Development of control system for actuation control and navigation of an autonomous mobile robot using ROS2

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Abstract- This research explores the design and development of a control system using the robot operating system (ROS) for an autonomous mobile robot (AMR) integrated with a 5-dof robotic arm the system is designed to enable autonomous navigation and precise object manipulation focusing on real-time synchronization between both systems the amr utilizes a 2d lidar sensor to perform simultaneous localization and mapping slam for navigation allowing it to autonomously map its surroundings and avoid obstacles in dynamic environments additionally a vision-based object detection system provides the robotic arm with 3d spatial data enabling it to identify approach and manipulate objects accurately this dual-sensor approach enhances the amr adaptability enabling seamless navigation and object interaction across unstructured and complex spaces to achieve precise object handling.

Keywords - Autonomous Mobile Robot, ROS, 5-DOF Robotic Arm, Simultaneous Localization and Mapping (SLAM),3D Vision System, Real-Time Navigation

1. INTRODUCTION

In the current technological advancement, the establishing manufacturing system alone is not perfect to ensure the sustainability of companies. Therefore, the integration of industry 4.0 is introduce [1].

The integration of Autonomous Mobile Robots (AMRs) with robotic arms represents a transformative approach to automation, addressing the complex needs of industries like logistics, warehousing, and manufacturing. In these environments, precision, adaptability, and operational efficiency are key to handling a high volume of tasks and ensuring uninterrupted workflows. AMRs, known for their autonomous navigation capabilities, are adept at moving through dynamic environments while avoiding obstacles and adjusting to constantly changing surroundings. In the field of robotics, mobile robot manipulators are generally combination of manipulator arm integrated with a movable base for performing remarkable jobs routinely in industries [2].

When combined with robotic arms, these systems extend their capabilities beyond simple mobility, enabling tasks such as object picking, placement, and sorting—functions that demand dexterity and precision. AMRs are depend on the widely adopted Robot Operating System (ROS) environment for the execution of autonomous operations. ROS offers a software packages and tools aimed at facilitating the programming and control of autonomous robots [3].

Modern industrial environments, especially large-scale facilities such as warehouses, require automated solutions that can handle various types of objects and adapt to different spatial configurations across multiple locations. A combined AMR and robotic arm system provides a unified solution that streamlines both navigation and manipulation tasks, reducing the need for separate systems or manual intervention. By incorporating both autonomous navigation and manipulation capabilities in a single, integrated system, such robots can optimize workflows, reduce labor costs, and maintain a higher level of operational efficiency. This project leverages the power of the Robot Operating System (ROS), an open-source framework widely used in robotics, to create a control system that synchronizes both navigation and object-handling capabilities. Using a 2D lidar sensor for navigation and a 3D vision system for object detection, the project's design enables the AMR to operate in complex environments while performing essential object-handling tasks autonomously. ROS's extensive libraries and tools provide the foundational support needed for both real-time communication and efficient processing, facilitating seamless coordination between the AMR and robotic arm as they execute tasks. Traditional automation solutions in dynamic environments encounter several limitations that reduce efficiency. Common challenges include difficulties with real-time mapping and obstacle avoidance, especially in spaces where the layout or objects may change frequently. Many AMRs face constraints in navigation accuracy, which impacts their ability to perform tasks reliably in complex environments. Similarly, robotic arms mounted on mobile platforms often struggle with handling diverse objects in varying orientations, which can hinder task completion or require frequent adjustments. Moreover, achieving efficient multi-sensor integration is a significant technical challenge, as the robot must interpret data from multiple sources to form a comprehensive understanding of its surroundings. Without this integrated perspective, the robot's ability to navigate and manipulate objects with precision and adaptability is limited. The primary objective of this project is to develop a ROS-based control framework that empowers an AMR equipped with a robotic arm to navigate and handle objects autonomously in complex, dynamic environments. This system employs a 2D lidar sensor with Simultaneous Localization and Mapping (SLAM) to generate accurate, real-time maps, allowing the AMR to navigate fluidly while avoiding obstacles, even as its surroundings change. In tandem with this, the project utilizes a 3D vision-based object detection system, which enables the robotic arm to accurately locate, identify, and manipulate objects within its environment. This capability is essential for tasks that require precise interactions, such as picking, placing, and organizing items in 3D space. The seamless integration of lidar and vision sensors within this ROS-based framework ensures that both navigation and manipulation tasks are coordinated and performed in real time, providing a holistic system that is well-suited for complex automation scenarios. The project's focus on sensor integration allows the AMR to respond dynamically to its environment, improving adaptability and precision across diverse tasks. By meeting these objectives, the system aims to enhance automation capabilities in warehousing, logistics, and similar settings, where efficiency and versatility are critical. The concept of robots finds its roots in science fiction literature. Their evolution from fictional constructs to tangible realities gained significant momentum between 1917 and 1921. During this period, the capek brothers, Joseph and Karel, authored stories that not only explored the concept of intelligent automation but also coined the term "robot," derived from the Czech word "robota" signifying servant or worker [4].

