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Titled:

Implementation of an AI Based Quality Control and Robotic Sorting System

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Abstract

This project presents an AI-Based Quality Control and Robotic Sorting System designed to automate product inspection and classification processes. The system combines Artificial Intelligence, Computer Vision, Robotics, and Industrial Automation technologies to detect defects and perform autonomous sorting operations in real time. The proposed solution improves inspection accuracy, reduces human intervention, and enhances operational efficiency. It can be adapted to any product or manufacturing process that requires quality control and automated sorting.

Résumé

Ce projet présente un système de contrôle qualité basé sur l'IA et de tri robotisé conçu pour automatiser les processus d'inspection et de classification des produits. Le système combine les technologies d'intelligence artificielle, de vision par ordinateur, de robotique et d'automatisation industrielle pour détecter les défauts et effectuer des opérations de tri autonomes en temps réel. La solution proposée améliore la précision de l'inspection, réduit l'intervention humaine et renforce l'efficacité opérationnelle. Elle peut être adaptée à n'importe quel produit ou processus de fabrication nécessitant un contrôle qualité et un tri automatisé.

ملخص

يقدم هذا المشروع نظاماً لمراقبة الجودة والفرز الروبوتي قائمًا على الذكاء الاصطناعي، والمصمم لأتمتة عمليات فحص المنتجات وتصنيفها. يجمع النظام بين تقنيات الذكاء الاصطناعي، والرؤية الحاسوبية، والروبوتات، والأتمتة الصناعية للكشف عن العيوب وإجراء عمليات فرز مستقلة في الوقت الفعلي. يعزز الحل المقترح دقة الفحص، ويقلل من التدخل البشري، ويرفع من الكفاءة التشغيلية. ويمكن تكييفه ليتوافق مع أي منتج أو عملية تصنيع تتطلب مراقبة الجودة والفرز الآلي.

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Table Of Abbreviations

Abbreviation	Meaning
AI	Artificial Intelligence
PCB	Printed Circuit Board
CV	Computer Vision
LCD	Liquid Crystal Display
PWM	Pulse Width Modulation
DC	Direct Current
GPIO	General Purpose Input/Output
I2C	Inter-Integrated Circuit
USB	Universal Serial Bus
CPU	Central Processing Unit
RAM	Random Access Memory
HMI	Human-Machine Interface
ML	Machine Learning
API	Application Programming Interface
QA	Quality Assurance
QC	Quality Control
RPi	Raspberry Pi
LDR	Light Dependent Resistor
IMX500	Intelligent AI Vision Sensor IMX500
Edge-AI	Edge Artificial Intelligent
Open CV	Open-Source Computer Vision Library
SSH	Secure Shelle
CNN	Convolution Neural Network

Key Words

Artificial Intelligence (AI)	Quality Control	Real-Time Monitoring
Computer Vision	Defect Detection	Autonomous Sorting
Robotics	Machine Learning	Embedded Systems
Industrial Automation	Smart Manufacturing	Industry 4.0

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General Introduction

Introduction

The rapid development of artificial intelligence (AI) and robotics is profoundly transforming modern industrial processes, bringing significant improvements in efficiency, safety, and flexibility. Increasingly, companies are adopting autonomous robotic systems capable of performing repetitive tasks, working in hazardous environments, and achieving precision difficult for humans to achieve.

A robot is a mechatronic device combining mechanics, electronics, and computing, designed to automatically perform tasks that mimic or reproduce human actions in a specific domain. The design of such systems falls under the scientific discipline of robotics, which originated in automation. The term "robot" first appeared in 1920 in Karel Čapek's play R.U.R. (Rossum's Universal Robots), inspired by the Czech word robota, meaning "work" or "chore." Since then, this concept has evolved to refer to intelligent machines capable of perceiving, deciding, and acting in a changing environment. [1]

Industrial robots, as defined by the International Organization for Standardization (ISO), are automated, versatile systems that can be programmed along three or more axes. There are two main categories: Cartesian robots, which move along linear axes (X, Y, Z), and polyarticulated robots, which have multiple joints allowing them to move in three dimensions with great flexibility. These machines are characterized by their range of action and payload capacity, essential parameters for their selection and use in industrial processes. Historically, the first automatons paved the way for modern robotics. In 1954, George Devol designed Unimate, the first articulated robotic arm, while KUKA developed the FAMULUS, the first six-axis electric robot, in 1973. Since then, robotics has established itself as a major tool in various sectors: automotive, food processing, electronics, metallurgy, plastics, and even medicine. [2]

In this context of continuous innovation, our project entitled **Syntrix** Intelligent Industrial Robot" is part of this dynamic. This project aims to demonstrate how the integration of artificial intelligence and autonomy into an industrial robot can optimize production tasks, increase operator safety, and provide flexibility to adapt to the needs of a modern, connected industry. This work focuses on the design, modeling, and implementation of an intelligent industrial robot capable of interacting with its environment while adapting to the constraints of the industrial environment.

Chapter One

Literature Review

Chapter One: Literature Review

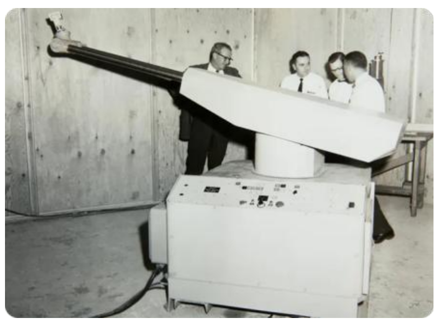
1 Historical Evolution of Industrial Robotics

1.1 Pre-robotic Era:

Before the advent of robotics, production relied on manual labor and steam-powered machines introduced during the Industrial Revolution. During the First Industrial Revolution (around 1760,1840), the introduction of steam engines and mechanized textile machines marked the beginning of automation in manufacturing. However, these machines lacked any form of intelligence or autonomy they required continuous human supervision to operate, adjust, and maintain. [3]

1.2 1950s–1980s: Birth of Industrial Robotics:

In 1954, George Devol invented Unimate, the first programmable robot capable of performing repetitive industrial tasks automatically. In 1961, General Motors deployed it for die casting and spot welding, marking the beginning of robotic automation in manufacturing. During the 1970s, advances in electronics and microprocessors made robots more precise, reliable, and efficient, leading to their wider adoption in automotive and electronics industries. [4]



Figures 1:1954-Birth of an industrial Robot in the US

1.3 1990s–2000s: Expansion and Improvement:

Robots became faster, more precise, and more affordable, expanding into sectors such as electronics, pharmaceuticals, and food processing. The rise of computers and sensors improved robot perception and control, while the Internet and AI research opened doors to autonomous and intelligent robots.By the 2000s, robots such Roomba who is a compact, computerized vacuum cleaner that automatically guides itself around your home. Like a conventional cleaner, it picks up dirt with spinning brushes and a vacuum, and the robot ASIMO these robots demonstrated significant progress in mobility and interaction, making them more present in everyday life. [5]

Figures 2:Roomba Robots

1.4 2010s–Present: Rise of Collaborative Robots (Cobots):

In 2010 The rise of collaborative robots (cobots), designed to work alongside humans, emerged, along with advances in AI-driven automation. Late 2010s significant improvements in sensor technology, AI, and machine learning enabled robots to perform more complex tasks, including surgery, warehouse automation, and autonomous driving. [6]

Figures 3:Collaborative Industrial Robot

2 Types of Industrial Robots:

Industrial robots are classified into several categories depending on their mechanical architecture and areas of application:

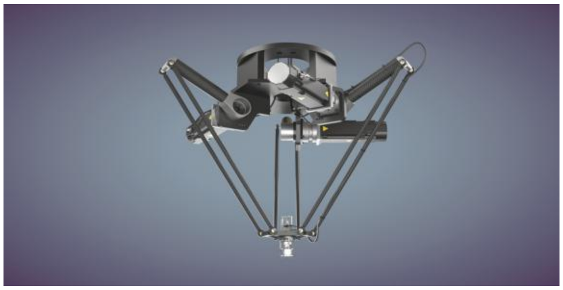
a. **Cartesian Robots:** Also called gantry robots, they move along the X, Y, and Z axes. Their simple design allows high precision, making them ideal for machining and automated handling. [7]

Figures 4:Cartesian Robot

b. **Articulated Robots**: Inspired by the human arm, these robots have several rotary joints that provide great flexibility. They are used for painting, assembly, and packaging. [7]

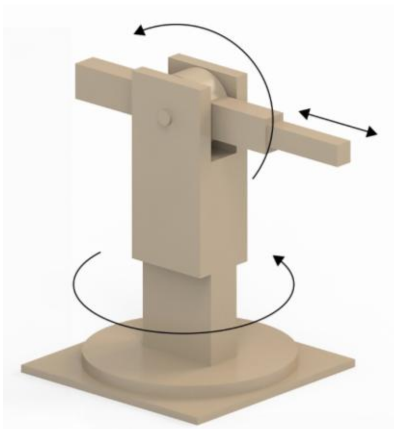
Figures 5:Articulated Robot

c. **Delta Robots**: Characterized by a lightweight triangular structure, they are fast and precise, suitable for sorting and packaging operations. [7]



Figures 6:Delta Robot

d. **Polar Robots**: Featuring a combination of rotary and linear joints, they provide a spherical range of motion, ideal for tasks requiring a wide reach. [7]



Figures 7:Polar Robot

e. **SCARA Robots (Selective Compliance Assembly Robot Arm)**: Combine two rotary joints and one linear axis, making them ideal for fast and precise horizontal movements, such as electronic assembly or food processing. [7]

Figures 8:SCARA Robot

3 Presentation of Major Industrial Robotics Companies:

3.1 ABB Robotics:

ABB Robotics is a multinational company based in Switzerland and Sweden, specifically in Zuric and Västerås. Specialized in energy technologies, automation, and robotics, it holds a leading global position in industrial robot manufacturing. Its solutions are used in various sectors such as automotive, electronics, metallurgy, and energy. [8]

3.2 Yaskawa:

Yaskawa is a Japanese company specializing in the design and manufacture of servo drives, motion controllers, motors, and industrial robots. Its flagship robot, **Motoman**, is widely used around the world in applications such as welding, handling, assembly, and painting. [9]

Figures 9:Yakawa Motoman Robot

3.3 Epson Robots:

Epson Robots, a subsidiary of the **Seiko Epson** group, is also based in Japan. It designs and manufactures Cartesian, SCARA, and 6-axis industrial robots, offering efficient and precise automation solutions for manufacturing industries. [10]

Figures 10:Epson Robot

3.4 FANUC:

FANUC, located in Japan, is considered the world's largest manufacturer of industrial robots. The company provides a wide range of products related to robotics and computer numerical control (CNC) systems. FANUC robots are commonly used in the aerospace, automotive, electronics, and logistics sectors. [11]

Figures 11:FANUC Authorized Integrator

3.5 KUKA:

KUKA is a German company specialized in the manufacturing of industrial robots and automation systems. Its robots are widely used in the automotive, plastics, metallurgy, and electronics industries. KUKA is distinguished by its innovations in collaborative robots and mobile robotics. [12]

Figures 12:KUKA Robots

3.6 Stäubli:

Stäubli, a Swiss mechatronics company, specializes in textile machinery, connectors, and industrial robotics. It produces and markets a wide range of **SCARA**, **4-axis**, and **6-axis** robots, contributing to the automation of many industrial processes. [13]

Figures 13:Robots industriels Stäubli Machines

4 Impact of Automation on Production Efficiency:

Technologies such as **A**rtificial Intelligence (AI), Computer Vision, the Internet of Things (IoT), and Edge Computing enhance the capabilities of automated systems. For example, in an electronics factory, robotic arms equipped with vision systems can precisely assemble tiny components, while AI-based systems inspect the quality of each step in real time. IoT sensors monitor environmental parameters such as temperature and vibrations, and edge computing allows the system to react instantly to anomalies. This technological synergy results in faster, more reliable, and more flexible manufacturing processes. [14]

5 Future Perspectives in Industrial Robotics:

- **Soft Robotics:** Inspired by biology, it uses flexible materials to create robots capable of delicate and complex movements. This approach could revolutionize fields such as minimally invasive surgery and precision agriculture.
- **Advanced Artificial Intelligence**: Will enable robots to learn, reason, and adapt autonomously to changing work environments.
- **Cyber-Physical Interconnectivity:** The deeper integration of robots with IoT will allow seamless synchronization between the physical and digital components of smart manufacturing. [15]

6 Conclusion:

In this chapter, we discussed the history of robots and their evolution over time, the most important current robot manufacturers, and future trends, especially in industrial robots, which are related to the project's topic. In the next chapter, we will explain all the components used in the project, both electronic and mechanical.

