Declaration

I, **BISHAL DUTTA**, hereby declare that the work presented in this internship report, titled "**Design and Development of an AI-Powered SCARA Robot for Industrial Automation**," is an authentic record of my own work carried out during the period from 10-06-2025 to 31-07-2025 as part of my industrial internship at Bishnu Engineering, Jorhat.

The information and data presented in this report are correct to the best of my knowledge. This work has not been submitted in part or full for the award of any other degree or diploma to any other university or institution.

BISHAL DUTTA
Roll no- 220710002021
Department of Mechanical Engineering
Jorhat Engineering College

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Abstract

This report summarizes an R&D internship project at Bishnu Engineering focused on developing a low-cost, AI-powered 4-DOF SCARA robot for autonomous pick-and-place tasks. The methodology covered the complete design cycle, beginning with mechanical design and component calculations, followed by **Computer-Aided Engineering (CAE)** simulations for structural validation. All custom parts were subsequently fabricated using **3D printing**.

The robot's intelligence is driven by a trained **YOLO object detection model** that identifies targets and provides their coordinates to the control system. This system then uses **Inverse Kinematics** to calculate the precise joint movements required to grasp the object. Although the final hardware assembly was not completed due to time constraints, the project successfully delivered a validated virtual design, all prototyped physical components, and a functional AI model. This internship provided invaluable hands-on experience in the multidisciplinary integration of mechanical design, simulation, and artificial intelligence.

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AI: Artificial Intelligence **BOM**: Bill of Materials **CAD**: Computer-Aided Design **CAE**: Computer-Aided Engineering **DOF**: Degrees of Freedom **FEA**: Finite Element Analysis **FK**: Forward Kinematics **HTTPS**: Hypertext Transfer Protocol Secure **I2C**: Inter-Integrated Circuit **IK**: Inverse Kinematics **IoT**: Internet of Things **ISO**: International Organization for Standardization **MQTT**: Message Queuing Telemetry Transport **SCARA**: Selective Compliance Assembly Robot Arm **SPI**: Serial Peripheral Interface **UART**: Universal Asynchronous Receiver-Transmitter **YOLO**: You Only Look Once

Introduction

1.1 Company Profile: Bishnu Engineering

Established in 2018, **Bishnu Engineering** initially made its mark in Jorhat as a prominent provider of **Aluminium Anodize and Powder Coating solutions**. Identifying the growing need for technological advancement in the regional industrial sector, the company strategically diversified its operations by establishing a separate segment dedicated to **Automation and Internet of Things (IoT) solutions**. This initiative has since flourished, positioning Bishnu Engineering as a prominent Automation solution provider in Upper Assam.

As an **MSME registered company**, Bishnu Engineering is committed to quality and excellence, a fact underscored by its prestigious **ZED GOLD and ISO certifications** for the Automation and IoT sector. To spearhead innovation and develop proprietary technology, a dedicated **Research and Development (R&D) Department** was formed. This department serves as the hub for creating next-generation automation systems, and it was within this dynamic environment that this internship project was undertaken.

1.2 Internship Overview and Objectives

This industrial internship represented a significant opportunity to engage with the practical challenges of modern product development within a forward-thinking R&D setting. The primary objective was to move beyond theoretical classroom knowledge and contribute to a tangible project at the intersection of mechanical engineering, electronics, and artificial intelligence. The key objectives set for this internship were:

- To gain comprehensive, hands-on experience in the entire design lifecycle of a mechatronic system, from conceptualization to a pre-production prototype.
- To apply and enhance skills in advanced engineering tools, including **3D CAD modeling**, **Computer-Aided Engineering (CAE)** for simulation, and **Additive Manufacturing** for rapid prototyping.
- To develop a foundational understanding of integrating AI-based machine vision systems with mechanical manipulators, a critical skill set in the era of Industry 4.0.

1.3 Problem Statement: The Need for Low-Cost Industrial Automation

The industrial landscape, particularly for Micro, Small, and Medium Enterprises (MSMEs) in Upper Assam, faces significant challenges in modernization and global competition. Repetitive, manual tasks such as material handling and assembly limit productivity, affect quality consistency, and pose ergonomic risks to workers. While industrial automation offers a clear solution, the high capital investment required for commercial robotic systems from international manufacturers often places it beyond the reach of these local enterprises. This creates a critical technology gap and a pressing need for indigenously developed, cost-effective, and flexible automation solutions that can empower local industries to enhance their capabilities and grow.

1.4 Project Goal and Scope

The principal goal of this project was to design and develop a **functional proof-of-concept for a 4-DOF SCARA robot**, intended to serve as a foundational platform for future low-cost automation solutions at Bishnu Engineering. The project's scope was comprehensive, encompassing all stages leading up to final assembly. This included:

- **Detailed Mechanical Design:** Creation of a complete 3D model of the robot and rigorous machine design calculations for all moving components.
- **Structural Validation:** Performing Finite Element Analysis (FEA) to simulate operational loads and ensure the structural integrity of the design.
- **Rapid Prototyping:** The fabrication of all custom parts using 3D printing technology.
- **AI System Development:** The training and validation of a custom object detection model to serve as the robot's vision system.

The project's defined endpoint for the internship period was the delivery of a complete set of validated and fabricated parts and a functional software system, ready for the final hardware assembly and integration phase.