The field of robotics has evolved to enable human-robot collaboration in tasks that are too complex to be fully automated or too costly to automate entirely. Collaborative robots (Cobots) have facilitated human-robot interaction (HRI) by allowing safe workspace sharing with human workers, in contrast to traditional industrial robot systems that require robots to be isolated from human co-workers to avoid accidents [5][6].

Machine vision (MV) system, which utilizing the optical tools and computer technology, could be applied to collect object data for processing and comprehension as well as to simulate human visual function [7].

It has been widely used in automobile, transportation, pharmaceutical, aerospace, military, and many other fields [8]

2. SYSTEM ARCHITECTURE

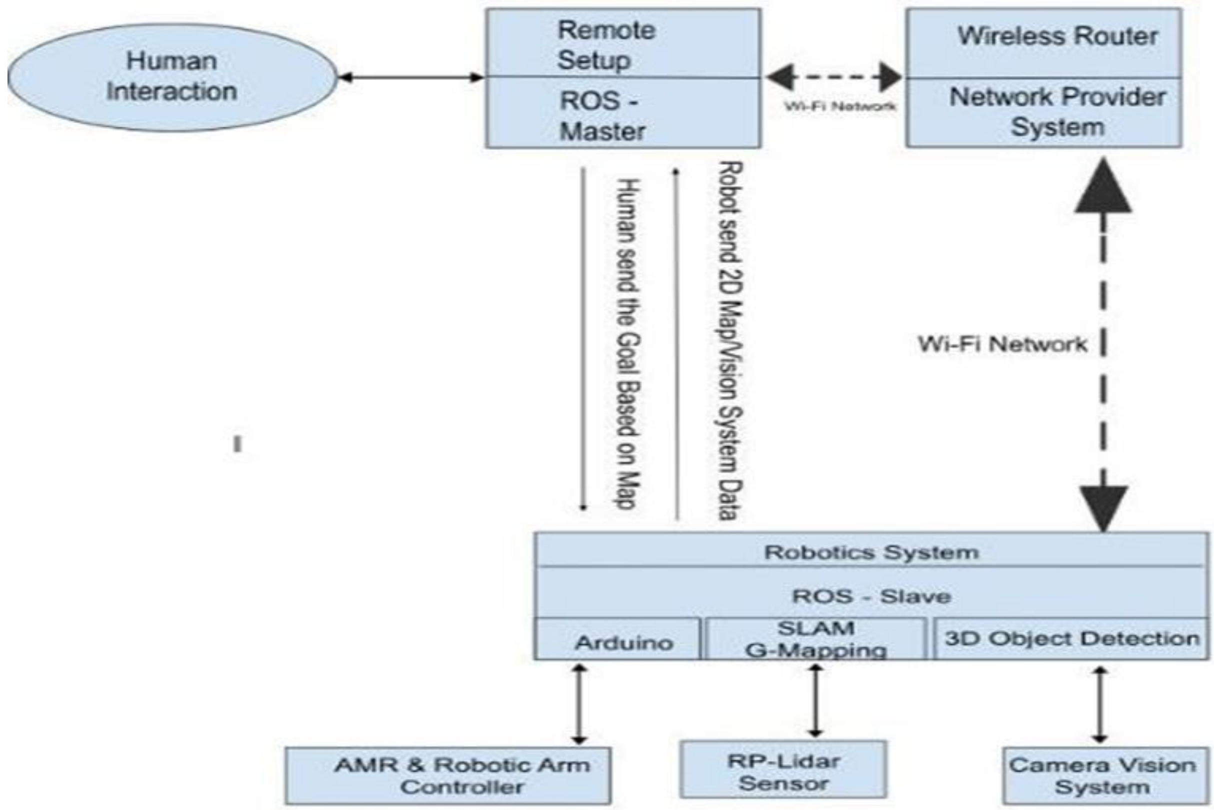
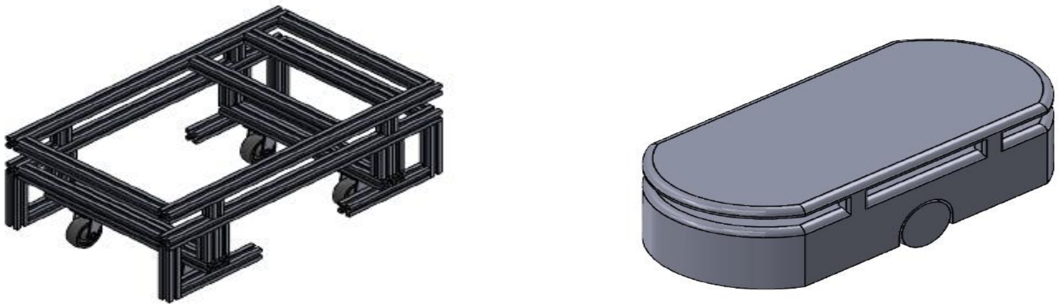