Chapter Two

System Architecture and Hardware Components

Chapter Two: System Architecture and Hardware Components

1 Introduction:

This chapter reviews the overall design and functional architecture of the prototype developed. The project relies on the integration of several subsystems, including the central processing unit, computer vision system, and motion control systems. This study aims to clarify the technical specifications of each selected component, explaining how these components interact to ensure the system performs its tasks with high efficiency in an industrial environment.

2 Description:

Robotic arms are devices that have been designed to do a given activity or job swiftly, correctly, and effectively. They're usually motor-driven consisting of a collection of joints, articulations, and manipulators, and are employed to accomplish heavy and/or repetitive processes quickly and consistently. They are particularly valuable in the industries of industrial production, manufacturing, machining, and assembly.

In addition to their fundamental design, current robotic arms including the one designed in this project incorporate sophisticated embedded systems and actuators to reach high degrees of freedom (DoF). Servo motors (e.g., MG90s and MG996R) control the mechanical movement with the required torque and exact angular positioning with Pulse Width Modulation (PWM) signals. The controllers may be specific such as the PCA9685 to control numerous axes at once to provide smooth and coherent movement. Moreover, with the application of AI vision systems and environmental sensors, these arms can go beyond the routine work and engage in intelligent interactions with the environment, make independent changes to it, and more complicated tasks, like sample gathering or other delicate work in dangerous areas.

3 Electronics Part:

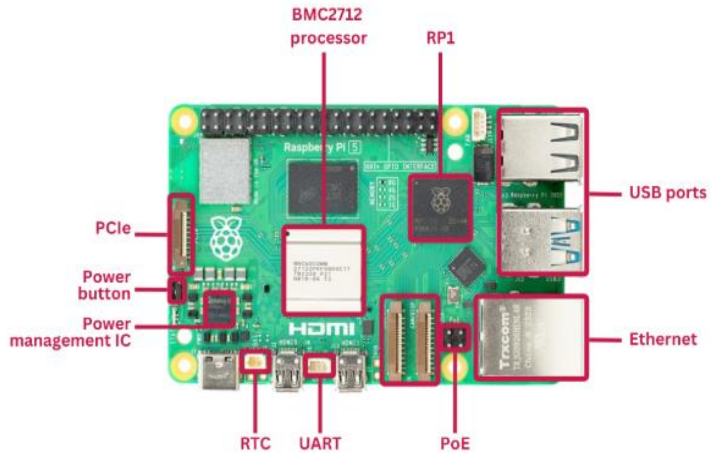
This part is devoted to electronic structure of the robotic arm as to the nervous system of the project. The major goal is to unite different hardware elements so that they should be controlled with high precision and process the data in real time. The heart of this system is the Raspberry Pi 5, which is the primary microcontroller to control the high-level tasks and AI algorithms. Also, this section describes the necessary peripherals such as environmental perception sensors, power control modules, and specialized drivers necessary to connect the processing unit with the mechanical actuators**.**

3.1 Main Controller:

3.1.1 Raspberry Pi:

It is a single-board nano computer that contains an ARM processor created by **Pr Eben Upton** and his team in the research laboratories of the University of Cambridge. It includes an ARM processor, GPU, RAM, and other ports such as HDMI, RG45 (not in all models), and even pins to which other components can be attached, such as a camera, sensors, etc. Raspberry Pi uses the SOC or System on

Chip model, meaning that all the above components are located on a single board. This nano computer supports operating systems based on Debian Linux and is even compatible with Windows OS. [16]



Figures 14:Raspberry Pi 5 Board

3.1.2 Key Technical Characteristics of Raspberry Pi 5:

- Processor (CPU): 2.4GHz quad-core 64-bit Arm Cortex-A76 CPU, which provides 2-3x the performance of the Raspberry Pi 4
- Graphics (GPU): 800MHz VideoCore VII GPU, supporting dual 4K display output and advanced graphical processing.
- Memory (RAM): Available in 4GB and 8GB LPDDR4X-4267 SDRAM options
- I/O Controller: Features the "RP1" southbridge, designed in-house to provide faster and more flexible peripheral communication (USB, GPIO, Ethernet).
- Connectivity: Dual-band 802.11ac Wi-Fi and Bluetooth 5.0 / BLE, 2 × USB 3.0 ports (supporting simultaneous 5Gbps operation), PCIe 2.0 interface (allowing for high-speed NVMe SSD connection).
- Power Management: Dedicated power button and support for 5V/5A DC power via USB-C.

3.1.3 Principle of Operation (How it works in our project):

The Raspberry Pi 5 executes high-level logic and control algorithms written in Python. Its operation follows a continuous loop cycle:

- Data Acquisition: It receives visual data from the AI Camera and environmental signals from the LDR sensor via its GPIO pins or specialized interfaces (CSI/I2C).
- Processing & Decision Making: Using its high-speed CPU, it processes AI models for object detection or gesture recognition. It calculates the coordinates for the robotic arm's movement.
- Command Execution: It sends control signals (via the I2C protocol) to the PCA9685 PWM Driver, which then translates these digital commands into precise electrical pulses to move the MG90/MG996R servo motors.
- Feedback Loop: It monitors the system status and power levels from the battery to ensure safe and stable operation.

3.2 Vision Module:

3.2.1 AI Camera:

The Raspberry Pi AI Camera is a compact camera module from Raspberry Pi, based on the Sony IMX500 Intelligent Vision Sensor. IMX500 combines a 12-megapixel CMOS image sensor with on-board inferencing acceleration for a variety of common neural network models, enabling users to develop sophisticated vision-based AI applications without the need for a separate accelerator.

The AI Camera transparently augments captured still images or video with tensor metadata, leaving the processor in the host Raspberry Pi free to perform other operations. Support for tensor metadata in the libcamera and Picamera2 libraries, and in the rpicam apps application suite, make it easy for beginners to use, while offering advanced users unparallelled power and flexibility. [17]

The Raspberry Pi AI Camera is compatible with all Raspberry Pi computers**:**

Sensor	→	**Sony IMX500**
Resolution	→	12.3 megapixels
Horizontal/vertical	→	4056 × 3040 pixels
Autofocus system	→	Manual adjustable focus
Cable connector	→	15 × 1 mm FPC or 22 × 0.5 mm FPC
Output	→	Image (Bayer RAW10), ISP output (YUV/RGB), ROI, Metadata.
Memory size	→	8388480 bytes for firmware, network weight file, and working memory.
Dimensions	→	25 × 24 × 11.9 mm.

This system is mainly aimed at the Real-time Automated Optical Inspection (AOI) of the AI Camera. Using the Computer Vision algorithms, the camera serves as the sensory input to Raspberry Pi 5 to recognise and detect the defect in electronic components, including Arduino boards. It is used to scan through the circuit board layout and identify its flaws, soldering, or missing parts, or short circuits. This rather enables the robotic arm to have high-precision quality control, which is traditionally prone to human error, and automate the fault detection process.

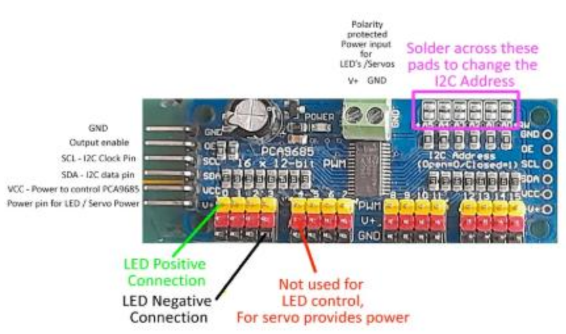
Figures 15:AI Camera Raspberry pi

3.3 PWM Driver:

3.3.1 ThePCA9685:

Is an I2C-bus controlled 16-channel LED controller optimized for Red/Green/Blue/Amber (RGBA) colour backlighting applications. Each LED output has its own 12-bit resolution (4096 steps) fixed frequency individual PWM controller that operates at a programmable frequency from a typical of 24 Hz to 1526 Hz with a duty cycle that is adjustable from 0 % to 100 % to allow the LED to be set to a specific brightness value. All outputs are set to the same PWM frequency. [18]

Each LED output can be off or on (no PWM control) or set at its individual PWM controller value. The LED output driver is programmed to be either open drain with a 25-mA current sink capability at 5 V or totem pole with a 25-mA sink, 10 mA source capability at 5 V. The PCA9685 operates with a supply voltage range of 2.3 V to 5.5 V, and the inputs and outputs are 5.5 V tolerant. LEDs can be directly connected to the LED output (up to 25 mA, 5.5 V) or controlled with external drivers and a minimum number of discrete components for larger current or higher voltage LEDs.

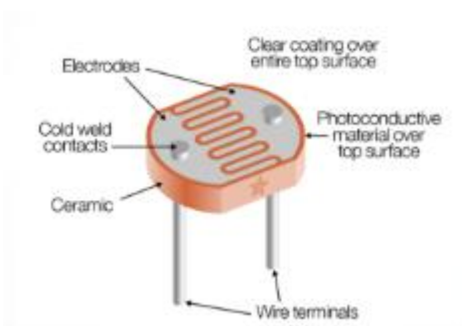


Figures 16:PCA9685 Servo DRIVER

3.4 Sensors:

3.4.1 LDR Sensor:

A Light Dependent Resistor (LDR) is a type of passive electronic sensor used to detect light. It's made up of two conductors separated by an insulator which becomes more conducting when exposed to high levels of light intensity, forming a variable resistor in the circuit. This allows it to measure the amount and brightness or darkness within its environment and provide information accordingly. In this system, the LDR sensor acts as a presence detection mechanism to synchronize the movement of the conveyor belt with the inspection process. Its primary role is to detect the arrival of an electronic board at the designated inspection station. [19]



Figures 17:LDR Sensor

3.5 POWER:

3.5.1 BATTRIE: The battery designation:

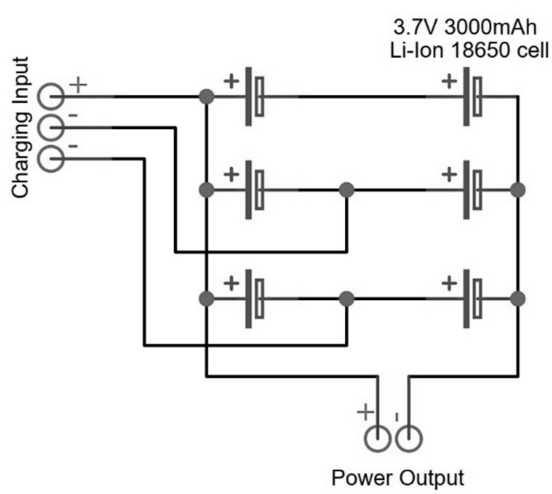
A battery pack is a complete energy storage unit made by combining multiple battery cells together. Unlike a single battery cell, a battery pack is designed to deliver usable voltage, capacity, power, and safety for real-world applications. [20]

Figures 18:2S3P Lithium-Ion Battery

- **2S3P battery configuration:**

S (Series): This means connecting the positive terminal of one cell to the negative terminal of the next cell. This connection increases the total voltage of the pack while maintaining the same capacity (ampere-hours, Ah) per cell. In the case of 2S, 2 cells are connected in series. For lithium-ion cells with a nominal voltage of approximately 3.7 volts, the total nominal voltage of the pack is: or depending on the specific chemistry of the cell.