1.5 Report Organization

This report is structured to provide a logical and detailed account of the project's progression. **Chapter 2** is dedicated to the core mechanical system design, covering the theoretical principles, component calculations, and validation through CAE. **Chapter 3** describes the physical realization of the design, focusing on the prototyping process via 3D printing and the development of the system's Bill of Materials. **Chapter 4** delves into the intelligent aspects of the robot, explaining the development of the AI vision system and the principles of robotic kinematics for control. Finally, **Chapter 5** concludes the report by summarizing the project's outcomes, discussing the challenges faced, highlighting the key learnings, and providing recommendations for future work.

Mechanical System Design and Analysis

The development of the SCARA robot began with a foundational phase of mechanical design and rigorous analysis. This chapter details the systematic approach taken, from selecting the appropriate robotic technology to validating the final design through advanced simulation tools. The objective was to create a robust, reliable, and manufacturable mechanical structure that could serve as the backbone for the entire automated system.

2.1 Introduction to SCARA Robot Technology

SCARA, an acronym for **Selective Compliance Assembly Robot Arm**, represents a specific class of industrial robots renowned for their high speed and precision in planar operations. The key characteristic of a SCARA robot is its "selective compliance," meaning it is significantly more rigid in the vertical direction (Z-axis) than in the horizontal plane (X-Y plane). This makes it exceptionally well-suited for tasks that require precise vertical insertion or placement, such as assembling electronic components or performing pick-and-place operations. A typical SCARA configuration consists of two parallel rotary joints that control movement across a plane and a third prismatic joint for vertical motion. This combination allows the robot to achieve high speeds and excellent repeatability, making it a strategic choice for this project's goal of creating an efficient automation solution.

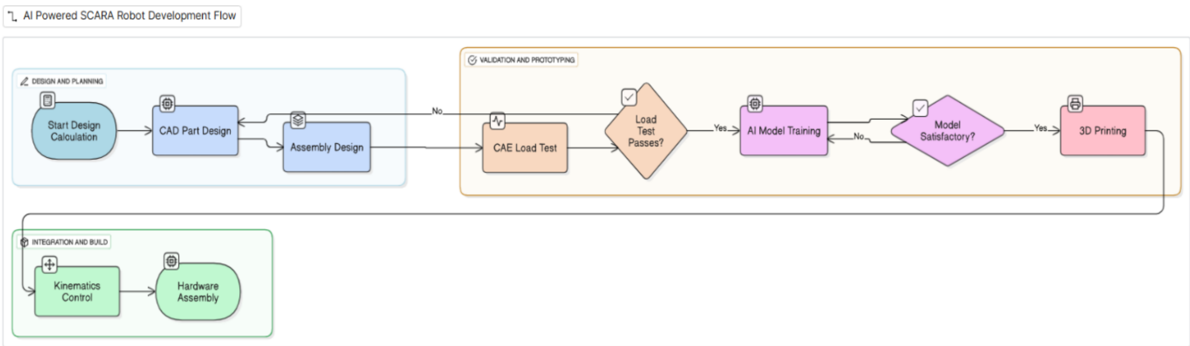

Figure 1: Complete Roadmap of Design and Development

2.2 Design of the 4-DOF SCARA Robot

The robot designed for this project features a **4-Degree-of-Freedom (DOF)** kinematic structure, providing the necessary flexibility for complex pick-and-place tasks. The four degrees of freedom are defined as follows:

1. **Joint 1 (Base Rotation):** A rotary joint that rotates the entire arm assembly around the central vertical axis.
2. **Joint 2 (Elbow Rotation):** A second rotary joint, parallel to the first, that controls the "elbow" of the arm, allowing it to extend and retract.
3. **Joint 3 (Z-Axis Translation):** A prismatic joint that provides linear vertical motion, allowing the end-effector to be raised and lowered.
4. **Joint 4 (Wrist Roll):** A final rotary joint at the end of the arm that controls the orientation of the end-effector or gripper.

This 4-DOF design ensures that the robot can reach any specified X, Y, and Z coordinate within its workspace and orient its gripper appropriately to grasp an object.

2.3 Machine Component Design and Selection

This section details the engineering rationale behind the selection and design of critical mechanical components for the SCARA robot. The primary goals are to ensure structural integrity, achieve precise motion control, minimize backlash, and guarantee long-term reliability under dynamic operating conditions. All components were selected based on a conservative design philosophy, prioritizing performance and safety over minimalism.

2.3.1 Bearing Selection and Load Calculation

Bearings are fundamental to the robot's operation, as they manage loads while ensuring smooth and precise rotational motion. The design employs a combination of thrust ball bearings and radial ball bearings, each serving a distinct purpose.

1. Bearing Types and Functions:

- **Thrust Ball Bearings:** These are specifically selected to handle **axial loads** (loads parallel to the axis of rotation). In this cantilevered arm design, the primary axial load is the gravitational force from the weight of the arms, motors, and payload. Their use is critical at each joint to prevent the arm from sagging and to maintain positional accuracy.
- **Radial Ball Bearings:** These bearings are used to support **radial loads** (loads perpendicular to the axis of rotation) and to ensure smooth, low-friction rotation of the shafts. They provide lateral stability to the joints.

2. Joint Analysis and Selection Rationale:

a) First (Base) Joint: This is the most critically loaded joint as it supports the entire weight of the subsequent robot structure.