Figure 1: System Architecture

This system architecture for the Autonomous Mobile Robot (AMR) is designed to facilitate autonomous navigation and object handling through a combination of ROS (Robot Operating System), SLAM (Simultaneous Localization and Mapping), and vision-based object detection. The human operator sends goal commands through the Remote Setup (ROS Master), which is connected to the AMR via a Wi-Fi network. These commands are then relayed to the robot's Robotics System (ROS Slave) setup, enabling seamless communication and control over the robot's activities. The wireless router and network provider system manage this connectivity, ensuring that data flows consistently between the remote operator and the robot, enabling real-time control and monitoring. The Robotics System on the AMR side comprises several modules, each with a specific function. The Arduino module controls the AMR and robotic arm, handling the robot's movement and object manipulation tasks. The SLAM G-Mapping module uses the RP-Lidar sensor to create a 2D map of the environment, allowing the robot to understand its surroundings and plan paths accordingly. Additionally, the 3D Object Detection module leverages a Camera Vision System to detect and recognize objects in the environment. This data is crucial for the robot's object-handling capabilities, as it enables the AMR to identify and approach objects autonomously. The system's design allows the robot to handle complex tasks in a dynamic 3D environment by combining mapping and vision capabilities. Feedback from the robot’s sensors is sent back to the ROS Master over Wi-Fi, providing the human operator with real-time data on the robot's position, environmental map, and object status. This setup enables the AMR to operate effectively in diverse scenarios, adjusting to changes in the environment and executing tasks autonomously based on the received goals. The integration of these components into a ROSbased architecture ensures flexibility, scalability, and robust control for autonomous navigation and object handling.

3. DESIGN



(a) (b)

Figure 2: Design of AMR (a) Aluminium frame & (b) Coated Body

The AMR having torque 22.5076 Kg-Cm for 10Kg payload capacity. According to this torque the motors are selected for the AMR as DC motor with Encoder. The Encoder are used for feedback the motion of that motors.

II. Robotic Arm

Below is the design of Robotic Arm which having payload capacity of 1 kg. The Gripper is made as per industrial standard so that it can pick any object in 3D space. If the object is either tilt or not in specific position then also it can pick the object by adjusting their gripper position by using Vision system. The robotic arm having 5 Degrees of freedom including the movement of gripper, that mean it can move in 5 different way. The gripper is attached to 4 link of robotic arm which is rotate in 360 degrees so that it takes the exact position for picking and placing the objects.