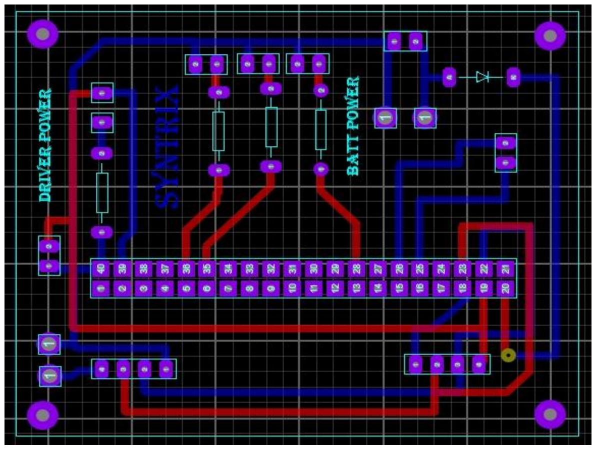
P (Parallel): This means connecting the positive terminals together and the negative terminals together. This increases the total capacity of the pack (mAh or Ah) while maintaining the same voltage of the series-connected group. In the case of 3P, three identical series are connected in parallel, doubling the total capacity of the pack compared to the capacity of a single series.



Figures 19:Lithium-ion battery pack

3.6 PCB:

A printed circuit board (PCB) is a mechanical base used to hold and connect the components of an electric circuit. PCBs are used in nearly all modern consumer electronic devices and accessories, including phones, tablets, smartwatches, wireless chargers, and power supply These multi-material, multilayer boards form the stable foundation of a PCB assembly (PCBA) and are responsible for directing current flow between both active and passive components. The base layer of a PCB is typically made from a combination of strong, nonconductive materials that provides insulation, water resistance, and temperature stability. Common PCB materials include FR4, metals, and polyimide (PI). Cost savings, functional performance (such as thermal expansion), and eco-friendliness are all factors for consideration when choosing materials for a PCB. [21]



Figures 20:PCD Design

The main integration point in the system is a custom-designed PCB (Printed Circuit Board), which is where the Raspberry Pi 5, the LDR sensor, and the PCA9685 motor driver are mounted. The main functions of this PCB include the way of organized connectivity and supply of strong power network. To protect the delicate electronics, the board contains a protection capacitor to add/subtract any transient voltage and smooth out the power supply when the motors require high current. It also includes a flyback diode to provide a protective mechanism against inductive back-EMF (electromotive force) produced by the motors to stop reverse current shorting the Raspberry Pi GPIO pins or the driver. This combined strategy reduces electromagnetic interference (EMI) and guarantees the durability of the control system of the robotic arm in the long run.

3.7 LCD:

An LCD display is a flat panel display technology that has become one of the most widely used screen technologies today. It functions by using liquid crystals, which are substances that can change their optical properties when subjected to an electric current. These crystals are sandwiched between two layers of polarized glass or plastic. LCD displays do not emit light by themselves; instead, they rely on a backlight (typically LED) to illuminate the crystals, which control how light passes through them to form images. The LCD screen in this project is used as an interface to display the board's status either Good or Bad. [22]

Figures 21:I2C LCD Display

3.8 LED:

A light-emitting diode (LED) is a small electronic device that emits light when an electric current flows through it. LED works by passing electricity through a semiconductor, which releases energy in the form of light. This process makes an LED highly efficient, durable, and versatile.

In this project, there are two types of LED lights: one glows green when everything is normal, and the other glows red when there is a problem. [23]

Figures 22:LEDs Indicators

4 Mechanical Part:

The mechanical subsystem of the proposed modular AI-based robotic inspection and sorting system consists of three main units:

- A robotic arm with several degrees of freedom
- Two conveyor units.
- A structural base platform that includes control electronic

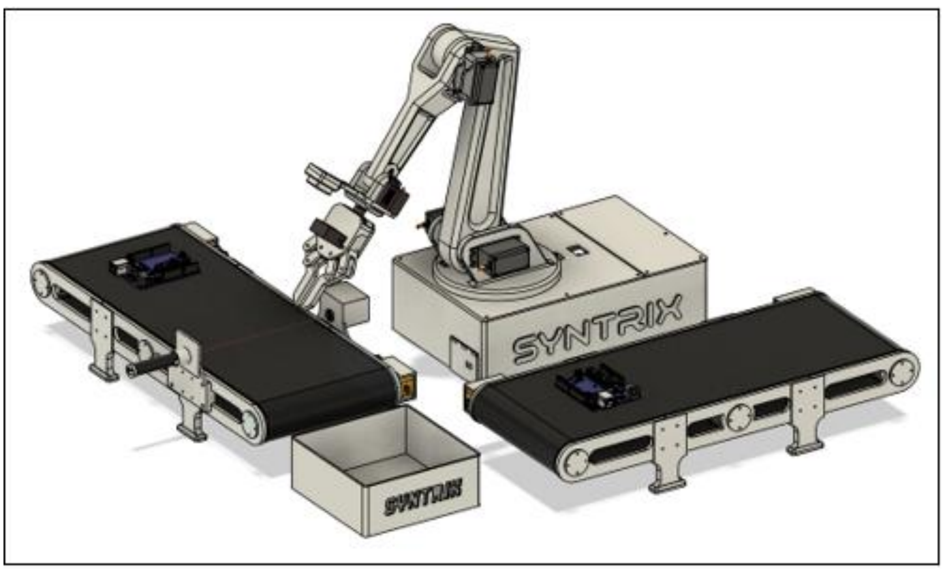
The system is designed to simulate an industrial production line environment where products are transported, inspected, and sorted automatically.

Mechanical architecture follows a modular and scalable principle. A robotic arm is provided, which is centrally fixed at one end on a rigid base enclosure, covering the embedded system, which includes Raspberry Pi5, the power management system, and the control system. On both sides of the robotic system, two conveyor belts are provided:

- The first conveyor carries the products (e.g., the PCB boards) to the inspection area.
- The second conveyor moves the validated products forward after the inspection

Near the robotic arm, a rejection box is placed for collecting the faulty products that are removed from the manufacturing process.

The entire mechanical construction is implemented using PLA components that are 3D printed, as well as metallic parts to provide sufficient rigidity, light weight, and even ease of prototyping.



Figures 23:Mechanical Design Implementation

4.1 Design Software:

The complete mechanical design has been carried out by utilizing Autodesk Fusion 360, which is a professional CAD/CAM/CAE design tool.

In addition, Autodesk Fusion 360 was employed for the design and development of the mechanical structure of the system. Autodesk Fusion 360 is an efficient computer-aided design tool for designing, developing, and modeling complex mechanical systems and structures, and it primarily incorporates 3D modeling, assembly simulation, and mechanical validation. With the tool, precise and accurate parametric modeling of the robotic arm and various parts of the system was made possible, which

Fusion 360

Figures 24:3D Design Software

assisted in the efficient development of the system.

The software, Autodesk Fusion 360, was chosen because:

- Parametric Design Capability
- Assembly simulation tools
- Joint and motion simulation
- While joint simulation
- Stress Visualization Tools

4.1.1 Assembly Simulation and Mechanical Validation:

The assembly of the robotic arm was simulated using Autodesk Fusion 360 software, where the motions of rotation of the base, rotation of the shoulder, rotation of the elbow, rotation of the wrist, and gripper movement were created using revolute joints.

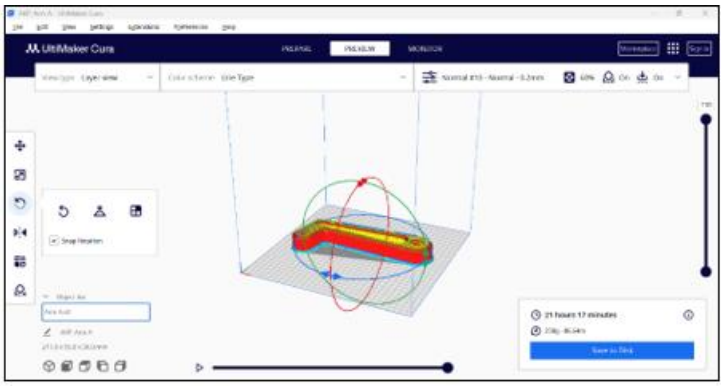
To further validate the mechanical aspects of the system, a mechanical validation process employed motion analysis and detection of collisions to check the reachable workspace, the distance between the arm and the conveyors, and positioning above the inspection area. This validation process ensured that the range of motion is appropriate and checked errors before fabrication.

Figures 25:Fusion 360 Animation assemble bar

4.2 3D Printing Software (Ultimaker Cura):

Ultimaker Cura is an open-source computer program used to prepare 3D designs for printing using a 3D printing machine. The program was used to prepare the 3D designs of the robotic arm and conveyor belt components created using computer-aided designs in the Autodesk Fusion 360 program. The program prepares the 3D designs for printing by converting them into machine-readable toolpaths.

Cura offers a wide range of settings related to printing, including layer height, fill density, printing speed, and temperature settings. Moreover, it allows the generation of supports, which were used in optimizing the mechanical properties, precision, and quality of the printed object. In addition, Cura offers simulation tools related to printing, enabling the identification of various printing flaws. This was also made easier using Ultimaker Cura software, which contributed to the achievement of consistent and reliable fabrication of the constituent parts of the robotic arm using the PLA material. [24]



Figures 26:Ultimaker Cura Slicer

4.3 3D Printing Setup:

The mechanical components of the system were produced utilizing 3D printing technology to turn the digital concept into a tangible prototype. Rapid prototype, design validation, and economical production were made possible by the components' Fusion 360 design and subsequent 3D printing. This method reduced development time and allowed for the very accurate fabrication of customized parts.

Figures 27:3D printer Setup

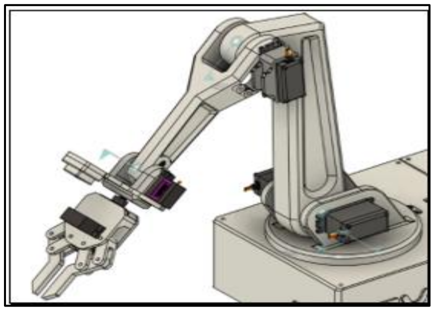
4.4 Robotic Arm Technical Details:

4.4.1 Degrees of Freedom (DOF):

To execute this task programmatically, the robotic arm can move in six different directions; such freedom of direction is necessary for a three-dimensional movement. The base can turn the arm horizontally, while the shoulder controls the upward and downward movements, and the extension of the arm is done by the elbow.

This configuration permits:

- Accurate vertical and horizontal positioning.
- Orientation control of handled objects Precise and Stable Product Placement.