- **Selected Bearings:**
  - **Thrust Ball Bearings:** Two 40x60x13 mm bearings. This size was chosen for its high load capacity and robust dimensions, which provide a stable foundation.
  - **Radial Ball Bearing:** One 35x47x7 mm (standard 61807 series). This bearing centres the main shaft and handles moderate radial loads.
- **Load Analysis and Verification:** A conservative load estimate is crucial for a robust design. The total mass of Arm 1, Arm 2, the Z-axis assembly, all motors, and a nominal payload is estimated to be **3.5 kg**.
  - The axial force due to gravity is: **F_{axial} = mass × g = 3.5 kg × 9.81 m/s² ≈ 34.3 N**.
  - However, operations involve acceleration, deceleration, and potential unexpected forces. A high **safety factor (SF) of 5** is applied to account for these dynamic conditions: **F_{design} = 34.3 N × 5 ≈ 172 N**.

- **Design Verification:** A standard 51108 thrust ball bearing (40x60x13 mm) has a **static load capacity (C0) of 39.0 kN** (39,000 N).
    - **Calculation:** 172 N (Design Load) <<< 39,000 N (Bearing Capacity) **Conclusion:** The selected bearing is exceptionally well-suited. It operates at a small fraction of its capacity, ensuring minimal deformation, extremely long service life, and high rigidity, which is paramount for the base joint's precision.

b) Second and Third Joints: These joints support progressively less mass; therefore, smaller, commercially available bearing sizes were selected to reduce weight and space.

- **Selected Bearings:** Thrust bearing 35x52x12 mm (standard 51107 series) and radial bearing 30x42x7 mm (standard 61806 series).
- **Verification:** The 51107 thrust bearing has a static load capacity of approximately 24.0 kN. The estimated design load for these joints is significantly lower than for the base joint, confirming that these bearings operate with a similarly high safety factor and are a safe and optimal choice.

c) Z-Axis Linear Motion:

- **Selected Components:** Four LM10UU linear ball bearings on 10mm diameter smooth rods.
- **Rationale:** The load is shared evenly between four bearings. Each LM10UU bearing is rated for a dynamic load of ~200 N. The total load capacity (~800 N) far exceeds the estimated weight of the moving Z-axis assembly, ensuring smooth and precise vertical translation without deflection.

2.3.2 GT2 Belt and Pulley System Design

The GT2 belt and pulley system is employed to achieve high gear reductions, transmit power from the motors to the joints, and eliminate the backlash typically associated with gear trains. The "GT2" profile, with its 2mm pitch and rounded teeth, is specifically designed for high positional accuracy and minimal backlash.

1. Design Strategy and Reduction Ratios: The system uses a two-stage reduction for the primary joints to achieve high torque multiplication without requiring excessively large pulleys.

- **Joint 1 (Base):** A **20:1** total reduction ratio is achieved using two stages. This high ratio is necessary to amplify the stepper motor's torque sufficiently to move the entire robot structure with authority and precision.
- **Joint 2:** A **16:1** total reduction ratio is achieved using a similar two-stage design, optimized for the lower inertia of the second arm.
- **Joint 3 (Wrist):** A **4:1** single-stage reduction is sufficient here, as it only needs to move the lightweight gripper and payload. This simplifies the design and reduces weight at the end of the arm, which is beneficial for overall performance.

2. Pulley Design and Selection: All pulleys are 3D printed using a parametric design. This allows for easy customization of the number of teeth. The tooth profile is precisely generated to match the GT2 belt specification, ensuring optimal engagement and power transmission. Common tooth counts (e.g., 20T, 60T, 80T) are used due to their market availability and design simplicity.

3. Belt Length Selection: The belt lengths (200mm, 300mm, 400mm) were determined by the 3D model's centre-to-centre distances between pulleys and the number of teeth on the pulleys. These specific lengths are standard off-the-shelf options for closed-loop GT2 belts, ensuring easy procurement and replacement. The design includes adjustable idler pulleys for tensioning, which is critical for maintaining accuracy and preventing slippage or backlash.

4. Torque Transmission Verification:

- **Motor Torque:** A typical NEMA 17 stepper motor has a holding torque of ~0.4 Nm. With the driver current limited for thermal management, the available running torque is estimated at **~0.2 Nm**.
- **Output Torque Calculation (Joint 1):** The output torque is calculated considering the gear ratio and system efficiency (estimated at 90% per stage for belt drives).

  T_output = T_motor × Gear_Ratio × Efficiency^(number of stages)

$T\_output = 0.2 \text{ Nm} \times 20 \times (0.9)^2$

$T\_output = 0.2 \times 20 \times 0.81 \approx 3.24 \text{ Nm}$

- **Conclusion:** This resulting **3.24 Nm** of torque at the joint is more than adequate to overcome static friction, accelerate the arm, and handle the anticipated payload, confirming that the 20:1 reduction ratio is well-chosen and the system is safely designed for its intended purpose.

Overall Conclusion: Every mechanical component in the SCARA robot has been selected and designed following conservative engineering principles. The bearings are vastly over-specified for their loads, guaranteeing longevity and stiffness. The GT2 drive system is correctly sized to provide the necessary torque and precision. The design is not only functionally effective but also robust and safe for continuous operation.

