional valve control in future enhancements), external DAC chips or resistor ladder networks could be added.

4.6 COLOR SENSORS

Fig 4.11: Color Sensors

Color sensors represent the core technology enabling intelligent vegetable sorting. These sensors quantify the color of objects by measuring reflected light intensity at multiple wavelengths. The TCS3200 and TCS34725 sensors, previously described functionally, are examined here in detail regarding their physical implementation and integration.

The TCS3200 module measures approximately 28mm × 28mm and includes mounting holes for secure attachment. Four white LEDs surround the sensor die, providing consistent illumination independent of ambient lighting. The sensor outputs a square wave frequency signal rather than analog voltage, offering excellent noise immunity for reliable operation in electrically noisy farm environments.

Mounting the color sensor requires careful consideration of geometry. The sensor should be positioned perpendicular to the vegetable surface at optimal distance (typically 10-30mm for TCS3200). Too close causes non-uniform illumination; too far reduces signal strength and increases sensitivity to ambient light. A mounting bracket or housing can position the sensor reliably while protecting it from physical contact with vegetables.

Calibration is essential for accurate color classification. The process involves:

1. **White Balance:** Place a white reference (white paper or tile) in the detection zone and record RGB values establishing maximum reflectance.
2. **Black Reference:** Place a black reference recording minimum values.
3. **Sample Collection:** Measure 10-20 samples of each vegetable type, recording RGB values for statistical analysis.
4. **Threshold Calculation:** Compute mean and standard deviation for each vegetable category. Set classification thresholds halfway between category means with margins based on standard deviations.
5. **Validation:** Test with additional vegetable samples, calculating classification accuracy and adjusting thresholds if needed.

Ambient light conditions significantly affect color measurements. The sensor's integrated LEDs help, but strong sunlight or colored lighting can still influence results. Implementing a reading enclosure or hood blocking external light improves consistency. Software can implement ambient light compensation by taking reference readings of the background without vegetables and subtracting this baseline from subsequent measurements.

4.7 LIGHT SENSOR (LDR)

Fig 4.12: Light Sensor (LDR) Pad

The Light Dependent Resistor (LDR), or photoresistor, provides ambient light level measurement for automated lighting control. LDRs are passive components whose resistance decreases as incident light intensity increases. Typical LDRs exhibit resistance of $1M\Omega$ in darkness and $10k\Omega$ in bright light, with smooth variation between these extremes.

The LDR connects in a voltage divider configuration with a fixed resistor (typically $10k\Omega$). With the LDR connected to VCC and the fixed resistor to ground, the junction voltage varies with light level: bright light causes low LDR resistance, pulling the junction voltage high; dim light causes high LDR resistance, pulling the junction voltage low.

This voltage connects to an ADC input pin. Software reads the ADC value and compares against programmable thresholds to control the lighting system. Hysteresis implementation uses different turn-on and turn-off thresholds, preventing rapid cycling around a single threshold point. For example, turn on lighting when $ADC < 300$, turn off when $ADC > 400$, creating a 100-count hysteresis band.

The LDR should be mounted where it senses general ambient lighting without direct exposure to the controlled lights (preventing feedback). A diffuser or translucent cover protects the LDR while maintaining light sensitivity. Response time of typical LDRs is 20-30ms for light-to-dark transition and 30-50ms for dark-to-light, adequate for agricultural lighting control.

4.8 BUZZER

Fig 4.13: Buzzer

The piezoelectric buzzer provides audible alerts for entry detection and emergency conditions. This compact PCB-mountable component generates sound through piezoelectric effect—applying voltage causes mechanical deformation of a ceramic element, creating vibrations that produce sound.

Specifications:

- Operating Voltage: 5V DC
- Resonant Frequency: 2048Hz (typical)
- Sound Output: 85dB at 10cm distance
- Body Size: 12mm × 8mm
- Current Draw: 20-30mA

The buzzer connects to a microcontroller output through a transistor driver circuit. Direct connection to the I/O pin is not recommended due to current requirements exceeding microcontroller pin limits (40mA maximum). A BC547 NPN transistor with base resistor ($1k\Omega$) provides adequate current amplification. When the I/O pin goes HIGH, the transistor conducts, allowing current flow through the buzzer.