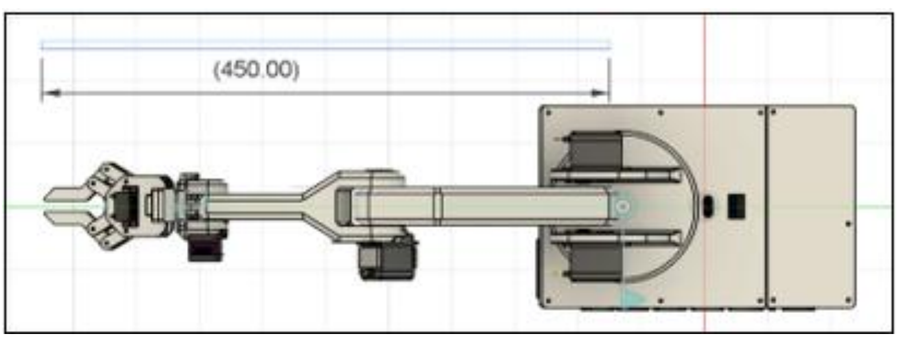


Figures 28:Robot Degree of freedom

Conveyors as well as the reject container. In addition, the clearance height was optimized to be able to deal with the PCBs safely.

Principal structural characteristics of the workspace:

- Movement diameter of about 45 cm for inspection and sorting zones.
- Compact mechanical construction is appropriate for installation alongside the conveyor.
- Approximate total mechanical weight is about 1.6 kg (without electronics).
- A low center of gravity for improved stability.
- Less vibration under dynamic conditions.



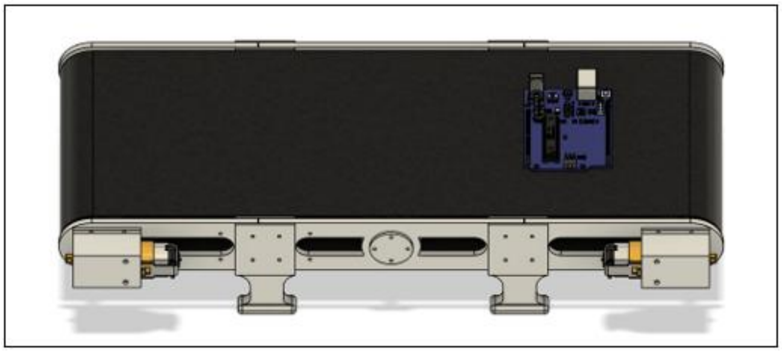
Figures 29:Robotic Arm Dimensions

4.5 Conveyor System Details:

4.5.1 Inspection Conveyor:

The role played by the inspection conveyor is to move the product from the production line to the actual point of quality inspection. The main role played by this machine is to position the PCB board properly to enable the correct reading by the artificial intelligent camera. The machine is controlled using a DC controlled motor with the ability to change its speed.

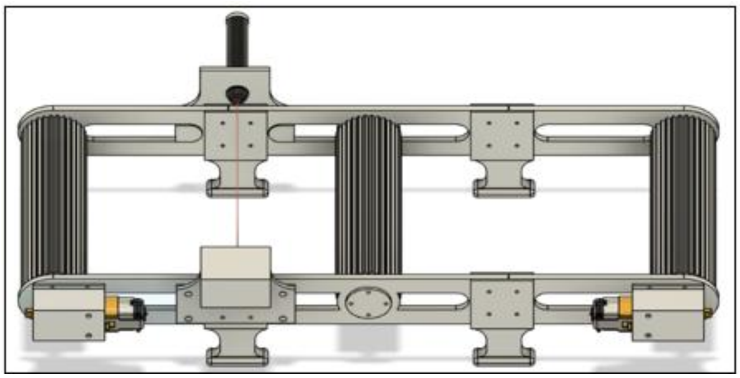
When a defective product is detected, the robotic arm intercepts and removes it before it reaches the output conveyor, ensuring proper separation between accepted and rejected products.



Figures 30:Conveyor Desing Implementation

Main characteristics:

- Controlled DC Motor for Speed Regulation.
- Flat and stable belt surface for product stability.
- Stop-and-scan positioning for precise inspection Automated Restart After Inspect Decision.



Figures 31:Automatic Conveyor Gears

4.6 Mechanical Actuation Components:

The mechanical movement of the system is done by:

a. MG996S Servo Motors:

The MG996R servo motors are utilized for the primary load-carrying joint locations of the robotic arm, which include base rotation, shoulder joint movement, elbow joint movement, and main wrist joint locations. The operating voltage of these motors' ranges from 4.8 V to 7.2 V and is made of metal gears to deliver high torque and high strength, required to perform the task of supporting the structure of the robotic arm. [25]

Figures 32:MG996R Servo Motor

b. MG90S Micro Servo Motors:

The MG90 micro servo motors used in the robotic arm include those used in the wrist orientation mechanisms as well as those used in the grippers. The reason these micro servo motors have been selected is due to their light weight, small size, and quick response time, which is appropriate for precision mechanisms. [26]

Figures 33:MG90S Servo Motor

c. DC motor:

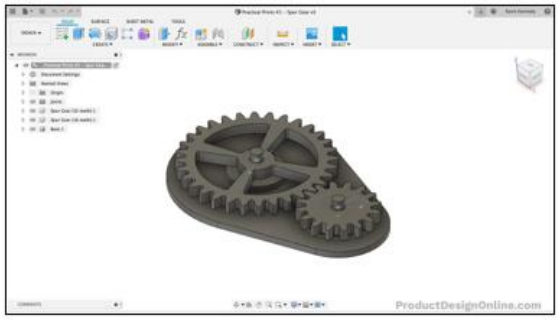
Two DC motors are involved in driving conveyor belts for product transportation. The first motor is assigned to the inspection conveyor for the transportation of PCB boards to the scanning station, while the second motor serves to drive the output conveyor that transfers approved products towards further production stages. DC motors were chosen regarding simplicity, capability of continuous rotation, easy speed control, and good compatibility with embedded control systems.

Figures 34:DC Motor

4.7 Mechanical Transmission Elements:

a. Gear Mechanisms:

The gear systems have a similar application in the robotic arm as well as the conveyor systems, where they help in the transmission of rotating motion from the motors to the mechanical structures. The gear systems within the robotic arm consist of gear reduction systems within the servo motors used for the robotic arms, where the high-speed motion of the motors is transmitted at a lower speed with a higher amount of torque. The rotating gear systems within the conveyor systems are helpful in the smooth and stable operation of the conveyor belt systems. [27]



Figures 35:Gears Mechanism

d. Bearings:

Bearings also have the role of reducing friction in the rotating joints and supporting the rollers used in conveyor systems. The role of the bearings in the robotic arm system is to ensure the smooth rotation of the joints, thus enhancing the stability of the mechanical components in the system. The robotic arm comprises connections that ensure smooth rotation, thus the role of the bearings in the system. The use of the robotic system also reduces the level of friction in the

Figures 36:608 Bearing

5 Conclusion:

This chapter covers all the electronic and mechanical components integrated into the project. What makes our robotic arm truly unique is the design process we followed from the very beginning, from the structural frame to the carrier, all designed and modeled using Fusion 360. We also explain the role of each component, whether electronic or mechanical. In the following chapter, we will discuss how the system operates and presents its final configuration.

Chapter Three

Building and testing the Industrial Robot

Chapter Three: Building and Testing the Industrial Robot

1 Industrial Robot System Description:

This section gives a summary of our automated inspection system; it starts with an elaborate start up process where Raspberry Pi 5 assumes control of the whole environment. Immediately the script is run, the system conducts a diagnostic test, which positions the robotic arm at its predefined home point using the PCA9685 servo driver and orienting the Sony AI Camera to receive an image. The LCD screen is displayed at this first stage with both the Green and Red LEDs off and this means that the system is on standby and ready to receive the first incoming unit.

After the setup is done, the process proceeds to the active detection phase where DC motors propel the primary conveyor belt. An Arduino board is set to move through the belt and in the process, it reaches the inspection station whereby an LDR sensor is located strategically. When the board is inserted and blocks the source of light, the LDR transmits a signal to the Raspberry Pi, which commands the conveyor to come to a halt instantly. Such synchronization is important because it makes the board completely still, eliminating any possible motion blur that might compromise the accuracy of the next AI scan. The vision system takes over with the board locked in position. The Sony AI Camera takes a high- resolution image of the board surface and the image is analyzed using after training camera with the help of the Brain Builder Model This is the smart side of the project, where the camera analyzes the board on whether there are manufacturing flaws or omissions. The

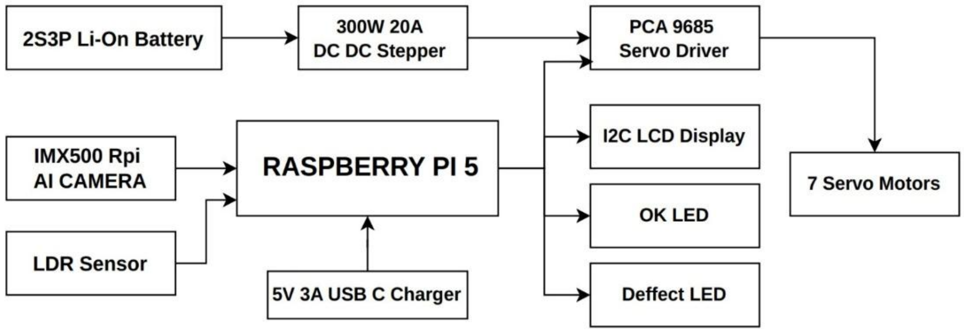
outcome of this analysis determines the subsequent physical action of the robot. When the board is recognized as 'Good', the system will give immediate feedback and turn on the Green LED and show a success message on the LCD. At the same time, the robotic arm is performing a pick-and-place motion, sliding the board off the inspection belt onto the Accepted conveyor.

However, when the AI model identifies an anomaly, the sorting logic and the safety of the system are activated. The Red LED will be illuminated, and a defect warning will be displayed on the LCD to warn the operator. Merely drives the board forward along the conveyor towards a box where it can be examined manually.

When the process of sorting the current board has been completed, the robotic arm will automatically go back to its home location, and the sensors will be reset, and the conveyor belt will restart to the next Arduino board into the station. The resulting loop guarantees that the workflow is entirely autonomous, with hardware modules and AI algorithms coexisting in perfect harmony to keep the production standards on a high level.

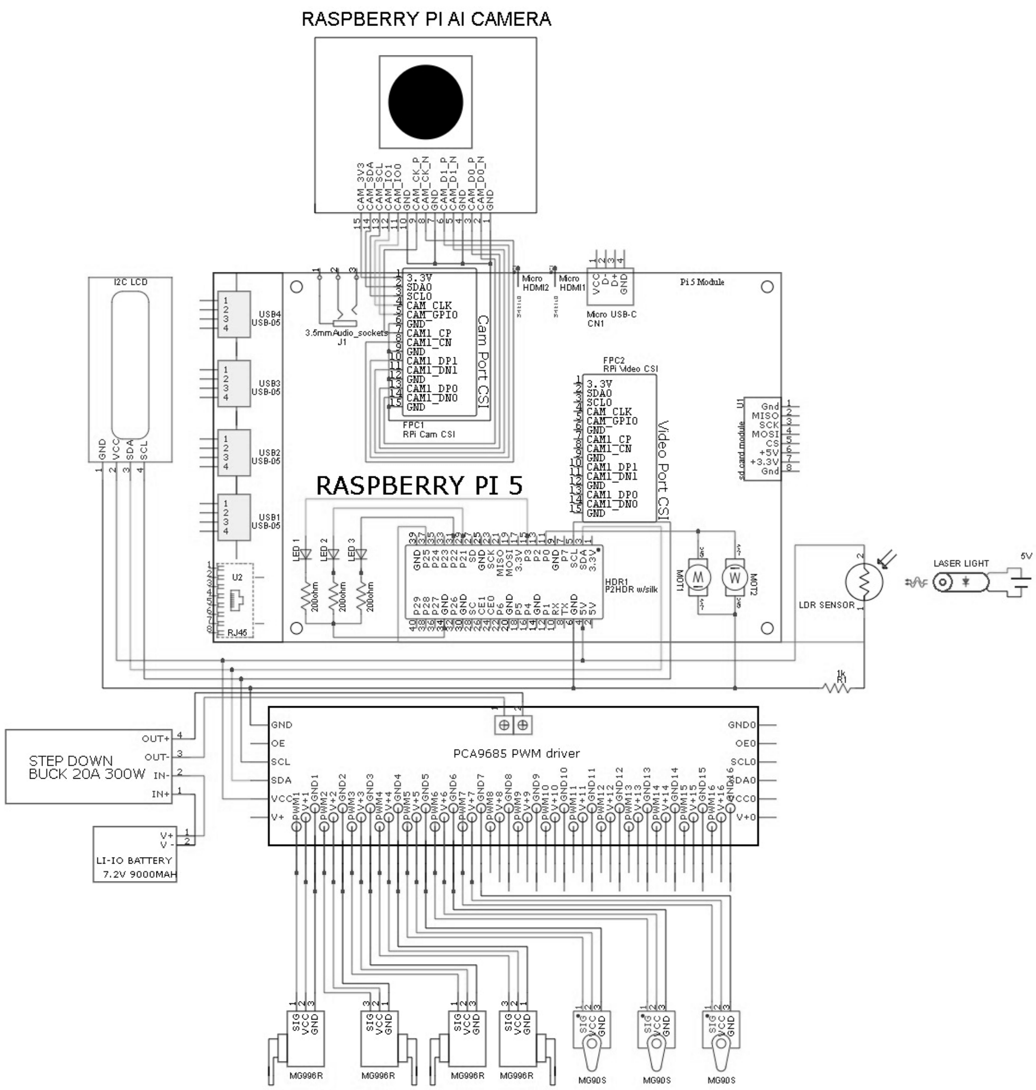
2 Control Logic:

2.1 Main System Diagram:



Figures 37:Main System Diagram

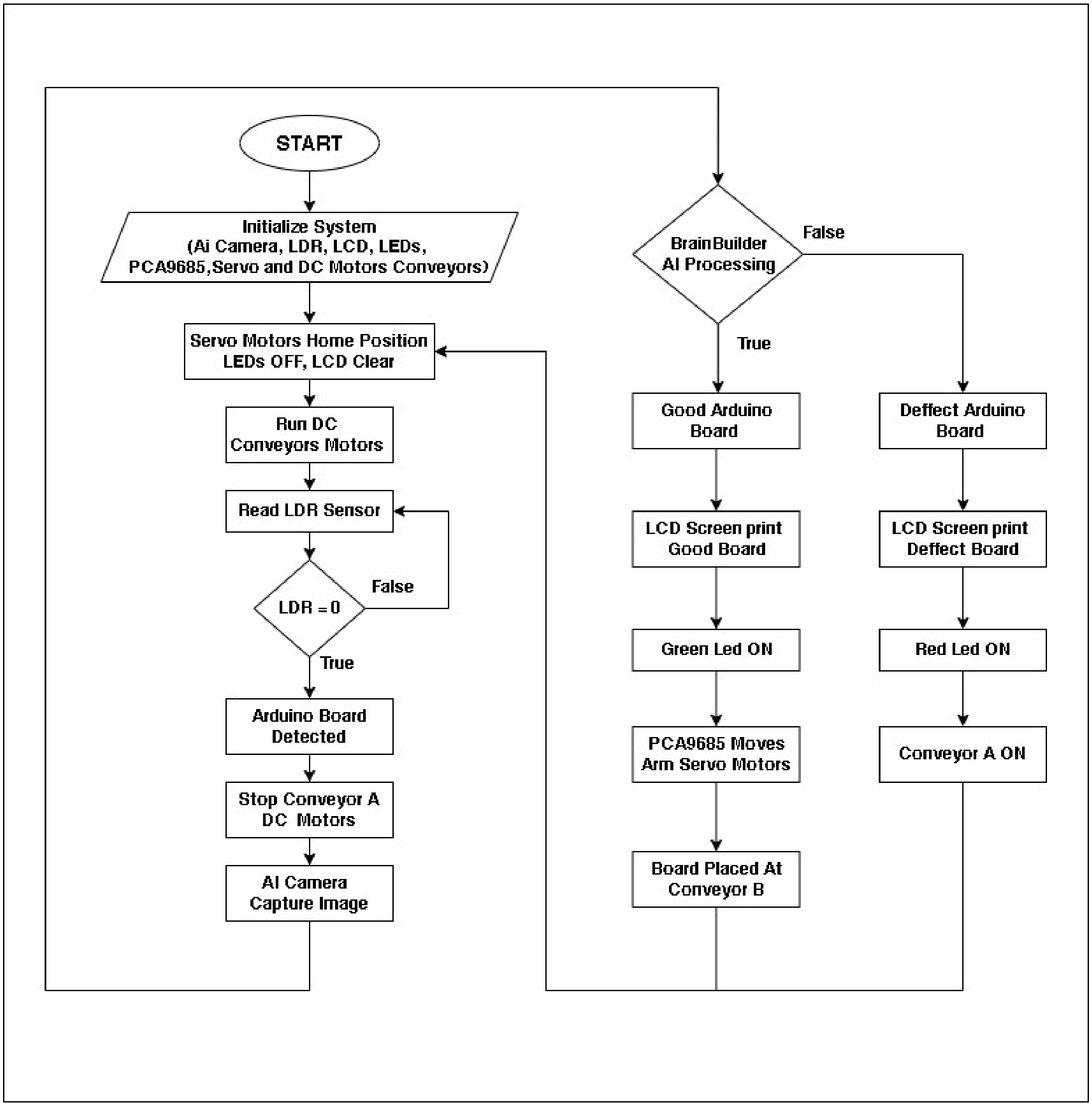
2.2 Main System Schema:



Figures 38:Main System schematic

2.3 Main System Algorithm:

In this subsection, Figure 3 introduces the flowchart of the whole system control of our project



Figures 39:Main system Algorithm

3 Hardware Assembly:

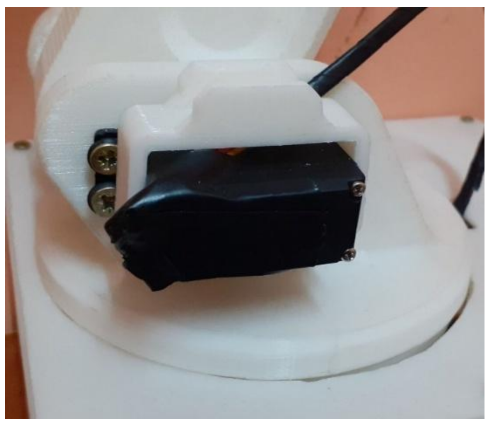
Hardware assembly process is done by combining the mechanical frame of the robotic arm and the electronic control system. This step is to make sure that everything is firmly fixed and that the electric cables will enable communication and distribution of power safely.

3.1 Mechanical Structure and Joint Assembly:

The robotic arm is designed as a multiaxis manipulator with 3 degrees of freedom (3-DOF), allowing it to reach any point within its workspace to pick and sort Arduino boards. The assembly process focused on ensuring structural rigidity and smooth angular movement.

3.2 Base and Waist (Rotation):

The base is a rotating base that is driven by MG996R servo motor and two MG90 servo This joint gives the horizontal scanning movement, which enables the arm to swing between the conveyor belt and the sorting areas (Success/Reject).



Figures 40:Robotic Arm Base

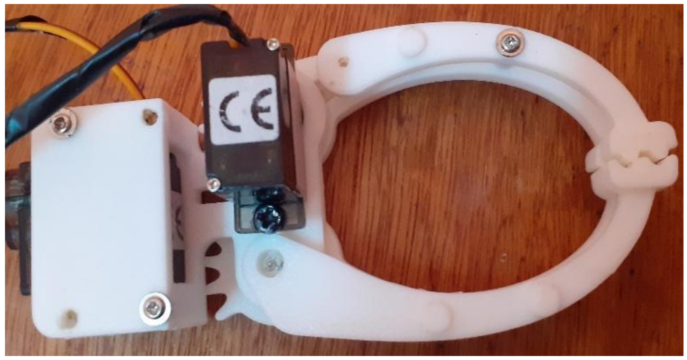
3.3 Shoulder and Elbow:

The shoulder and elbow joints are responsible for controlling the primary lifting force. Since significant torque is required to overcome the force of the mass of the payload, MG996R high-torque servos were employed at these joints. The links connecting these joints are lightweight yet strong, reducing inertia while maintaining the structural integrity needed to perform repetitive sorting tasks.

Figures 41:Robotic Arm Shoulder and Elbow

3.4 Wrist and End-Effector (Gripper):

The last joint is the wrist, which operates the gripper. To minimize the weight at the end of the arm, two MG90S micro servo were chosen for this part. The gripper has a special jaw geometry to firmly hold the Arduino boards without damaging the fragile electronic components attached to their surface.



Figures 42:Robotic Arm Gripper

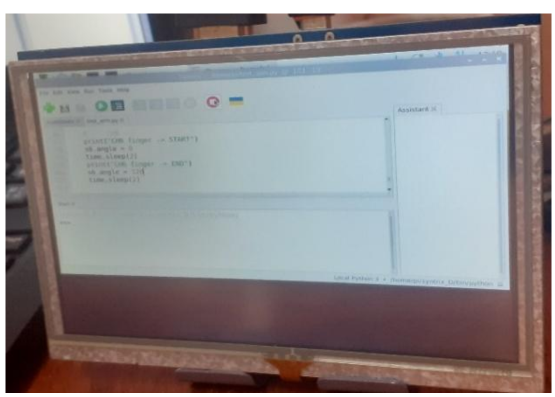
3.5 Control Unit and Custom PCB Integration:

The control unit, which serves as the main intelligence of the system, represents the hardware and software intersection that implements the sorting logic. The Raspberry Pi 5 is the core component of this unit and handles high-level functions, including AI-based image processing and decision-making.

3.6 System Access and Configuration Methods:

The first way is Direct Interface. Here, we use the compact HDMI screen (as seen in Figure) connected directly to the Pi. By adding a mouse and keyboard, the robot basically becomes its own computer. This method to be the most reliable during the first stages of the project, especially for things like calibrating the LDR sensor and debugging the OpenCV code on the spot. It's the best choice when we need to see exactly what the AI camera sees without any lag or network issues.

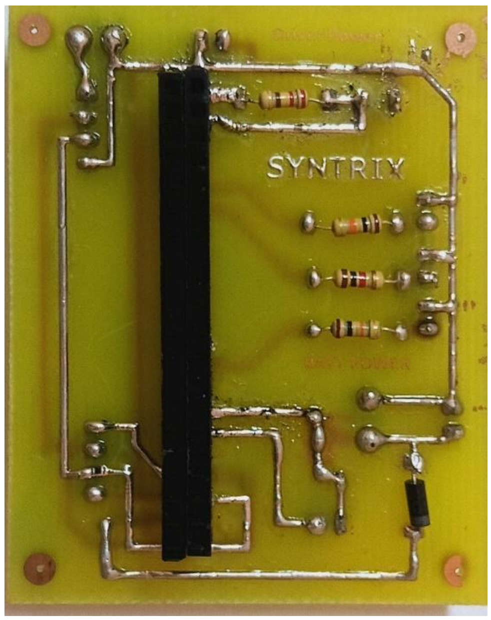
The second way is the Remote Interface, which is more practical for an industrial setup. Instead of using a physical screen, we use SSH and VNC to connect to the Pi from our laptop over Wi-Fi. SSH allows us to run commands quickly, while VNC gives us a full view of the Pi's desktop on our own PC screen. This 'Headless' approach is much cleaner because it removes all the extra cables and monitors from the robot’s base. It allows us to monitor the Anomaly Detection results and control the arm wirelessly.