2.4 3D Modelling using Computer-Aided Design (CAD)

The entire SCARA robot was modelled virtually using **Autodesk Fusion 360**, a powerful and integrated 3D CAD platform. This digital design phase was critical for transforming the conceptual idea into a precise and manufacturable engineering model. The process was divided into two primary stages:

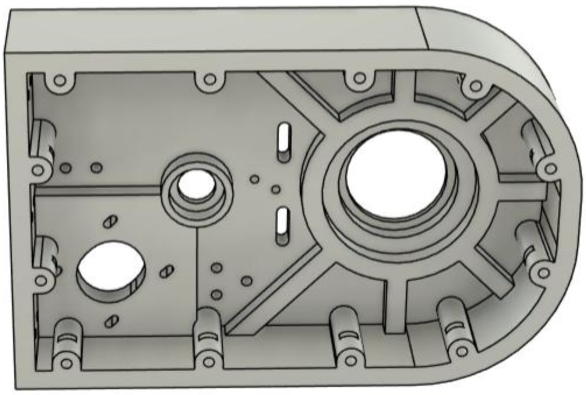

Figure 2: Base of SCARA Robot

Figure 3: GT2 Pulley 110 Teeth

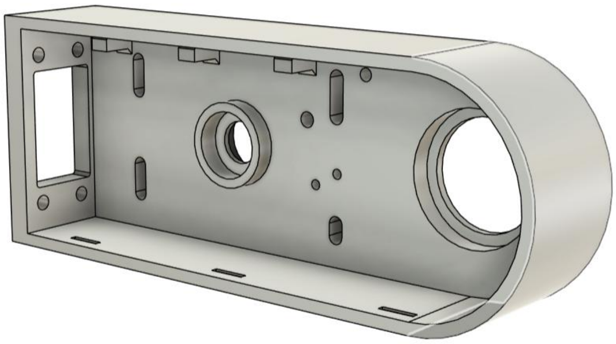

Figure 4: Arm 1 of SCARA Robot

- **Part Modelling:** Every custom component required for the robot was meticulously designed as an individual 3D solid model. This comprehensive list of parts included foundational elements like the **Base** and **Z-axis Mount Platform**; the primary structural links such as **Arm 1** and **Arm 2**; and complex mechanical interfaces like the **J1, J2, and J3 Couplers**. A key aspect of this stage was the parametric design of the power transmission system, which involved creating a series of **GT2 Pulleys** with varying teeth counts (e.g., 110-teeth, 92-teeth, 80-teeth) to achieve the specific gear reductions needed for each joint. All components of the end-effector, including the **Gripper End**, **Gripper Hand**, and **Gripper Servo Holder**, were also modelled in this phase.
- **Assembly Modelling:** Following the completion of individual part models, they were all brought together in Fusion 360’s assembly environment. Using a combination of rigid and revolute joints, a full digital assembly of the robot was constructed. This virtual prototype was invaluable for verifying the design's integrity. It allowed for interference detection to ensure no parts would collide during operation and for motion studies to visualize the robot's overall structure and range of motion. This verification step was crucial for guaranteeing a seamless fit of all components before committing resources to physical production.

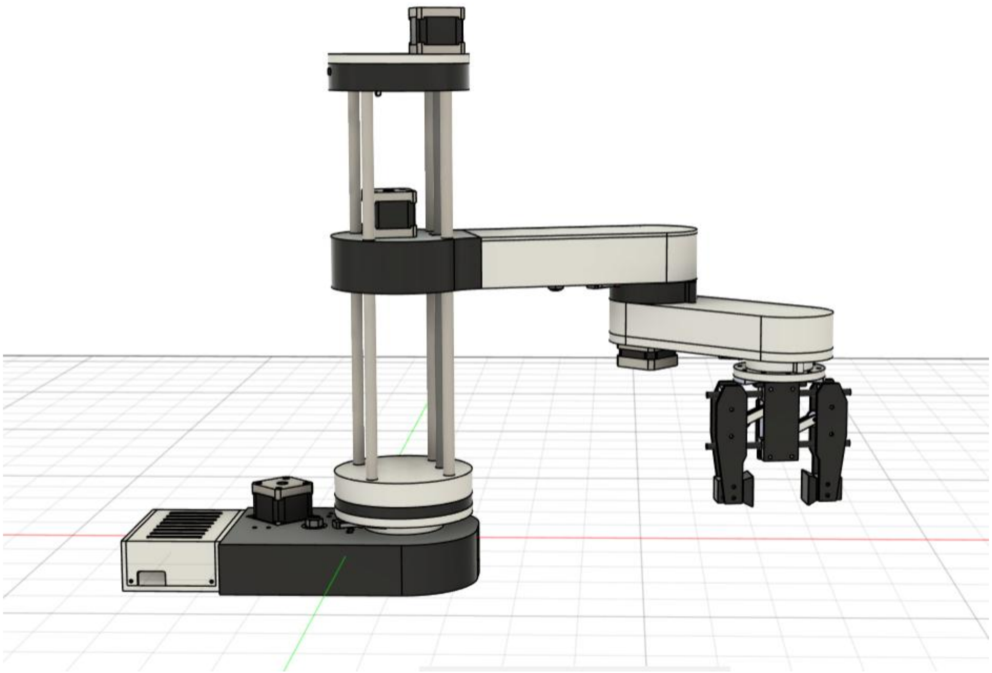

Figure 5: 4-DOF SCARA Robot Assembly

2.5 Design Validation using Computer-Aided Engineering (CAE)

To ensure the mechanical design was not only functional but also structurally sound, it was validated using **ANSYS**, a dedicated **Computer-Aided Engineering (CAE)** software. A **Finite Element Analysis (FEA)** was conducted on the most critical load-bearing components, such as the primary arm (**Arm 1**) and the main joint couplers, to certify their ability to withstand operational stresses.