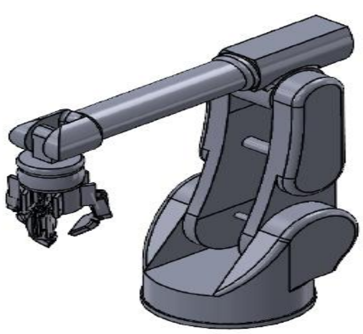


Figure3:Design of Robotic Arm

According to DH parameter (as shown in table 1) the torque of the motors that are used to pick or place the object of 1kg payload. By using this table we find the torque for the motor joints. So, by doing all the calculation we integrate both the design and figure 4 shows exact design of robot

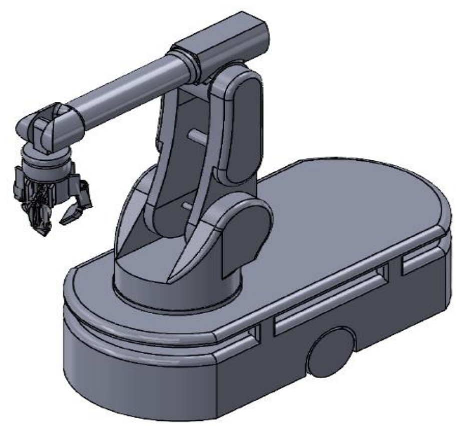


Figure 4: Design of Integration of both AMR and Robotic Arm

Joint(i)	Link length(a)m	Twist angle(α)	Joint offset(d)	Joint angle(ϴ)
1	0	90	0	0
2	0.1414	0	0	45
3	0.3	0	0	90
4	0.4	180	0	45
5	0.115	0	0	-90

Table 1: DH parameter of robotic arm

III. Gripping force and Torque

Gripping force required to prevent the object from slipping is given by:

$$Fg = \frac{W}{2\mu} \text{ x s} \quad (1)$$

Weight of Object (W) = 1 x 9.81 N (2)

Friction coefficient (μ) = 0.5 (3)

Safety Factor(S) = 2 (4)

By calculating the weight of and object, friction coefficient and safety factor in equation (2), (3) and (4). Substitute that in equation (1):

$$\text{Gripping Force (Fg)} = \frac{9.81}{3*0.5} \text{ x } 2$$

Fg = 13.08 N (5)

So that gripping force is calculated for 1Kg payload is 13.08N.

The torque also depends on the design of the gripper, particularly the distance from the pivot point (joint) of the gripper finger to the point where the force is applied (i.e., the contact point with the object).

Therefore, it is calculated as 6.66 Kg-cm.

We take different object for operation as box and Rod as shown in figure 5.

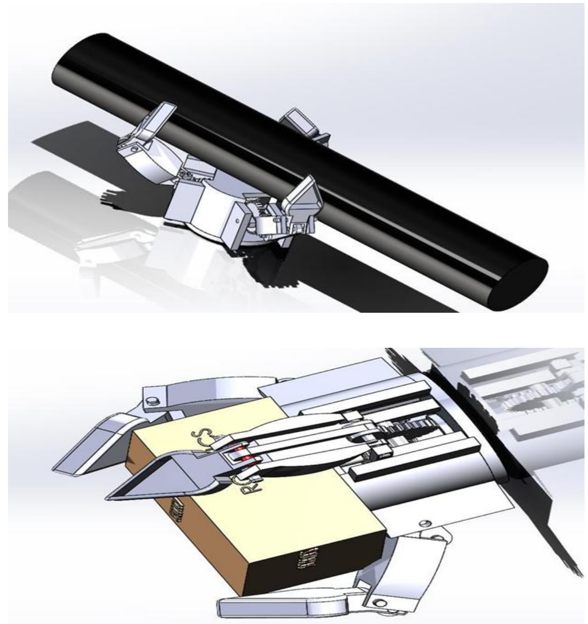


Figure 5: Different object are pick by the gripper

4. ANSYS

From the above calculation of the torque and force we do ANSYS and from this we can say that our design is great to fit and having no deformation for the 8 kg payload capacity. The equivalent stress is of 2.4395e6 is occurred at the joints of top plate.as shown in figure. And total deformation is of 9.6075e6 occurred at same place.