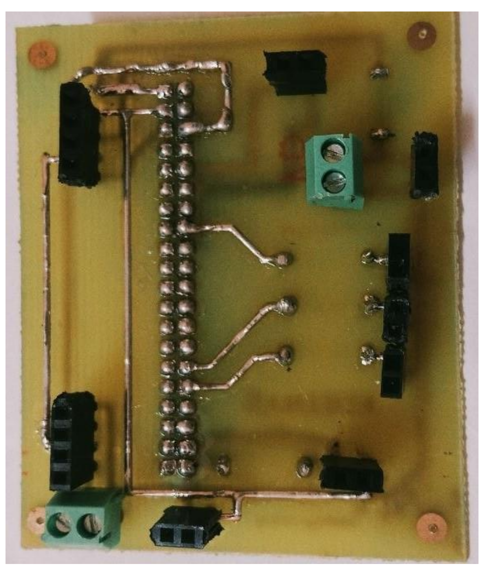
Figures 43:Raspberry Pi's Screen

3.7 PCB:

To ensure system stability, a PCB custom was designed to act as the central hardware interface. The board uses a 40-pin header to connect the Raspberry Pi 5, and a dedicated mount for the PCA9685 PWM driver to eliminate loose wiring. Its primary engineering function is to manage dual power architecture: it isolates the high-current battery power required by the four servo motors from the regulated logic power required by the processor. This isolation is critical to prevent electrical noise, and voltage drops during servo actuation. To protect the hardware, the board incorporates diodes to guard against reverse polarity damage, and capacitors to suppress abrupt voltage spikes. By integrating power distribution, motor control, and protection circuitry into a single PCB, a compact yet robust, industrial-quality assembly was achieved small enough to fit within the base of the robot.



Figures 45:PCB Top Face



Figures 44:PCB Bottom Face

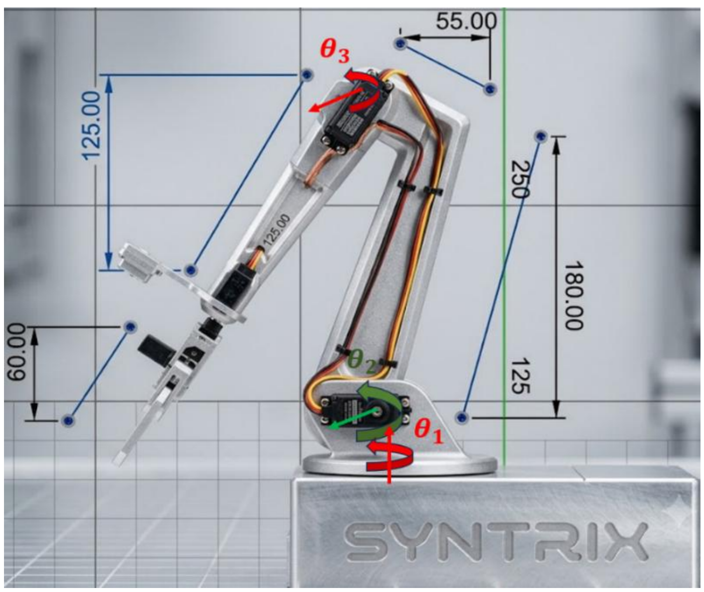
4 Sensory System: Image Acquisition and Object Detection.

For high level of accuracy in the inspection process, we adopted a synchronized sensory system that incorporates digital trigger and sophisticated AI vision sensor.

- **RPi5 AI Camera (Sony IMX500):** The Sony AI Camera is the center of our vision system, it is not in fact an imaging sensor, rather an Edge-AI processing unit, so we built this camera because it has an on-board hardware accelerator that can directly run the BrainBuilder models on it, and at high speed, and without latency, which is important because it means the main system does not need to do a lot of computation to tell us that a defect has been detected.
- **The LDR Trigger:** the LDR sensor is the 'Mechanical Trigger' of the system, we mounted the LDR opposite a light source to detect the physical presence of an Arduino board, which, in technical terms, prevents the AI model to run in a continuous, redundant loop.

4.1 Kinematic Modeling of the Robotic Arm:

The Syntrix robot is a 3R (RRR) robot,



Figures 46:Robotic Arm kinematic Modeling

4.1.1 Direct Geometric Model

For our anthropomorphic RRR robot, the Direct Geometric Model (DGM) involves determining the position and orientation of the end-effector based on the joint variables:

$$[q = [\theta_1 \quad \theta_2 \quad \theta_3]^T]$$

4.1.2 Définition des repères

On adopte la convention DH suivante :

Articulation	Variable	Paramètres DH
1	(θ_1)	$(\alpha_1 = 0, \alpha_1 = 90°, d_1 = L_1)$
2	(θ_2)	$(\alpha_2 = L_2, \alpha_2 = 0, d_2 = 0)$
3	(θ_3)	$(\alpha_3 = L_3, ; \alpha_3 = 0, ; d_3 = 0)$

With:

- (L_1) : shoulder height
- (L_2) : arm length
- (L_3) : forearm length

2. Elementary homogeneous matrix DH

The standard homogeneous matrix is:

$$A_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- **Calculation of $(A_1 = T_0^1)$**

for: $a_1 = 0, \quad \alpha_1 = 90^\circ, \quad d_1 = L_1$

we get:

$$A_1 = \begin{bmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

With $c_1 = \cos\theta_1, s_1 = \sin\theta_1$

- **Calculation of $\boldsymbol{A_2 = T_1^2}$**

For: $a_2 = L_2, \alpha_2 = 0, d_2 = 0$

$$A_2 = \begin{bmatrix} c_2 & -s_2 & 0 & L_2c_2 \\ s_2 & c_2 & 0 & L_2s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- **Calculation of $\boldsymbol{A_3 = T_2^3}$**

For: $a_3 = L_3, \alpha_3 = 0, d_3 = 0$

$$A_3 = \begin{bmatrix} c_3 & -s_3 & 0 & L_3c_3 \\ s_3 & c_3 & 0 & L_3s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- **Calculation of $\boldsymbol{T_0^2 = A_1A_2}$**

After matrix multiplication:

$$T_0^2 = \begin{bmatrix} c_1c_2 & -c_1s_2 & s_1 & L_2c_1c_2 \\ s_1c_2 & -s_1s_2 & -c_1 & L_2s_1c_2 \\ s_2 & c_2 & 0 & L_1 + L_2s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- **Calculation of $\boldsymbol{T_0^3 = T_0^2 A_3}$**

Let's:

$$c_{23} = \cos(\theta_2 + \theta_3)$$
$$s_{23} = \sin(\theta_2 + \theta_3)$$

After multiple :

$$T_0^3 = \begin{bmatrix} c_1 c_{23} & -c_1 s_{23} & s_1 & c_1(L_2 c_2 + L_3 c_{23}) \\ s_1 c_{23} & -s_1 s_{23} & -c_1 & s_1(L_2 c_2 + L_3 c_{23}) \\ s_{23} & c_{23} & 0 & L_1 + L_2 s_2 + L_3 s_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This matrix is **the full MGD**.

Position extraction

The last column of T_0^3 gives the position of the effector:

$$P = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

With

$$x = c_1(L_2 c_2 + L_3 c_{23})$$
$$y = s_1(L_2 c_2 + L_3 c_{23})$$
$$z = L_1 + L_2 s_2 + L_3 s_{23}$$

- **Orientation extraction**

The rotation matrix is:

$$R_0^3 = \begin{bmatrix} c_1 c_{23} & -c_1 s_{23} & s_1 \\ s_1 c_{23} & -s_1 s_{23} & -c_1 \\ s_{23} & c_{23} & 0 \end{bmatrix}$$

Thus:

$$T_0^3 = \begin{bmatrix} R_0^3 & P \\ 0 & 1 \end{bmatrix}$$

- Digital template for our robot

If we take:

$$L_1 = 125\ mm$$
$$L_2 = 180\ mm$$
$$L_3 = 125\ mm$$

so:

$$x = \cos\ \theta_1(180\cos\ \theta_2 + 125\cos(\theta_2 + \theta_3))$$
$$y = \sin\ \theta_1(180\cos\ \theta_2 + 125\cos(\theta_2 + \theta_3))$$
$$z = 125 + 180\sin\ \theta_2 + 125\sin(\theta_2 + \theta_3)$$

3. Geometric Jacobian

Le MGD is:

$$x = c_1(L_2 c_2 + L_3 c_{23})$$
$$y = s_1(L_2 c_2 + L_3 c_{23})$$
$$z = L_1 + L_2 s_2 + L_3 s_{23}$$

With

$$c_{23} = \cos(\theta_2 + \theta_3)$$
$$s_{23} = \sin(\theta_2 + \theta_3)$$

- **Calculation of derivatives**

✓ **First column**

$$\frac{\partial x}{\partial \theta_1} = -s_1(L_2c_2 + L_3c_{23})$$
$$\frac{\partial y}{\partial \theta_1} = c_1(L_2c_2 + L_3c_{23})$$
$$\frac{\partial z}{\partial \theta_1} = 0$$

✓ **Second column**

$$\frac{\partial x}{\partial \theta_2} = -c_1(L_2s_2 + L_3s_{23})$$
$$\frac{\partial y}{\partial \theta_2} = -s_1(L_2s_2 + L_3s_{23})$$
$$\frac{\partial z}{\partial \theta_2} = L_2c_2 + L_3c_{23}$$

✓ **Third column**

$$\frac{\partial x}{\partial \theta_3} = -c_1L_3s_{23}$$
$$\frac{\partial y}{\partial \theta_3} = -s_1L_3s_{23}$$
$$\frac{\partial z}{\partial \theta_3} = L_3c_{23}$$

Final Jacobienne

$$J = \begin{bmatrix} -s_1(L_2c_2 + L_3c_{23}) & -c_1(L_2s_2 + L_3s_{23}) & -c_1L_3s_{23} \\ c_1(L_2c_2 + L_3c_{23}) & -s_1(L_2s_2 + L_3s_{23}) & -s_1L_3s_{23} \\ 0 & L_2c_2 + L_3c_{23} & L_3c_{23} \end{bmatrix}$$

The speed ratio becomes:

$$\dot{X} = J(q)\dot{q}$$

Inverse Geometric Model (IGM)

We are looking for:

$$q = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}$$

Starting at:

$$P = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

- **Step 1: base angle**

$$r = \sqrt{x^2 + y^2}$$
$$\theta_1 = \text{atan2}\,(y, x)$$

- **step 2: projection onto a plan**

$$s = z - L_1$$

- **step 3: Elbow calculation**

Using the low of cosines:

$$D = \frac{r^2 + s^2 - L_2^2 - L_3^2}{2L_2L_3}$$

Two solutions:

$$\theta_3^{(1)} = \text{atan2}\,\left(+\sqrt{1 - D^2}, D\right)$$
$$\theta_3^{(2)} = \text{atan2}\,\left(-\sqrt{1 - D^2}, D\right)$$

- **step 4: shoulder calculation**

For each value of θ_3

$$\theta_2 = \text{atan2}\,(s, r) - \text{atan2}\,(L_3 \sin\,\theta_3, L_2 + L_3 \cos\,\theta_3)$$

4. Dynamic Model

Dynamic model is obtained using the Lagrange method.

- **Generalized coordinates**

$$q = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} \quad \dot{q} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix}$$

- **Centres of gravity**

Let's suppose:

r_1 distance from the arm's center of gravity 1.

r_2 distance from the arm's center of gravity 2.

r_3 distance from the arm's center of gravity 3.