The validation process followed a systematic workflow:

1. **Model Preparation and Meshing:** The 3D models of the critical parts were exported from Fusion 360 and imported into ANSYS. The solid geometry was then discretized into a fine mesh of thousands of small elements, which forms the basis for the simulation.

2. **Applying Boundary Conditions and Loads:** The model was constrained to mimic real-world conditions. For example, the mounting holes of the arm were fixed to simulate their connection to a joint. A virtual load, representing the combined weight of the subsequent links and a maximum payload, was then applied at the end of the arm.

3. **Analysis and Post-Processing:** The software solved the underlying mathematical equations to calculate the internal stresses and deformations resulting from the applied load. The results, visualized through von Mises stress plots and deformation maps, confirmed that the maximum stress levels were well within the safety limits of the specified 3D printing material (PLA+). This successful validation provided the engineering confidence needed to proceed with physical prototyping, significantly mitigating the risk of mechanical failure.

(Insert Figure 2: CAE Stress Analysis of the Primary Robot Arm in ANSYS here)

Prototyping and System Development

Following the successful completion of the digital design and simulation phases, the project transitioned into the physical prototyping and system development stage. This chapter details the process of converting the validated virtual models into tangible components through additive manufacturing. It also covers the systematic planning of all necessary components through a Bill of Materials (BOM) and discusses the practical experiences and challenges encountered during the initial assembly phase.

3.1 Additive Manufacturing: 3D Printing of Components

Additive Manufacturing, specifically **Fused Deposition Modeling (FDM) 3D printing**, was selected as the primary method for fabricating the robot's custom structural components. This technology was chosen for its ability to produce complex geometries with high accuracy directly from CAD models, making it an ideal choice for rapid prototyping in an R&D environment. It offered significant advantages in terms of speed and cost-effectiveness compared to traditional manufacturing methods.

3.1.1 Material Selection (PLA+)

The material selected for the majority of the structural parts was **PLA+ (Polylactic Acid Plus)**. PLA+ is an enhanced bioplastic known for its excellent printability, low warping, and superior mechanical properties compared to standard PLA. It offers improved strength, layer adhesion, and toughness, making it suitable for functional mechanical prototypes that need to withstand operational loads. For certain components like the pulleys and gripper, standard PLA was also utilized. This material choice provided a good balance between structural integrity, ease of fabrication, and cost.

3.1.2 Printing Process and Parameters

The fabrication of all components required approximately **60 hours** of total printing time. To ensure the quality and dimensional accuracy of the parts, key printing parameters were carefully calibrated. This included setting an optimal layer height for a balance between print speed and surface finish, and adjusting the infill density to provide internal strength without adding excessive weight.

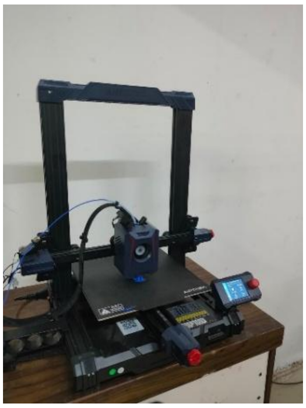

Figure 8: 3D Printing of SCARA Robot Parts

A critical parameter that was adjusted in the slicing software was the **Horizontal Expansion**, which was set to –0.1mm. This minor adjustment was crucial for achieving high dimensional accuracy, ensuring a precise fit for mechanical components like bearings and shafts, which is often a challenge in 3D printing.

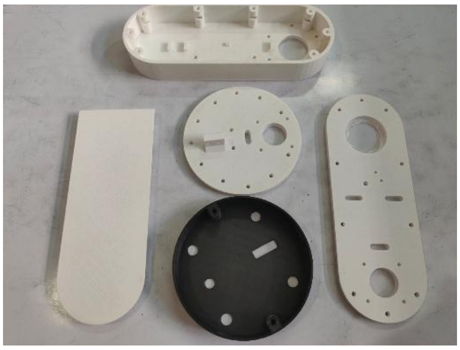
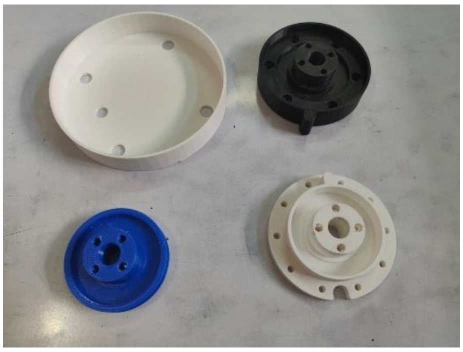

Figure 9: 3D Printed Parts

3.2 Bill of Materials (BOM) for Electrical and Mechanical Components

A comprehensive **Bill of Materials (BOM)** was created to systematically list every component required for the complete assembly of the robot. Creating a BOM is a critical step in the engineering design process as it ensures all necessary parts are accounted for, aids in procurement, and allows for accurate cost estimation. The BOM was categorized into three main sections:

- **Structural Components:** All custom parts designed in CAD and fabricated via 3D printing, such as the base, arms, and couplers.
- **Standard Mechanical Components:** Off-the-shelf hardware, including the various **thrust and radial ball bearings**, **GT2 timing belts**, fasteners (nuts and bolts), and smooth rods.
- **Electrical and Electronic Components:** The core components that drive and control the robot, including four **NEMA 17 stepper motors**, four **A4988 stepper drivers**, an **Arduino UNO board** paired with a **CNC shield**, and a 12V DC power supply.

