CYPRUS INTERNATIONAL UNIVERSITY

FACULTY OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

DIGITAL TECHNOLOGIES IN INDUSTRY

By

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OLUTOYE OPEYEMI

Date: February 12, 2025

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ABSTRACT

The research introduces CIU_Fox as an autonomous guided vehicle (AGV) that develops capabilities to transform factory and warehouse internal transportation operations. The designed AGV features autonomous navigation with a safe lifting capability using obstacle detection and collision avoidance systems for moving loads up to 200 kg. This system combines LIDAR with time-of-flight (ToF) sensors and barcode scanners to create a precise automated navigation system which monitors operations and handles loading duties. The mechanical structure incorporates an aluminum alloy frame together with a scissor-compartment mechanism and NEMA 23 stepper-motor powered differential steering. A Raspberry Pi 4 manages the system through ESP32 modules that run software programs built in Python and C++ within the ROS framework. The robot development followed four sequential stages that led to its physical assembly. Resources limitations required the project team to conduct final stage testing through the Gazebo simulation pipeline instead of building physical components. Coding for path planning alongside obstacle avoidance and load management functions while achieving complete integration of mechanical electronic software system components stands as major accomplishments. The commercial application scope of the AGV remains promising in multiple industrial sectors including manufacturing storage facilities and logistics operations because it shows potential to optimize operational efficiency while decreasing expenses and protecting worker safety. This work illustrates why interdisciplinary teams need to bring innovative solutions to modern industrial design using state-of-the-art technology applications. Research efforts will focus simultaneously on two fronts which include enhancing the AGV's operational excellence while evaluating opportunities to connect it with broader industrial system networks.

ÖZET

Araştırma, fabrika ve depo içi taşıma operasyonlarını dönüştürme yetenekleri geliştiren özerk bir yönlendirmeli araç (AGV) olarak CIU_Fox'u tanıtmaktadır. Tasarlanan AGV, 200 kg'a kadar yük taşıyabilmek için engel algılama ve çarpışma önleme sistemleriyle donatılmış güvenli kaldırma kabiliyetine sahip otonom navigasyon özellikleri sunar.

Bu sistem, operasyonları izleyen ve yükleme görevlerini gerçekleştiren hassas bir otomatik navigasyon sistemi oluşturmak için LIDAR, zaman-uçuşu (ToF) sensörleri ve barkod tarayıcıları birleştirir. Mekanik yapı, alaşımlı alüminyum çerçeve, makaslı kompartman mekanizması ve NEMA 23 step motorla çalışan diferansiyel yönlendirme sistemi içerir.

Sistem, ROS çerçevesinde Python ve C++ ile geliştirilen yazılım programlarını çalıştıran ESP32 modülleri aracılığıyla bir Raspberry Pi 4 tarafından yönetilir. Robot geliştirme süreci, fiziksel montaja kadar uzanan dört aşamalı bir sırayla tamamlanmıştır. Kaynak kısıtlamaları nedeniyle fiziksel bileşenler yerine Gazebo simülasyon ortamında son aşama testleri gerçekleştirilmiştir. Yol planlama, engel önleme ve yük yönetimi fonksiyonlarının kodlanması ile mekanik-elektronik-yazılım bileşenlerinin tam entegrasyonu projenin temel başarıları arasındadır.

AGV'nin ticari uygulama kapsamı, üretim tesisleri, depolama alanları ve lojistik operasyonlar gibi çeşitli endüstriyel sektörlerde operasyonel verimliliği artırma, maliyetleri düşürme ve işçi güvenliğini koruma potansiyeli nedeniyle umut vaat etmektedir. Bu çalışma, disiplinlerarası ekiplerin en son teknoloji uygulamalarını kullanarak endüstriyel tasarıma yenilikçi çözümler getirmesi gerektiğini vurgulamaktadır. Araştırma çabaları, AGV'nin operasyonel mükemmelliğini artırmanın yanı sıra endüstriyel sistem ağlarına bağlanma fırsatlarını değerlendirmek üzere iki paralı hedefe odaklanacaktır.