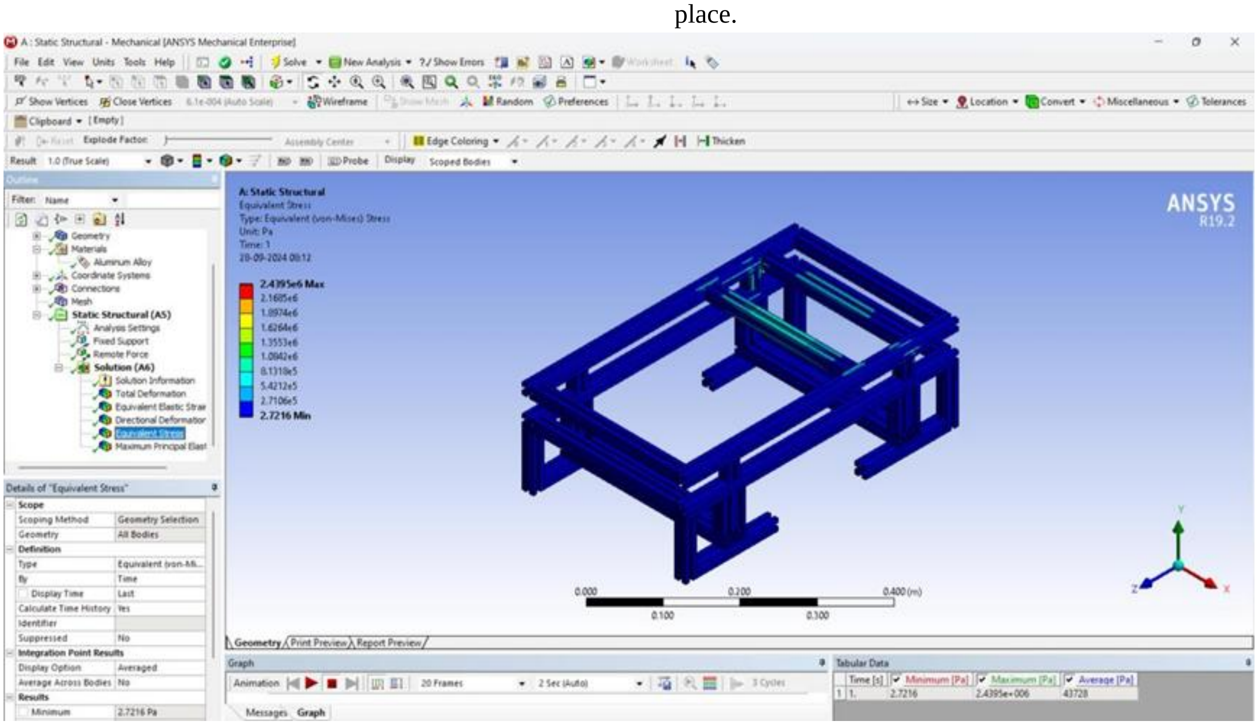


Figure 6: Equivalent Stress

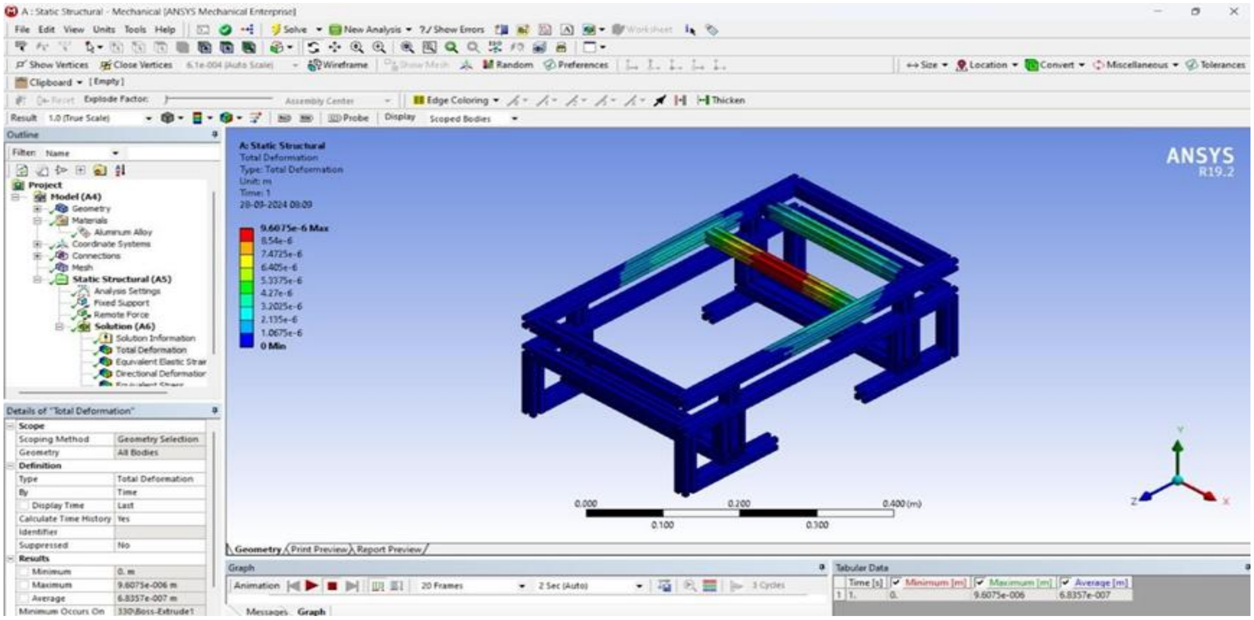


Figure 7: Total Deformation

5. CIRCUIT DIAGRAM

The circuit diagram having 4 different circuit for the specific controls as for Main power supply, USB connection for Camera and Lidar sensor through Raspberry pi and rest of 2 circuit are for motor controlled of AMR and Robotic Arm. The wiring diagram as shown in figure 8 depicts a setup for a Main power supply, which includes key components for controlling motors and servos. A battery serves as the primary power source, delivering DC power to the circuit. Buck converters are employed to step down the battery voltage to suitable levels required by various components. The central control unit is a Raspberry Pi, which runs the software to manage the system, sending control signals to different motor drivers. A primary motor driver is connected to manage larger motors, allowing for bidirectional control and speed adjustments. Additionally, a micro motor driver is incorporated to handle smaller motors with lower current needs. To control multiple servos, a PWM (Pulse Width Modulation) servo controller is used, providing precise position control