The detailed BOM is provided in Appendix A of this report.

3.3 Hands-on Assembly Experience and Challenges

The final stage of the internship involved beginning the physical assembly of the robot, which provided invaluable hands-on experience. This process involved carefully fitting the selected bearings into their respective 3D-printed housings, mounting the stepper motors, and beginning the construction of the primary joints. This practical work highlighted the critical difference between a perfect digital model and a physical object, where factors like material tolerances and fitment become paramount.

One of the key technical challenges identified during this phase was the potential for **backlash** in the joints, which can arise from minor gaps between fasteners and their holes or from improperly tensioned belts. This underscored the importance of precise manufacturing and careful assembly. However, the most significant challenge was the **time constraint** of the internship period. The complexity and precision required for the full assembly process meant that it could not be completed before the conclusion of the internship. Nonetheless, the initial assembly provided a clear roadmap for the project's future completion.

AI Vision System and Robotic Control

While the mechanical structure forms the body of the robot, the integration of an artificial intelligence (AI) vision system and a robust control scheme constitutes its brain and eyes. This chapter delves into the advanced technologies and principles that transform the robot from a simple manipulator into an autonomous system capable of perceiving its environment and making intelligent decisions. The focus is on the two core pillars of this intelligence: the computer vision system that allows the robot to "see" and the kinematic calculations that enable it to "act."

4.1 Introduction to Computer Vision in Robotics

Computer vision is a field of artificial intelligence that trains computers to interpret and understand the visual world. In the context of robotics, it serves as the primary sensory input, granting the robot the ability to perceive its workspace in a manner analogous to human sight. This capability is transformative, elevating a robot from a machine that can only follow pre-programmed, repetitive paths to one that can adapt to dynamic environments. By analyzing a video feed from a camera, a vision-enabled robot can identify objects, determine their location and orientation, and perform tasks that would be impossible with simple position-based control. This project leverages computer vision to locate randomly placed objects, which is the foundational requirement for any flexible and intelligent automation system.

4.2 Object Detection using YOLO Model

Object detection is a specific task within computer vision that focuses on identifying and locating instances of objects within an image or video. For this project, the **YOLO (You Only Look Once)** algorithm was selected as the core of the vision system. YOLO is a state-of-the-art, real-time object detection model renowned for its exceptional speed and high accuracy. Unlike other models that scan an image in multiple passes, YOLO looks at the entire image just once to predict bounding boxes and class probabilities simultaneously. This single-pass architecture makes it incredibly fast and efficient, which is a critical requirement for robotic applications where decisions must be made in real-time.

4.2.1 Data Collection and Labelling

A neural network like YOLO does not inherently know what to look for; it must be trained on a custom dataset of examples. The first step in this process was **data collection**, where hundreds of pictures of the target objects were taken. To ensure the model would be robust, these images were captured from various angles, under different lighting conditions, and against diverse backgrounds.

Following data collection was the meticulous process of **data labeling** (or annotation). Using a specialized software tool, a bounding box was manually drawn around the target object in every single image. Each box was then assigned a class label. The quality and diversity of this labeled dataset are the most critical factors influencing the final accuracy and reliability of the object detection model.

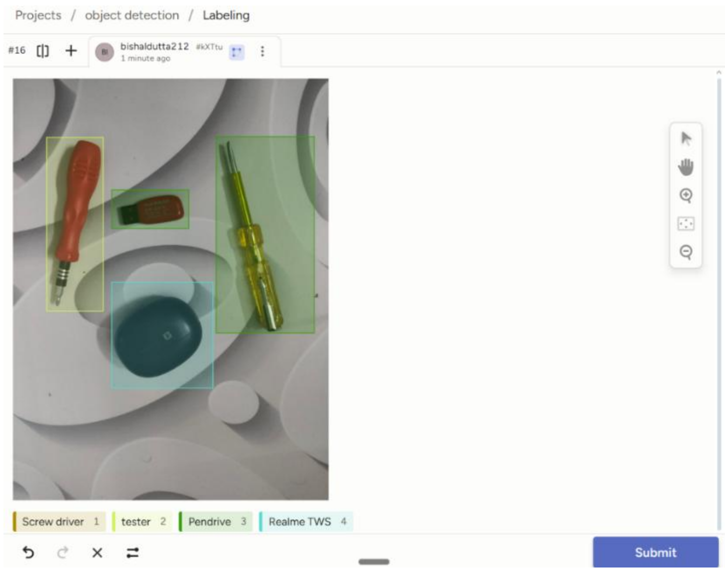

Figure : Data Lebeling and annotation process

4.2.2 Model Training and Validation

With the labelled dataset prepared, the **model training** process began. The dataset was fed into the YOLO neural network, which iteratively adjusts its internal parameters (weights and biases) to learn the visual features—such as shape, colour, and texture—that define the target object. This computationally intensive process essentially teaches the model to recognize the object based on the examples provided.

To ensure the model could generalize its learning to new, unseen images, a portion of the dataset was set aside for **validation**. After training, the model's performance was evaluated on this validation set to measure its accuracy. This step is crucial for preventing a common issue known as "overfitting," where a model performs well on the data it was trained on but fails to accurately detect objects in new scenarios.