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Chapter 1

INTRODUCTION

The manufacturing industry is undergoing a digital transformation, driven by advancements in technologies like artificial intelligence, autonomous robots, and the Internet of Things. These innovations aim to enhance efficiency, productivity, and competitiveness in industrial processes. TEKNOFEST's Digital Technologies in Industry Competition challenges participants to design an autonomous guided robot for factory logistics, addressing real-world tasks such as navigation, load handling, and mapping. This report explores the strategies used to overcome these challenges and achieve the competition's objectives. By doing so, it highlights the critical role of digitalization in advancing industrial automation and fostering innovation.

1.1 TEKNOFEST COMPETITION RULES

The following rule apply to the operation of guided robots during the competition:

1.1.1 Autonomous Operation

The guided robot must perform all tasks autonomously within the specified scenarios, including line-following.

1.1.2 Overload Warning

The robot must issue an overload warning if it lifts a load exceeding the specified limit and continue carrying the load only after the weight is reduced below the limit.

1.1.3 Charging Task

If the robot's charge level falls below a certain threshold, teams can earn additional points by having the robot autonomously navigate to the charging area and begin charging. Teams must inform the jury in advance if they wish to perform this task, which will be conducted at a time deemed appropriate by the jury.

1.1.4 Obstacle Navigation

The robot should autonomously stop at loading/unloading points and navigate around obstacles if they are not removed. Obstacles will be detected by sensors, and the robot must stop at an appropriate distance. If the obstacle remains, the robot should autonomously go around it and complete its tasks.

1.1.5 QRCODE Labels

QRCODE labels at loading and unloading positions must be readable by appropriate sensors on the robot.

1.1.6 Control Screen (GUI)

Teams must prepare a graphical user interface (GUI) that allows them to monitor the vehicle's status and issue commands when necessary. However, interventions via the control panel will incur penalty points.

1.1.7 No Manual Control

The robot cannot be controlled by joysticks, portable hand controls, phones, or tablets.

1.1.8 Load Handling Display

The pick-up or dropping of loads must be displayed on the control panel (GUI) using sensors.

1.1.9 Mapping for Advanced Competitors

Advanced-level competitors are required to map the track. For mapping, advanced teams will be given a specific amount of time after the loaded course is revealed. The teams are expected to map and display the competition area within the allocated time.

Mapping should be performed using devices such as laptops and tablets belonging to the team members at the control desk. Additionally, teams are expected to create a control

panel (GUI) that displays competition details such as speed and total task time. The mapping should be detailed, and QRCODE labels should be displayed on the map as they are read.

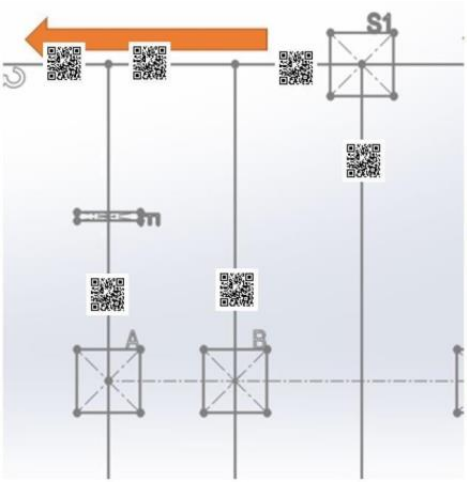


Figure 1.1: QRCODE Layout

1.2 DETAILS OF THE COMPETITION AREA

For the competition, there will be 2 rectangular-shaped representative factory areas of approximately 150 square metres each. These areas will include a track representing the layout of roads and internal logistics roads. Additionally, there will be a separate area where a table is located for each participating competitor team to use. The following details apply:

1.2.1 Power Supply

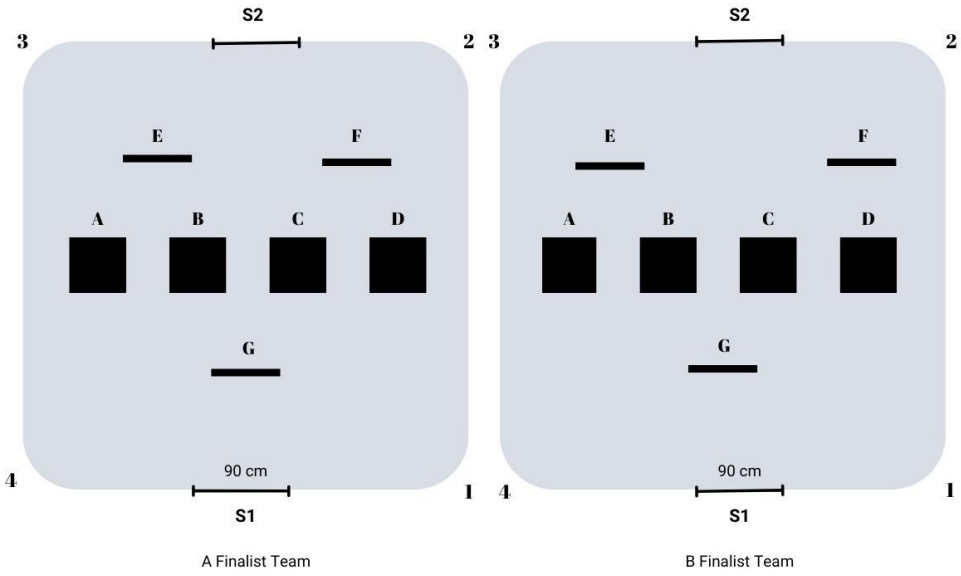
The competition area will have a 220 VAC power supply. A control desk will be located at the edge of the track for the competing team to control their guided robot. At the control desk, 220 VAC voltage will be provided, and each team is responsible for performing AC/DC conversion using their own converter. The highest DC voltage level that can be used is 50V.

1.2.2 Track Layout

The track will resemble a factory area with designated pick-up and drop-off points. The distribution of these points may vary for each competing team, as determined by the referees. The track area will consist of two similar sections, allowing two different teams to compete simultaneously.

1.2.3 Sample View of the Track

The sample view of the track will be provided separately for reference(fig. 1.3).



S1, S2 : Starting points
A,B,C,D : Load handling - Load unloading points
E,F : Fixed obstacle
G: Moving obstacle

Figure 1.2: Sample Track Area

1.3 LOAD HANDLING ROBOT TECHNICAL SPECIFICATIONS AND LIMITATIONS

The maximum dimensions of the load handling robot are as follows: 1,000 mm in length, 900 mm in width, and 500 mm in height. The dimensions of the load handling robots must not exceed these specified limits. However, when the mechanism used to lift the load platform is operated, the robot may exceed the height limit. The height restriction applies only to the situation where the vehicle is not operating under load.

The maximum load amount that robots must carry is 125 kg. Robots that lift more than 125 kg and do not provide an overload warning will be deemed to have failed to fulfill this task. The competition organization will provide loads with dimensions of 30 cm x 30 cm x 10 cm (fig. 1.3a)and a weight of 25 kg each. These loads will be placed on a platform with a maximum height of 50 cm from the ground)(fig. 1.3b), allowing the robot to easily position itself underneath and lift the load from all directions. The weight of the load platform provided by the competition organization will also be 25 kg.

The positions for load pick-up and drop-off will be defined using QRCODE tags. These tags will ensure precise identification of the designated locations for the robot to perform its tasks.