Typically:

$$r_2 = \frac{L_2}{2}$$
$$r_3 = \frac{L_3}{2}$$

- **Positions of the centres of mass**

✓ **Link 2**

$$x_{G2} = c_1(r_2 c_2)$$
$$y_{G2} = s_1(r_2 c_2)$$
$$z_{G2} = L_1 + r_2 s_2$$

✓ **Link 3**

$$x_{G3} = c_1(L_2 c_2 + r_3 c_{23})$$
$$y_{G3} = s_1(L_2 c_2 + r_3 c_{23})$$
$$z_{G3} = L_1 + L_2 s_2 + r_3 s_{23}$$

- **Kinetic energy**

For each arm :

$$T_i = \frac{1}{2} m_i v_i^T v_i + \frac{1}{2} \omega_i^T I_i \omega_i$$

and:

$$T = T_1 + T_2 + T_3$$

- **Potenial energy**

$$V = m_1 g z_{G1} + m_2 g z_{G2} + m_3 g z_{G3}$$

- **Lagrangian**

$$L = T - V$$

- **Lagrange's equations**

For each joint:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = \tau_i$$

- **Final matrix form**

After development:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau$$

where:

$$M(q) = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}$$

Is the inertia matrix.

$$C(q,\dot{q}) = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

Includes the coriolis and centrifugal forces.

$$G(q) = \begin{bmatrix} 0 \\ g_2(q) \\ g_3(q) \end{bmatrix}$$

Is the gravitational vector.
The complete mathematical model includes:

$$\boxed{M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau}$$

With

$$q = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}$$

Jacobiane

$$\dot{X} = J(q)\dot{q}$$

With

$$J = \begin{bmatrix} -s_1(L_2c_2 + L_3c_{23}) & -c_1(L_2s_2 + L_3s_{23}) & -c_1L_3s_{23} \\ c_1(L_2c_2 + L_3c_{23}) & -s_1(L_2s_2 + L_3s_{23}) & -s_1L_3s_{23} \\ 0 & L_2c_2 + L_3c_{23} & L_3c_{23} \end{bmatrix}$$

Potenial energy

The first axis is vertical, so:

$$V = m_2g(r_2\sin\ \theta_2) + m_3g(L_2\sin\ \theta_2 + r_3\sin\ (\theta_2 + \theta_3))$$

or:

$$V = g[(m_2r_2 + m_3L_2)\sin\ \theta_2 + m_3r_3\sin\ (\theta_2 + \theta_3)]$$

Kinetic energy

$$T = \frac{1}{2}\dot{q}^T M(q)\dot{q}$$

where $M(q)$is interia matrix.
Interia Matrix $\boldsymbol{M(q)}$
For an anthropomorphic RRR robot:

$$M(q) = \begin{bmatrix} M_{11} & 0 & 0 \\ 0 & M_{22} & M_{23} \\ 0 & M_{23} & M_{33} \end{bmatrix}$$

With:

$$M_{11} = (m_2r_2^2 + m_3L_2^2)\cos^2\theta_2 + m_3r_3^2\cos^2(\theta_2 + \theta_3) + 2m_3L_2r_3\cos\ \theta_2\cos\ (\theta_2 + \theta_3) + I_{1z}$$

$$M_{22} = I_2 + I_3 + m_2r_2^2 + m_3(L_2^2 + r_3^2 + 2L_2r_3\cos\ \theta_3)$$

$$M_{23} = I_3 + m_3(r_3^2 + L_2r_3\cos\ \theta_3)$$

$$M_{33} = I_3 + m_3r_3^2$$

Coriolis and centrifugal matrix

We define:

$$h = m_3 L_2 r_3 \sin\ \theta_3$$

The Coriolis matrix becomes:

$$C(q,\dot{q}) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -h\dot{\theta}_3 & -h(\dot{\theta}_2 + \dot{\theta}_3) \\ 0 & h\dot{\theta}_2 & 0 \end{bmatrix}$$

The associated vector is:

$$C(q,\dot{q})\dot{q} = \begin{bmatrix} 0 \\ -h(2\dot{\theta}_2\dot{\theta}_3 + \dot{\theta}_3^2) \\ h\dot{\theta}_2^2 \end{bmatrix}$$

Gravitational vector

$$G(q) = \begin{bmatrix} 0 \\ G_2 \\ G_3 \end{bmatrix}$$

With:

$$G_2 = g[(m_2 r_2 + m_3 L_2)\cos\ \theta_2 + m_3 r_3 \cos\,(\theta_2 + \theta_3)]$$

$$G_3 = m_3 g r_3 \cos\,(\theta_2 + \theta_3)$$

- **Full dynamic model**

The robot's equation becomes:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau$$

That is to say:

$$\begin{bmatrix} M_{11} & 0 & 0 \\ 0 & M_{22} & M_{23} \\ 0 & M_{23} & M_{33} \end{bmatrix}\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} + \begin{bmatrix} 0 \\ -h(2\dot{\theta}_2\dot{\theta}_3 + \dot{\theta}_3^2) \\ h\dot{\theta}_2^2 \end{bmatrix} + \begin{bmatrix} 0 \\ G_2 \\ G_3 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix}$$

- **Control law based on calculated torque**

We chose:

$$e = q_d - q$$
$$\dot{e} = \dot{q}_d - \dot{q}$$

And:

$$\tau = M(q)(\ddot{q}_d + K_d\dot{e} + K_p e) + C(q,\dot{q})\dot{q} + G(q)$$

This law transforms the nonlinear robot into three decoupled second-order systems:

$$\ddot{e} + K_d\dot{e} + K_p e = 0$$

5 System Integration Software Architecture:

5.1 AI inference:

The inspection process is carried out using an inference engine. We train the custom model and then export it from the **Brain Builder** application, where it is integrated into a Python script using the **OpenCV** framework. [28]

5.2 AI model Brain Builder:

Brain Builder for **AITRIOS** simplifies the creation of deep learning models. Prepare a dataset, create and train a deep learning model, evaluate the inference results, and deploy the model to an AI camera, Brain Builder supports three AI tasks: Classification, Detector, and Anomaly Recognize. [29]

5.3 AI Model Development Workflow using Brain Builder:

Figures 47:AI Model Development Workflow Brain Builder for AITRIOS.

We integrated the Brain Builder platform into our workflow because it provides a professional environment to customize the Sony AI Camera's behavior. It is important to clarify that the camera does not perform quality control automatically; it requires a rigorous training process based on (CNN). We chose to focus specifically on the Object Detection capability to teach the system how to recognize the Arduino board and its key components with high precision. Our role was to build the 'Knowledge Base' for the camera. We collected, annotated, and fed a specific dataset into the platform, ensuring the model could distinguish between a healthy board and one with manufacturing errors. Brain Builder then allowed us to convert this training into a format the camera can process internally. By doing this, we transformed the camera from a simple lens into an active inspector capable of analyzing products and making real-time decisions. This approach shows that while the software facilitates the process, the accuracy of the quality control depends entirely on the quality of the data and the training parameters we established.

5.3.1 OpenCV:

After training our model in Brain Builder to detect the Arduino board and its components, This is where OpenCV comes in. Instead of just getting raw data from the camera, we used OpenCV to build a visual bridge. Its first job is to align the live video feed perfectly with the trained model's requirements, ensuring the Object Detection we worked on stays accurate.

The real value of OpenCV in workflow is how it handles the Heatmap Blending. Since our trained model identifies defects as a 'probability map', it's just a bunch of math that the user can't see. We used OpenCV to transform that math into a red heatmap overlaid on the live image. So, when the AI we trained in Brain Builder finds a missing part or a soldering error, OpenCV immediately highlights it on the screen. This makes the whole 'Quality Control' process clear and interactive, we used OpenCV to prove exactly where the defects are happening based on our training. [28]

5.3.2 Experimental Phase: Exploring Alternative AI Training Methods:

The process of training an AI model for industrial quality control is not a one-size-fits-all solution. We explored several approaches, but throughout our experimentation, we encountered a number of technical challenges, including low detection performance and difficulties exporting the model as an Edge AI model.

Below are the key methods we tried and the reasons they were not suitable for our final implementation:

5.3.3 YOLO and Roboflow:

Yolo is a computer vision model that is used for object detection, segmentation and classification. Robo flow inference used to deploy a Yolo API on hardware, it can deploy the model on CPU (Raspberry Pi, AI PCs) and GPU devices (NVIDIA Jestion…).

Our first attempt with the YOLO architecture on Roboflow to manage the dataset worked well, but we experienced significant challenges to convert and optimize the model to the Sony AI Camera. The conversion of the model to an Edge-AI format was not as straightforward and we had trouble sustaining the real-time performance that we required. [30]

5.3.4 Google Colab:

Colab is a Python development environment that runs in the browser using Google Cloud.We used Google Colab to code and run custom training code, but the environment was too complex and required too much time to manage it manually to our custom hardware needs. It was too time-consuming to focus on the actual inspection logic. [31]

3 TensorFlow Lite (TFLite) Object Detection:

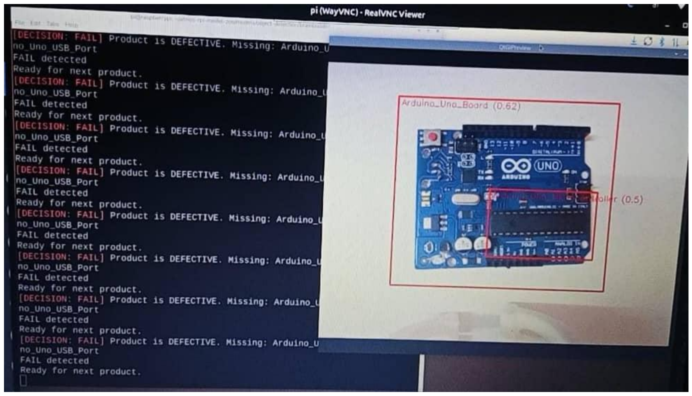
In another attempt, we tried to use TFLite Object Detection, which is made to work with mobile and edge devices, but we had problems with the integration of the exported. tflite models with our own proprietary AI camera. This time around we found the accuracy of detection to be lower than what we would achieve later. [32]

5.4 Test and Results:

As the last step of the work, we tested the robot's logic in real time to understand how it reacts to various statuses of the board in a fully automatic process. Here, we illustrate how the system responds when a board is detected on the conveyor belt.

5.5 Detection of a Defective Board (Fail):

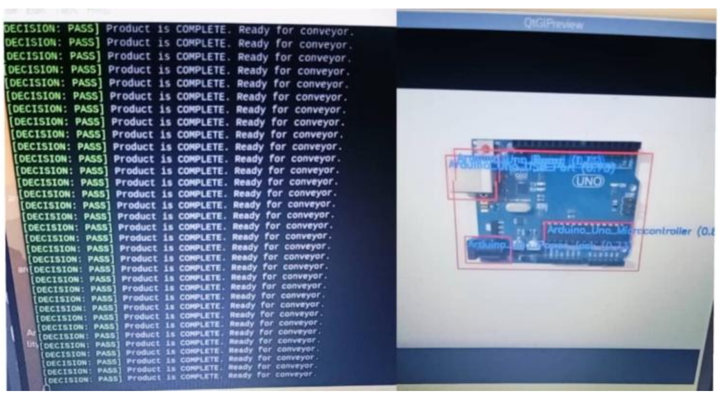
The process begins as the board moves along the conveyor belt. Once it reaches the inspection area, a sensor detects its presence and automatically stops the belt to allow the camera to scan it. When the camera identifies an error (like a soldering mistake), the HDMI screen immediately shows a 'Fail' status with a red heatmap showing the exact location of the defect. In this case, the Robotic Arm stays in its home position. The belt then starts moving again, allowing the faulty board to continue its path until it falls naturally into the 'Defective Products' box. This proves the system can automatically filter out bad products.