for each servo motor. This configuration ensures effective power distribution and control signal management, enabling coordinated motor and servo operation for applications like robotics.

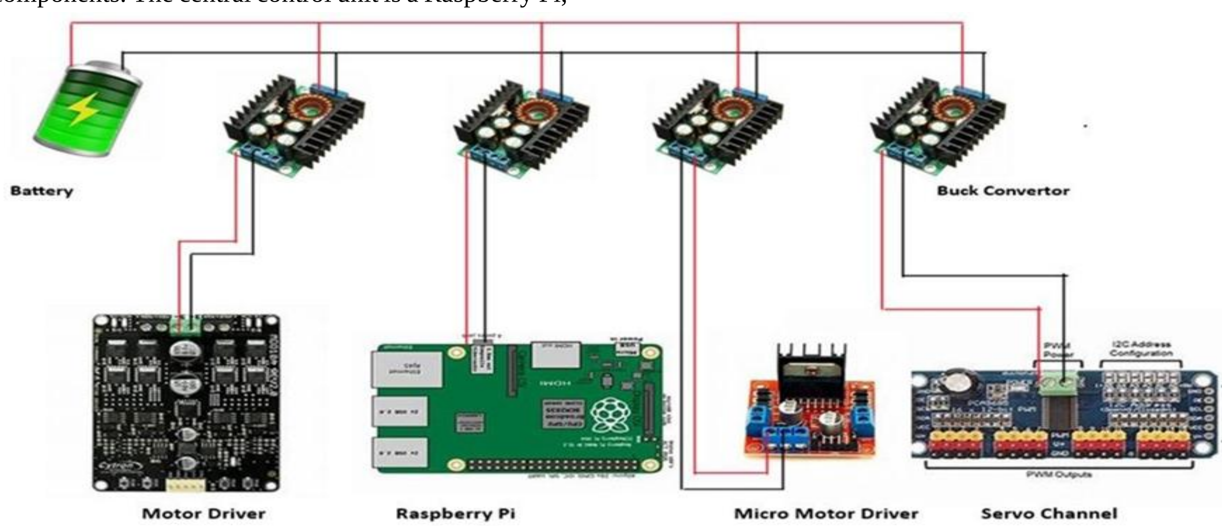


Figure 8 : Circuit Diagram of Main Power Supply

The diagram (shown in figure 9) represents a USB-connected setup for an Autonomous Mobile Robot (AMR) using ROS. At the core is a Raspberry Pi, which serves as the main processing unit and manages real-time communication across all components. A USB-connected camera provides vision data for tasks like object detection, publishing images to ROS topics for processing. This camera is situated at gripper for the object detection purpose. The RPLIDAR A1M8, also connected via USB, supplies 2D lidar data essential for navigation and obstacle detection. Additionally, two `Arduino boards are linked via USB to control the robot's motors and actuators. These Arduinos receive movement commands from the Raspberry Pi and send feedback, such as encoder data, enabling precise movement control. Through ROS, this setup coordinates the data from the camera, lidar, and motor feedback, facilitating autonomous navigation and object handling.