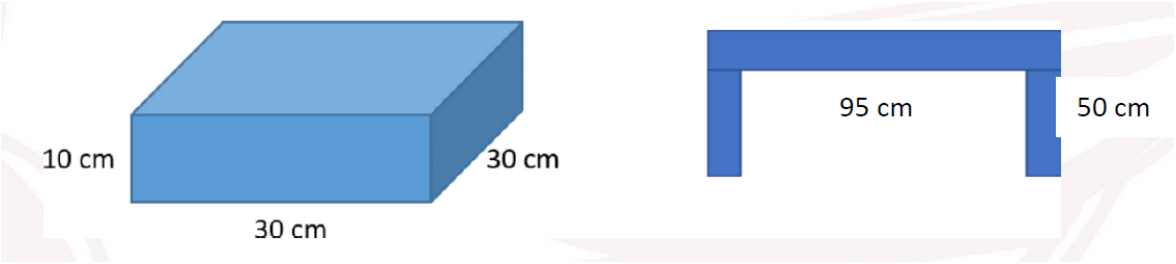


Figure 1.3: Load (a) and platform (b)

1.4 SAMPLE SCENARIO

The robot must first navigate around the corner points according to the scenario type, starting from the initial position without any load, and return to the starting point. During this process, teams are required to complete the mapping task. A total of four unloaded scenarios are illustrated in fig. 1.4.

Following the unloaded navigation, the robot should proceed to point A from the starting point to pick up a load and then continue to point C. Upon reaching point C, the robot must leave the load there and proceed to point D without carrying any load. After arriving at point D, the robot should pick up another load and transport it to point B. Once the load is delivered at point B, the robot must complete the task by returning to the starting point without any load. fig. 1.5 depicts four loaded scenarios, which vary depending on the starting points.