Figure: Testing and Validation of Trained YOLO model

4.3 Robot Kinematics for Autonomous Operation

Kinematics is the branch of mechanics that describes the motion of objects without considering the forces that cause them. In robotics, it provides the essential mathematical framework that connects the robot's abstract control commands to its physical movements. It is the bridge that allows the coordinates generated by the AI vision system to be translated into precise mechanical actions.

4.3.1 Coordinate System Transformation

The AI model provides the location of a detected object in **2D pixel coordinates**, relative to the camera's image frame. However, the robot operates in a **3D world coordinate system**, relative to its own base. A critical step for autonomous operation is to translate the data from one frame of reference to the other. This **coordinate system transformation** is achieved through camera calibration and mathematical operations (often involving rotation and translation matrices) to convert the 2D pixel location (u, v) from the image into a real-world 3D coordinate (X, Y, Z) that the robot can use as a target.

4.3.2 Forward and Inverse Kinematics (FK/IK) Calculation

The control of the SCARA robot's arm relies on two fundamental types of kinematic calculations:

- **Forward Kinematics (FK):** This is the process of calculating the final position and orientation of the robot's end-effector based on the known angles of each of its joints. FK answers the question: "If my joint angles are θ1 and θ2, where is my gripper located in space?"
- **Inverse Kinematics (IK):** For this project's goal, IK is the more critical and complex calculation. It does the reverse of FK: given a desired target position for the end-effector (as determined by the vision system), IK calculates the specific angles that each joint must move to in order to reach that target. IK answers the question: "To move my gripper to the target coordinate (X, Y), what should my joint angles θ1 and θ2 be?" Solving the IK equations is the final step that enables the robot to autonomously and accurately move to grasp the object detected by the AI.

Conclusion and Learnings

This final chapter synthesizes the outcomes of the internship project at Bishnu Engineering. It provides a summary of the work accomplished, highlights the key achievements, and reflects on the challenges encountered throughout the development process. Furthermore, this chapter discusses the personal and technical skills gained from this practical R&D experience and outlines potential avenues for future work to build upon the foundation established by this project.

5.1 Summary of Work and Project Status

This project involved the end-to-end design and pre-production development of a 4-DOF SCARA robot intended for low-cost industrial automation. The work began with conceptualization and proceeded through detailed mechanical design, component selection, and rigorous structural validation using CAE tools. Following the digital phase, a complete set of custom parts was fabricated using 3D printing. In parallel, an AI-based computer vision system was developed, which included creating a custom dataset, training a YOLO object detection model, and formulating the kinematic equations (IK/FK) necessary for autonomous control.

As of the conclusion of the internship period, the project has successfully reached the **pre-assembly stage**. A complete and validated set of digital assets (CAD models, CAE results), all required physical components (3D printed parts, ordered hardware), and a functional AI perception model are ready for the final integration phase. The hardware assembly was not completed due to the time constraints inherent to the internship schedule.

5.2 Key Achievements

Despite the incomplete assembly, the project yielded several significant technical achievements that form a solid foundation for the robot's future completion. The key achievements include:

- **A Complete and Validated Mechanical Design:** A fully detailed 4-DOF SCARA robot was designed in CAD, and its structural integrity was successfully verified through Finite Element Analysis.
- **Successful Rapid Prototyping:** All custom structural components were successfully fabricated using 3D printing, demonstrating the viability of additive manufacturing for this application.
- **A Functional AI Vision System:** A custom YOLO model was trained and validated, capable of accurately detecting and locating target objects in real-time.
- **A Comprehensive Control Blueprint:** The necessary kinematic models and coordinate transformation logic were developed, creating a complete software framework for autonomous operation.

5.3 Challenges Encountered and Solutions

Several technical challenges were encountered during the project, providing valuable problem-solving experience.

- **Dimensional Accuracy of 3D Prints:** A primary challenge was ensuring a precise fit for mechanical components like bearings within the 3D-printed parts. This was addressed by methodically calibrating printer parameters and applying a negative

Horizontal Expansion setting in the slicing software to compensate for material extrusion.

- **Time Management for a Complex Project:** The most significant challenge was the limited timeframe of the internship. To manage this, the project scope was strategically focused on completing all foundational design, validation, and prototyping stages, ensuring a robust and well-documented base for future work rather than rushing an incomplete assembly.

5.4 Personal and Technical Skill Development

This internship was a profound learning experience that significantly enhanced both technical and personal skills.

- **Technical Skills:** Practical proficiency was gained in advanced software tools, including **Autodesk Fusion 360** for complex part and assembly modeling and **ANSYS** for performing FEA. Hands-on skills were developed in 3D printer operation, AI model training, and the practical application of robotic kinematics.
- **Personal and Professional Skills:** The project cultivated strong **project management** skills, including phase planning and creating a Bill of Materials. It provided deep insight into the professional R&D process and fostered the ability to integrate different engineering disciplines—mechanical, electrical, and software—to create a cohesive mechatronic system.

Future Work and Potential Improvements

The successful completion of the foundational work opens up clear pathways for the project's continuation and enhancement.

- **Immediate Future Work:** The primary next step is the complete mechanical and electrical assembly of the robot. This will be followed by the calibration of the joints and the vision system to ensure positional accuracy. Finally, the AI control software will be integrated to conduct full-system tests of the autonomous pick-and-place capabilities.
- **Potential Improvements:** For future iterations, the robot's performance could be enhanced by designing a more versatile, modular gripper system. The control algorithms could be optimized for increased speed and smoother motion paths. Additionally, the vision system could be expanded to classify multiple types of objects, making the robot more adaptable to different tasks.