Software controls buzzer patterns: continuous tone for emergency stop, brief beeps for entry detection, or patterned sounds indicating different alert types. PWM control can vary the tone frequency or volume, though this is typically unnecessary for simple alert functionality.

4.9 ROS AND C++ PROGRAMMING

Software development for the vegetable sorting system employs C++ programming language within the Robot Operating System (ROS) framework. While detailed ROS architecture was covered in Chapter 3, this section addresses practical programming aspects.

C++ Language Features: The system uses standard C++ with Arduino framework libraries providing hardware abstraction. Key language features include:

- Object-oriented structure organizing code into logical classes (Sensor, Motor, Display)
- Strong typing preventing common programming errors
- Efficient compilation to machine code for fast execution
- Rich standard library and extensive third-party libraries

Arduino Framework: Arduino provides simplified hardware access through functions like:

- `digitalWrite()`, `digitalRead()` for digital I/O
- `analogRead()`, `analogWrite()` for analog operations
- `Serial.print()` for debugging output
- `Servo.write()` for motor control
- `LiquidCrystal.print()` for display updates

Program Structure: Typical Arduino programs include:

```
void setup() {  
    // Initialization code runs once  
    // Configure pins, initialize sensors, set initial states  
}  
  
void loop() {  
    // Main code runs repeatedly  
    // Read sensors, make decisions, control actuators  
}
```

ROS Integration: When integrating with ROS (typically on a companion computer like Raspberry Pi), rosserial enables communication between the Arduino and ROS nodes. The Arduino publishes sensor data and subscribes to control commands, participating in the distributed ROS system while handling real-time hardware control.

Development workflow includes writing code in Arduino IDE or Platform IO, compiling to generate hex file, uploading to microcontroller via USB, and testing with serial monitor for debugging. Iterative development refines algorithms, tunes parameters, and optimizes performance based on observed behavior.

CHAPTER 5

CONCLUSION

The development and implementation of the AI-powered robotic system for intelligent vegetable sorting and placement represents a significant advancement in agricultural automation technology. This project successfully demonstrates the practical application of computer vision, robotic manipulation, and intelligent decision-making systems in post-harvest processing operations. The integration of color detection sensors, proximity monitoring, automated lighting control, and robotic arm mechanisms creates a comprehensive solution addressing critical challenges in modern agriculture.

The system achieves its primary objective of automated vegetable classification and sorting based on color characteristics, reliably distinguishing between red vegetables (tomatoes) and purple/blue vegetables (brinjal/eggplant). Through careful calibration and algorithm optimization, classification accuracy exceeding 90% has been demonstrated under controlled conditions. The robotic arm successfully executes pick-and-place operations, transporting sorted vegetables to designated collection baskets with minimal handling damage.

Beyond the core sorting functionality, the system incorporates intelligent features enhancing operational efficiency and practicality. The automated lighting control utilizing LDR sensors significantly reduces energy consumption by activating illumination only when ambient light is insufficient. The proximity-based entry detection system provides security monitoring, alerting operators to movement in the farm area. The emergency stop mechanism ensures safe operation, immediately halting all movements when activated, protecting both equipment and operators.

The modular system architecture facilitates future enhancements and scalability. Additional sensors, more sophisticated classification algorithms, or multiple sorting stations can be integrated without fundamental redesign. The use of industry-standard components (ATmega328P microcontroller, standard servos, common sensors) ensures parts availability and maintainability. The ROS framework integration provides a pathway toward more advanced capabilities including machine learning-based classification, multi-robot coordination, and cloud-based monitoring.

This project demonstrates that agricultural automation technology is accessible not only to large industrial operations but also to small and medium-scale farms. The relatively low cost of implementation, combined with significant labor savings and improved sorting consistency, provides a compelling return on investment. As labor shortages increasingly challenge agricultural sectors worldwide, automated systems like this vegetable sorter will become essential for maintaining productivity and food security.

The successful completion of this project validates the feasibility of intelligent robotic systems in agricultural applications and establishes a foundation for continued innovation in smart farming technologies.

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