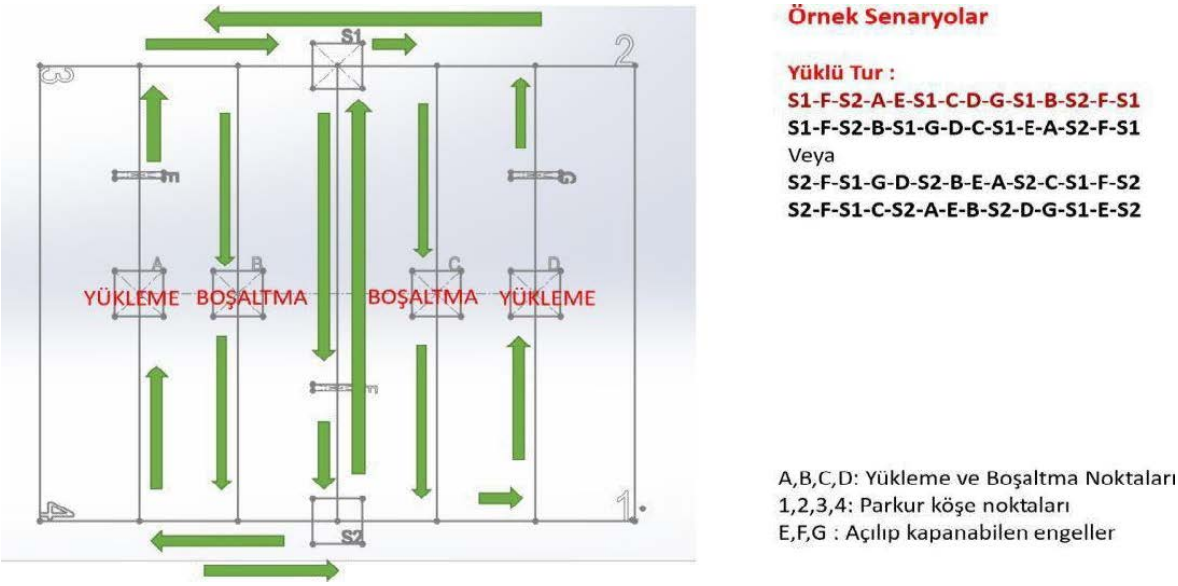


Figure 1.4: Sample Loaded Scenario

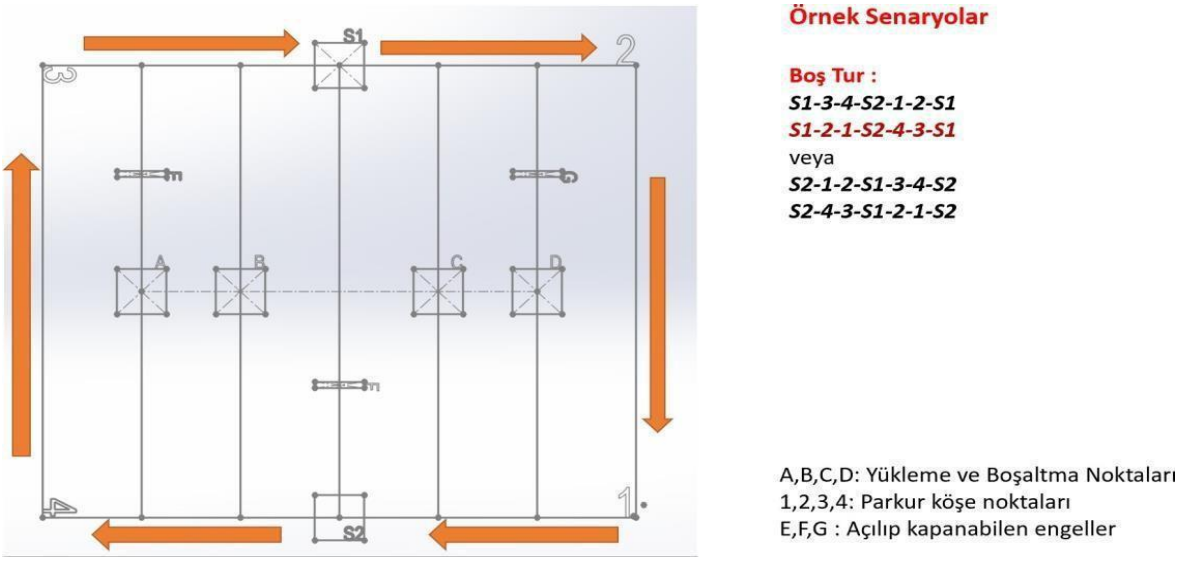


Figure 1.5: Example No Load Scenario

Chapter 2

LITERATURE SURVEY

Today's industries activity have merged with the robotic and automation world and day by day having the precise and betterquality product make the sense of using new technology. Between all types of robot, the AGV (automated guided vehicle) robot has the special place between others and improvement in technology helps this design to grow and become more helpful in various applications. The AGV robot is a programmable mobile robot integrated sensor device that can automatically perceive and move along the planned path [2] This system consists of various parts like guidance facilities, central control system, charge system and communication system [3].

The initial used and Invention AGV is not clear exactly and was mentioned in different articles and reference for many times but the earliest time of using this system in industries is mentioned in 1950s [4] (fig. 2.1) and even mentioned in some reference that the first AGV in the world was introduced in UK in 1953 for transporting which was modified from a towing tractor and can be guided by an overhead wire [3].

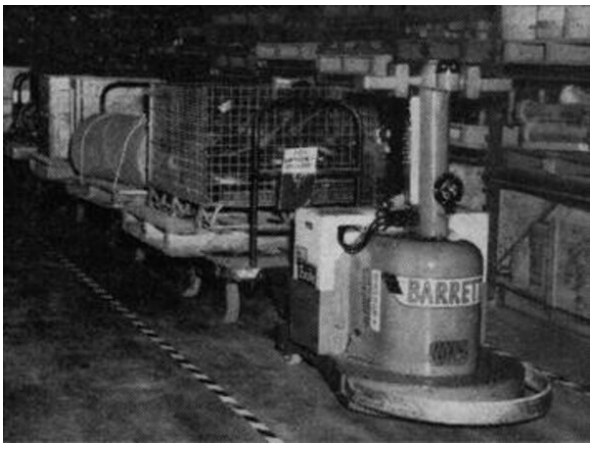


Figure 2.1: one of the Old AGV picture

AGVs are widely applied in various kinds of industries including manufacturing factories and repositories for materialhandling. After decades of development, it has a wide applica-

tion due to its high efficiency, flexibility, reliability, safety and system scalability in various task and missions. AGV operates all day long continuously that cannot be achieved by human workers. Therefore, the efficiency of material handling can be boosted by having the collaborating task with number of AGV . In this case, administrator can enable more AGVs as the system is extensible. AGV has capability of collision avoidance and emergency braking, and generally the running status is monitored by control system so that reliability and safety are ensured. Generally, a group of AGVs are monitored and scheduled by a central control system. AGVs, ground navigation system, charge system, safety system, communication system and console make up an AGV system. [5]. This report examines the design aspects and considerations for this type of robot, providing readers with key insights into the technologies commonly utilized in this field.