Figure 9 : Circuit design for camera and LIDAR sensor

This wiring diagram (as shown in figure 10) presents a system for controlling two encoder motors with an Arduino Mega and a motor driver board. The Arduino Mega serves as the central controller, sending commands to the motor driver through various connections, including power, ground, and control signal lines. Each motor includes an encoder, which provides essential feedback on the motor's position, speed, and direction, feeding this data back to the Arduino. With this closed-loop setup, the system can accurately adjust motor functions, achieving precise speed and position control. This design is ideal for robotics and automation projects that require synchronized movement and real-time feedback.

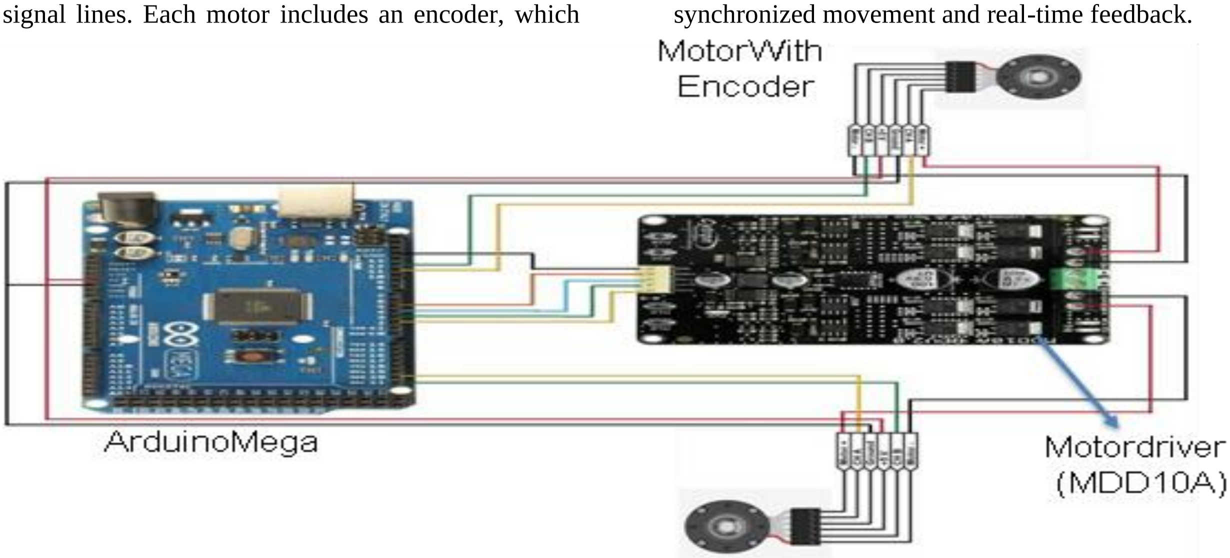


Figure 10 : Circuit Diagram of AMR motor controlled

This wiring diagram (see figure 11) shows a robotic setup where an Arduino Mega 2560 controls multiple servos and a DC motor for operating a gripper. The Arduino communicates with a PWM servo driver board via I2C, allowing it to manage multiple servos independently. These servos are ideal for precise movements, such as those required for a robotic arm or other articulated parts. By expanding the number of PWM outputs, the servo driver board enables the Arduino to control each servo with detailed position control, making it suitable for complex robotic tasks. Additionally, the Arduino is connected to an L298N motor driver, which operates a DC motor dedicated to the gripper mechanism. The motor driver controls the direction and speed of the DC motor, allowing the gripper to open and close with precision. The Arduino sends control signals to the motor driver, which adjusts the DC motor based on the required grip strength and position. This setup enables coordinated control of both the gripper and other servo-driven components, making it highly effective for versatile robotic applications.