Figures 48:Detection of Deffective product

5.6 Detection of a Functional Board (Pass):

In the second case, the board again stops under the camera by the sensor. Once the scan is complete, the HDMI screen changes to indicate a green Pass to ascertain that the board is healthy. Here is where the system activates the Robotic Arm which will move the gripper to the exact position to grab the board off the stopped belt. The arm then spins and puts it in the 'Successful Products' box. This shows how well the sensors, the AI vision on the screen and the robotic sorting logic are synched.



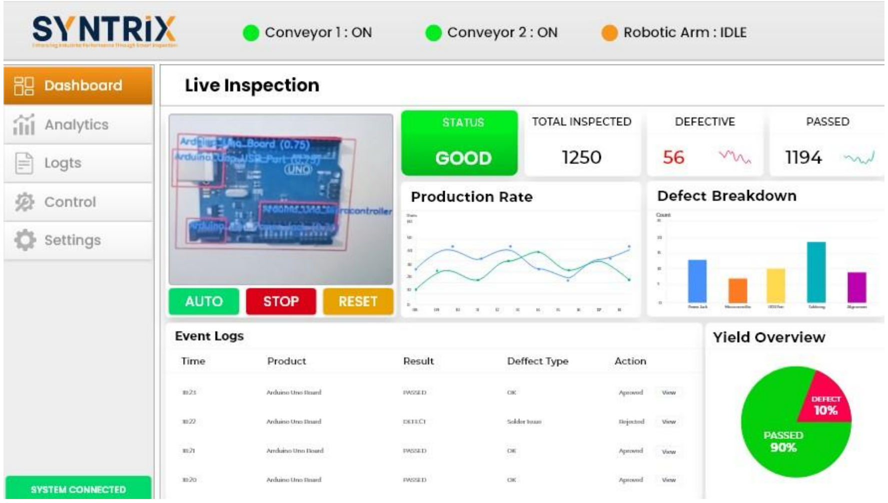
Figures 49:Detection of a good product

5.7 Smart Data Management:

In addition to physical sorting, we developed a conceptual interface of a central management application. The concept is to shift towards a simple automated sorting to a data-driven system where all inspection results are stored and used by the company.

The system is a data collector instead of merely checking products and passing them on. The application would give a complete history of the production line of the client. Take the case where we are testing electronic boards such as Arduino, the app will not simply tell us whether a board is Good or Bad, but it will also record the data on the most common defects that happen during the day. This will assist the company to know what section of the production line is giving the company the biggest problem.

With this data collected, the factory will be able to work towards predictive maintenance. This implies that they will be able to check the statistics on the app, pinpoint the areas where failures are on the rise, and repair the machines before they crash.



Figures 50:Syntrix data monitoring software

5.8 Future enhancements:

The developed prototype has proven its effectiveness and can be adapted to industries other than electronic boards. The system's design and performance can be significantly improved to achieve higher levels of accuracy, reliability, and ease of use. Several recommendations have been proposed for future improvements, from a simple prototype to a fully functional and highly efficient system:

5.8.1 Generic Detection:

The current system is trained for detecting defects in electronic boards. But the software is designed for product flexibility. By capturing a new set of images (e.g., fruits, mechanical bolts, medicine bottles) and re-training the CNN model (using Brain Builder), the system can be re-applied in other industries. This ensures that we don't need to redesign the hardware, making the machine a versatile and cost-effective solution for small and medium enterprises (SMEs).

5.8.2 Faster Sorting (Delta and Scara Robots):

In a high volume industrial manufacturing, speed is everything. Our prototype system works, but for mass production, we propose to upgrade the system by using Delta and Scara robots. These robots are built for high speed 'pick-and-place' operations with sub-millimeter precision. Adopting such robots would enable the conveyor belt to run at higher speeds; therefore, more parts can be inspected per minute without sacrificing quality.

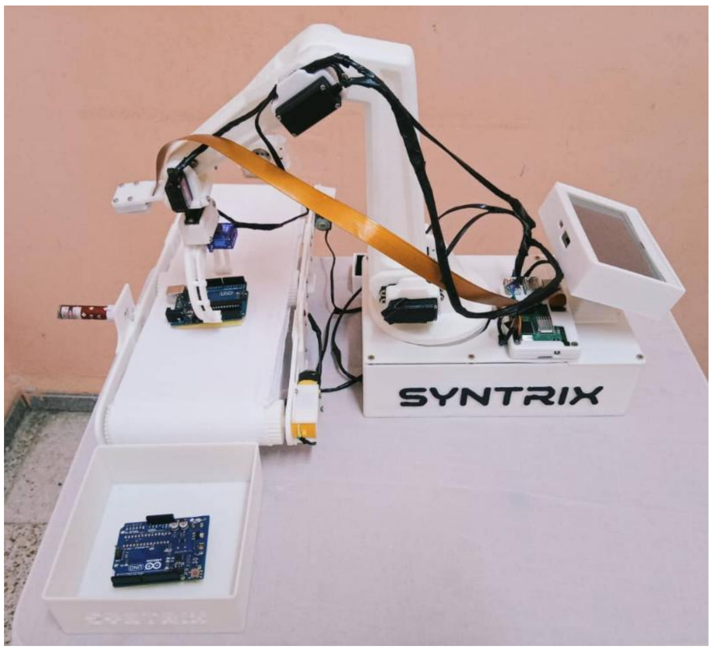
5.8.3 Multicriteria Sorting (Sensors):

To take the project beyond mere visual inspection, a multi-sensorial quality station can be developed. This system could include high-precision scales (load cells) and laser scanners that could detect internal product defects which the camera may not be able to detect - such as an empty package, or a part with wrong thickness. This 'sensor fusion' approach guarantees a 360-degree quality check, considering visual, physical and dimensional criteria all at once.

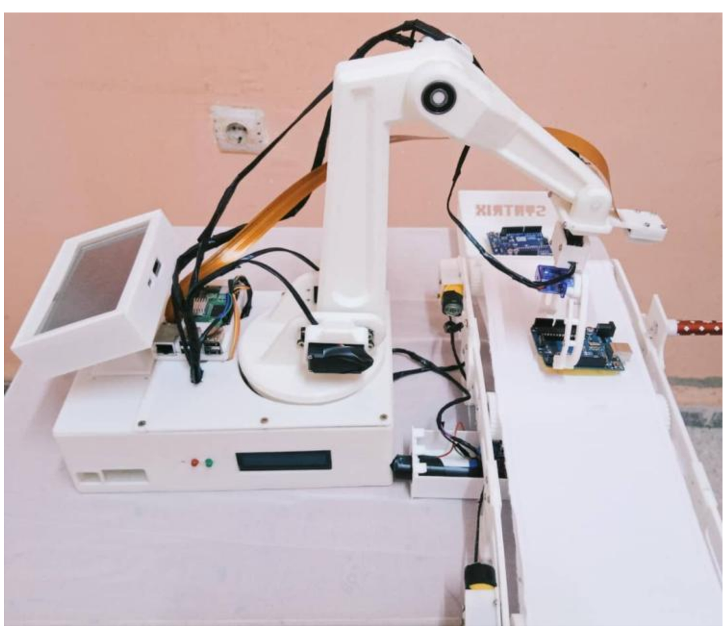
5.8.4 Industrial Internet of Things, Monitoring from anywhere:

IoT stands for the Industrial Internet of Thing, and as the name suggests it refers to the use of Internet of Things technology. To make a project highly efficient, we propose to integrate it with the Industrial Internet of Things (IIoT). Real-time data can be transmitted to a cloud-connected dashboard, where production health can be monitored globally. This paves the way for 'Predictive Analytics' - where the system could notify the engineers if the defect count rises, meaning that one of the machines on the production line may require maintenance before it breaks down.

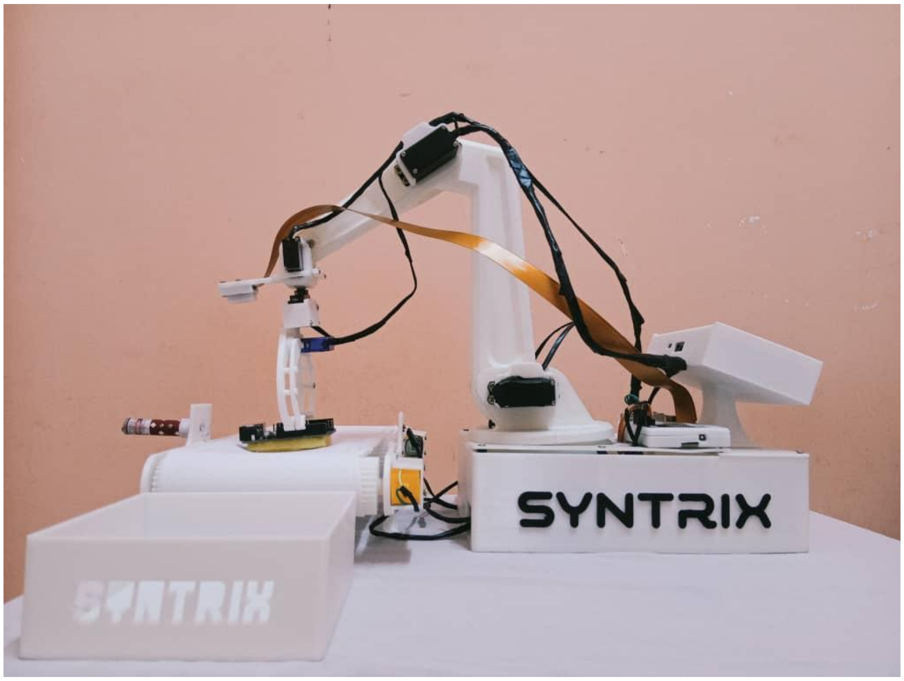
5.9 Final Prototype Project Overview



Figures 52:Final Prtotype Overview 1



Figures 51:Final Prototype Overview 2



Figures 53:Final Prototype Overview 3

6 Conclusion:

The prototype successfully demonstrated the full implementation of our automated quality control system, integrating a Sony smart camera, a Raspberry Pi 5, and a sorting mechanism. Through the Brain Builder platform, we trained a CNN model that transformed the camera into an intelligent inspector capable of detecting defects in real time. This hardware and software combination forms the core of our project, delivering a fast, accurate, and scalable solution for industrial applications.

General Conclusion

Conclusion

In conclusion, this project shows the development of an AI-Based Quality Control and Robotic Sorting System designed to automate product classification and inspection in industrial environments. Through the integration of robotics, computer vision, artificial intelligence, and industrial automation technologies, the system can identify defects and carry out autonomous sorting tasks in real time. Enhancing overall operating efficiency, lowering human intervention, and improving product quality are the primary objectives of this project.

By integrating robotic manipulation and automated visual inspection into a single architecture, the developed system offers manufacturing industries a flexible and intelligent solution. By using deep learning algorithms and real-time decision-making, the project shows a dependable and economical approach to quality control that can be tailored to various products and industrial applications.

Throughout the development process, several challenges were encountered, including dataset preparation, lighting variations, system integration, and real-time performance optimization. Despite these challenges, the finished prototype successfully completed autonomous sorting and accur ate defect identification, demonstrating the viability of combining robotics and artificial intelligence in to a single industrial solution.

Future developments will be focused on upgrading the robotic system for quicker and more accurate operations, integrating cloud-based analytics for remote monitoring and predictive maintenance, and increasing detection accuracy through bigger datasets and more sophisticated AI models. Expanding the system's capabilities to serve a greater variety of industrial products and quality control requirements, as well as deploying it on larger production lines, could be additional improvements.

Overall, all things considered, this project demonstrates the potential of intelligent automation in modern production and provides a solid foundation for additional developments in intelligent quality control systems. The suggested method advances Industry 4.0 technologies and facilitates the shift to more effective, reliable, and intelligent industrial processes by integrating robotic sorting with AI-powered inspection.

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