Chapter 3

Realistic Constraints

3.1 DESIGN CONSTRAINTS

3.2 ENGINEERING STANDARDS AND LIFELONG LEARNING

The successful deployment of an Automated Guided Vehicle (AGV) system relies heavily on adherence to established engineering standards. These standards provide a framework for the design, implementation, and operation of AGVs, ensuring they meet safety, reliability, and performance requirements.

Compliance with these guidelines is essential not only for regulatory approval but also for fostering a culture of continuous learning and improvement in AGV technology and its applications.

3.2.1 AGV Safety Standards and Their Importance

Various international standards govern the safety of AGVs, ensuring their integration into industrial, healthcare, and logistics environments without compromising human safety.

Notable among these are **ISO 3691-4** [6], which outlines safety requirements for driverless industrial trucks, and **ANSI/ITSDF B56.5** [7], which provides American safety guidelines for automated guided industrial vehicles.

The **EN 3691-4** [8] standard mirrors the ISO regulations for European markets, emphasizing risk reduction and operational reliability. Meanwhile, **RIA R15.08** [9]is an evolving effort to create comprehensive safety guidelines for mobile robots in industrial settings.

These standards establish essential safety features for AGVs, including **emergency stop mechanisms, audible alarms, warning lights, and collision avoidance systems**.

They also define environmental considerations such as clear pathways, adequate lighting, and obstacle detection to enhance the safe operation of AGVs.

Additionally, operational protocols for **startup, shutdown, emergency response, and**

periodic maintenance are emphasized to prevent malfunctions and ensure continuous performance.

3.2.2 Categorization of Machinery Safety Standards

Engineering safety standards are categorized into three types to ensure a structured approach to risk mitigation:

- **Type-A Standards:** These provide general safety principles applicable to all machinery, focusing on fundamental design requirements.

- **Type-B Standards:** These cover protective devices and safety measures that apply to a wide range of machines, ensuring standardization across different industries.

- **Type-C Standards:** These are specific to particular types of machinery, including AGVs, and take precedence over Type-A and Type-B standards when addressing specific risks.

While these standards ensure a structured approach to AGV safety, they do not account for additional hazards such as **severe environmental conditions, nuclear operations, or public-road navigation**, necessitating customized engineering solutions for such applications.

3.2.3 Designing AGVs for Public Interaction

Most AGVs are deployed in controlled industrial environments, operated by trained professionals.

However, in certain sectors, they may interact with **untrained personnel, visitors, or even the general public**.

For instance, in healthcare settings, robots used for hospital logistics must safely coexist with **doctors, nurses, patients, and visitors** who may be unfamiliar with automated systems.

Similarly, in retail and hospitality sectors, AGVs designed for service roles must incorporate intuitive safety mechanisms and user-friendly interfaces to prevent accidents.

To ensure safe public interaction, they must be designed with **intelligent obstacle detection, adaptive navigation, and fail-safe mechanisms** that allow them to adjust their behavior in real time.

Features such as **voice alerts, digital displays, and intuitive stop/start functionalities** help bridge the gap between automation and human interaction.

3.2.4 Lifelong Learning and Continuous Development in AGV Engineering

The field of AGV technology is rapidly evolving, necessitating **continuous education and lifelong learning** among engineers, operators, and industry stakeholders.

Given the advancements in **artificial intelligence, sensor technologies, and machine learning**, professionals must stay updated on emerging safety protocols, regulatory changes, and new engineering methodologies.

Training programs, certifications, and industry workshops play a crucial role in ensuring that **engineers, technicians, and operators** remain proficient in the latest AGV technologies.