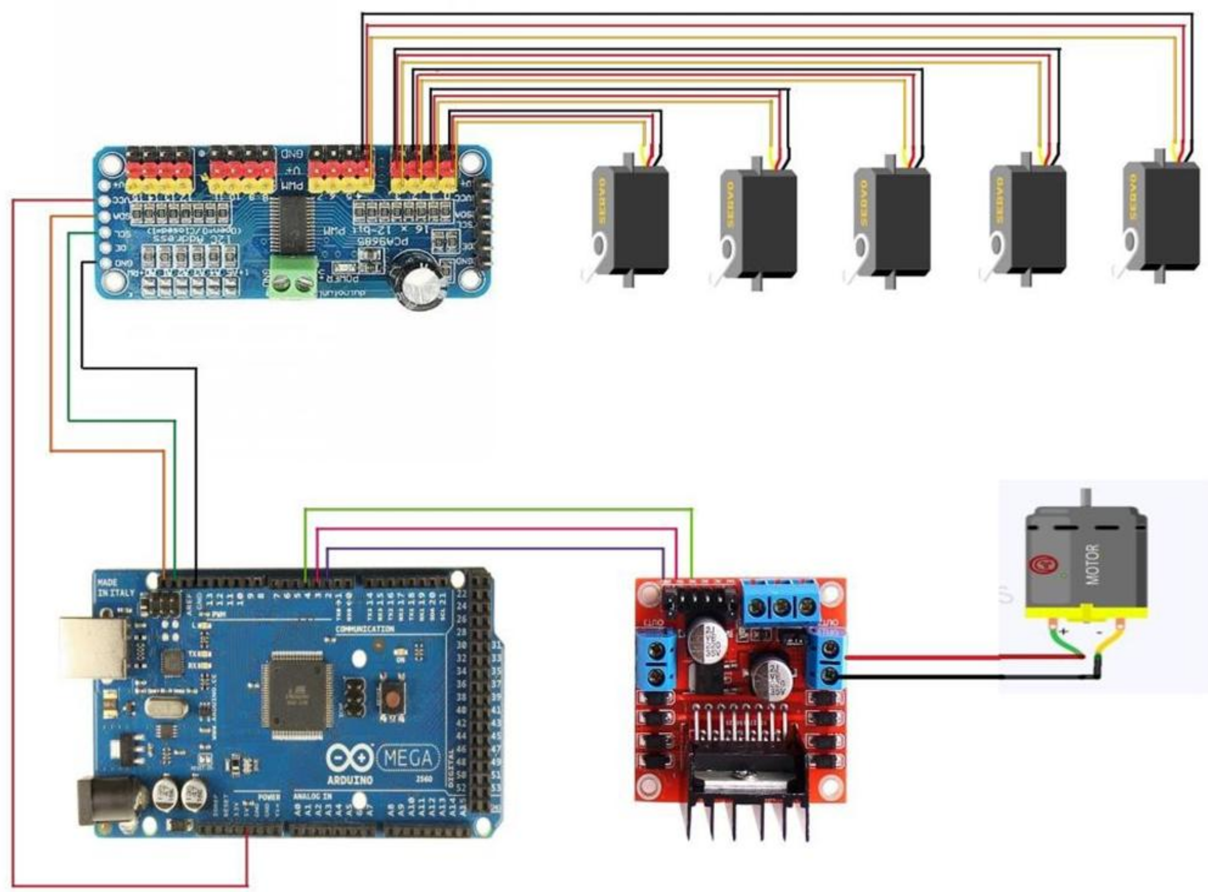


Figure 11 : Circuit design of Robotic Arm

In this study, we successfully designed and developed a ROS-based control system that integrates an autonomous mobile robot with a robotic arm for effective object handling and navigation in dynamic environments. This integrated system utilizes SLAM for precise navigation and localization, while the robotic arm, equipped with a vision system, demonstrates efficient object recognition and manipulation in 3D space. Our approach addresses key challenges in autonomous object handling, particularly in enhancing spatial awareness and adaptability of the AMR in complex settings. Experimental results indicate that our system achieves reliable navigation accuracy and stable grasping, laying a solid foundation for further exploration in multi-robot coordination and expanded automation applications. This research contributes to advancements in robotic autonomy and ROS-based control integration, providing a scalable solution for various industrial and research-based applications in object handling and navigation.

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