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Appendices

Appendix A: Detailed Bill of Materials (BOM)

Table A-1: Bill of Materials

Item No.	Component Name	Specification	Category	Quantity
1	NEMA 17 Stepper Motor	1.8-degree step, 42mm	Electronic	4
2	Arduino UNO	R3 with ATmega328P	Electronic	1
3	CNC Shield	Version 3	Electronic	1
4	A4988 Stepper Driver	With heatsink	Electronic	4
5	DC Power Supply	12V, 6A	Electronic	1
6	Thrust Ball Bearing	40x60x13mm (for Joint 1)	Mechanical	2
7	Thrust Ball Bearing	35x52x12mm (for Joint 2/3)	Mechanical	4
8	Radial Ball Bearing	For various joints	Mechanical	6
9	Linear Ball Bearing	10mm ID	Mechanical	4
10	GT2 Timing Belt	200mm, 300mm, 400mm lengths	Mechanical	Various
11	Smooth Rod	10mm diameter, 400mm length	Mechanical	4
12	Lead Screw	8mm diameter, 380mm length	Mechanical	1
13	M3, M4, M5 Bolts & Nuts	Various lengths	Mechanical	Various
14	3D Printed Parts	Base, Arm 1, Arm 2, Couplers, etc.	Structural	35 parts

Appendix B: Key Engineering Drawings

- This appendix contains the 2D orthographic engineering drawings for the key custom components designed for the SCARA robot. The drawings are created to standard engineering practices and include critical dimensions, tolerances, and title blocks.

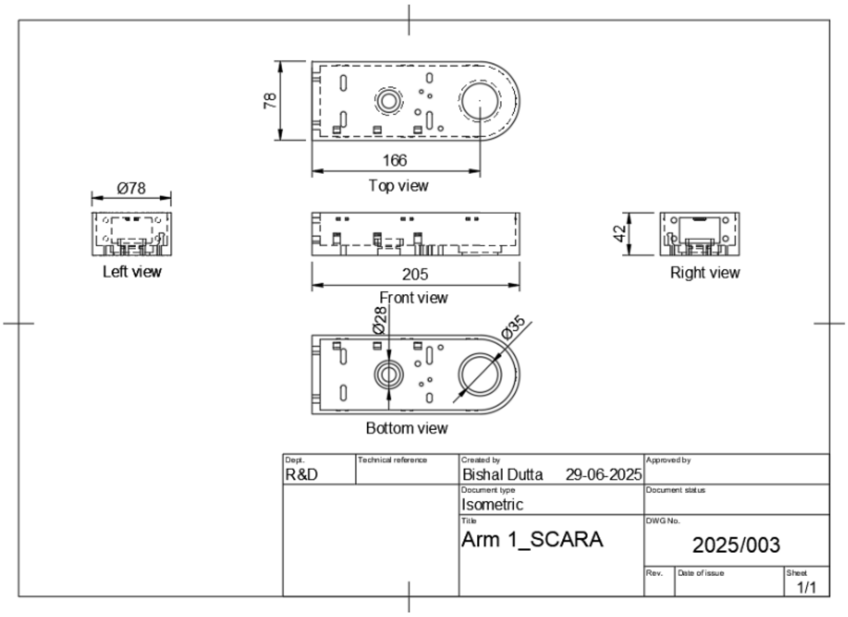

Figure : Drawing B-1: Arm 1

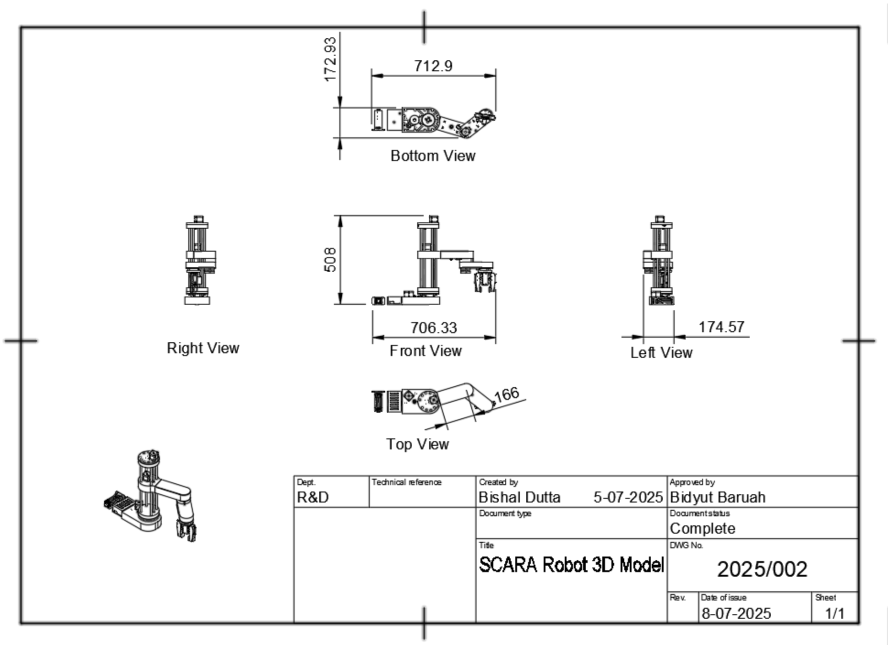

Figure : Drawing B-2: SCARA Robot