Furthermore, the increasing adoption of **Robot-as-a-Service (RaaS)** models means that companies must not only invest in AGV technology but also continuously train their workforce to adapt to evolving automation trends.

Engineering standards form the backbone of AGV safety, reliability, and efficiency, guiding their deployment across various industries.

The integration of **rigorous safety measures, structured categorization of standards, and adaptive public interaction mechanisms** ensures that AGVs can function seamlessly while maintaining workplace safety.

Additionally, the fast-paced evolution of AGV technology demands a culture of **lifelong learning and professional development**, enabling engineers and industry professionals to keep pace with advancements in automation and robotics.

Through adherence to standards and continuous education, businesses can maximize the benefits of AGVs while fostering a safer, more efficient work environment

3.3 ECONOMIC ANALYSIS OF INDUSTRIAL AUTOMATED GUIDED VEHICLES (AGVS)

Developing Automated Guided Vehicles (AGVs) requires a substantial financial investment for engineers and companies aiming to automate material handling and logistics operations. While AGVs significantly enhance efficiency and productivity, a thorough economic analysis is essential to assess direct costs, such as equipment and installation, as well as indirect costs, including unforeseen expenses.

A well-planned budget and strategic approach ensure that the cost of building AGVs remains within the initial projected expenditure, preventing cost overruns and maximizing return on investment. Building Automated Guided Vehicles (AGVs) in the TRNC presents unique financial challenges due to the region's geographical location and limited local manufacturing capabilities. One of the most significant hurdles is the complexity of sourcing components, which often need to be imported from various countries such as China, Germany,

and the United States. This reliance on international suppliers introduces several direct and indirect costs that can strain budgets and complicate project timelines.

3.3.1 Sourcing Components Across Borders

The construction of AGVs requires highly specialized parts, including advanced sensors, navigation systems, robotic arms, and durable materials for vehicle frames. Many of these components are not readily available locally and must be ordered from manufacturers abroad. For example, high-precision sensors may come from Germany, battery systems from the United States, and certain electronic modules from China.

The process of coordinating shipments from multiple countries adds layers of complexity, delays, and additional expenses. Furthermore, some parts are custom-made to meet the specific requirements of the Teknofest competition, leading to longer lead times and higher procurement costs.

3.3.2 Direct Costs: Purchasing Parts and Shipping

The direct costs associated with building AGVs in the TRNC include the purchase price of components and shipping fees. Importing parts from distant countries like China or the U.S. involves significant freight charges, especially for bulky or heavy items such as motors and chassis materials.

Additionally, currency exchange rates can further inflate costs, as fluctuations may increase the price of goods purchased in foreign currencies. These factors make it difficult to accurately forecast expenditures and maintain budgetary control during the development phase.

3.3.3 Indirect Costs: Taxes, Customs Fees, and Regulatory Compliance

Beyond the direct costs, there are substantial indirect costs tied to importing parts into the TRNC. Customs duties, value-added taxes (VAT), and other regulatory fees can add a considerable percentage to the overall cost of components. For instance, certain high-tech equipment may attract steep import tariffs, while VAT rates in the region can further escalate expenses.

These regulations requires expertise and administrative effort, which can divert resources away from core engineering tasks. Moreover, delays at customs due to paperwork issues or inspections can disrupt production schedules, causing additional financial strain.

3.4 SUSTAINABILITY

The integration of Automated Guided Vehicles (AGVs) in material handling and logistics has ushered in a new era of sustainability, offering significant advantages over traditional methods such as forklifts.

As industries increasingly prioritize environmentally friendly solutions, these vehicles have emerged as a critical component in reducing environmental impact while simultaneously improving operational efficiency. Their ability to operate on electric power, optimize movement, and minimize waste positions them as a sustainable choice for modern warehouses and logistics operations.

One of the most notable contributions to sustainability is their energy efficiency. Unlike conventional forklifts, which rely on fossil fuels and emit harmful pollutants, these systems are electrically powered, producing zero direct emissions. Equipped with advanced route optimization and intelligent navigation, they ensure the most efficient paths, reducing unnecessary energy consumption.

Furthermore, many modern models utilize lithium-ion batteries, which offer longer operational cycles and shorter charging times compared to traditional lead-acid batteries. Some even incorporate regenerative braking technology, enabling them to recover and reuse energy that would otherwise be lost, further enhancing their efficiency.

Another key advantage lies in their ability to reduce waste. With precise movement capabilities and advanced sensor technology, these systems minimize product damage during transportation, significantly lowering material waste. Traditional equipment, such as forklifts, often leads to inventory losses due to human error or accidents.

In contrast, these automated systems are designed to handle goods with care and accuracy, preserving inventory integrity. By preventing unnecessary waste and reducing the need for product replacements, they contribute to a more sustainable and cost-effective supply chain. Beyond energy efficiency and waste reduction, these vehicles also support sustainability through optimized space utilization and reduced labor dependency. Their compact design and ability to operate in tight spaces allow warehouses to maximize storage capacity, reducing the need for expansive facilities.

Additionally, they can operate continuously without fatigue, minimizing reliance on human labor and lowering operational costs over time. Beyond energy efficiency and waste reduction, these vehicles also support sustainability through optimized space utilization and reduced labor dependency. Their compact design and ability to operate in tight spaces allow warehouses to maximize storage capacity, reducing the need for expansive facilities. Additionally, they can operate continuously without fatigue, minimizing reliance on human labor and lowering operational costs over time.

3.5 ETHICAL IMPLICATIONS OF AGVS IN LOGISTICS AND MATERIAL HANDLING

Automated Guided Vehicles (AGVs) in logistics and material handling brings not only sustainability benefits but also significant ethical challenges. While AGVs enhance efficiency and reduce environmental impact, their adoption raises critical concerns related to job displacement, data privacy, workplace safety, and environmental responsibility. Addressing these issues is essential for businesses to ensure ethical and responsible implementation.

3.5.1 Job Displacement and Workforce Transition

The widespread adoption of AGVs and autonomous systems has the potential to disrupt not only individual workers but also entire communities and economies. As these technologies replace human labor in industries such as logistics, warehousing, and transportation, the ripple effects extend beyond job loss. Local economies that depend on these industries may experience reduced consumer spending, declining tax revenues, and increased demand for social services, creating a cycle of economic stagnation.

Furthermore, the displacement of workers in lower-wage, manual labor roles can lead to broader societal challenges, such as increased income inequality and reduced social mobility. Communities heavily reliant on these jobs may face higher rates of poverty and unemployment, exacerbating existing social divides. On a macroeconomic level, the shift toward automation could alter labor market dynamics, potentially leading to a mismatch between available jobs and the skills of the workforce.

3.5.2 Data Privacy and Security

Another ethical challenge is the handling of data collected by AGVs. These systems rely on advanced sensors, cameras, and AI-driven software to navigate and optimize operations. In the process, they gather vast amounts of data on operational efficiency, movement patterns, and even worker behavior. Without proper management, this data could be misused, leading to concerns about workplace surveillance and privacy violations.

3.5.3 Workplace Safety

Safety is a critical ethical consideration in AGV deployment. While AGVs are designed to reduce accidents and enhance workplace safety, their interaction with human workers requires careful oversight. Malfunctions, software errors, or unexpected obstacles could lead to accidents if safety protocols are not strictly followed. Employers must ensure that AGVs are equipped with reliable collision avoidance systems and that employees receive adequate

training to work alongside automated systems. Regular maintenance and system updates are also essential to prevent operational failures that could endanger workers.

3.5.4 Environmental Responsibility

Beyond operational sustainability, the environmental impact of AGV production and disposal raises ethical concerns. While AGVs contribute to greener logistics during their operation, their manufacturing involves resource-intensive components such as lithium-ion batteries. Responsible sourcing of materials, fair labor practices in manufacturing, and proper recycling programs for outdated AGVs are essential to minimize their environmental footprint. Companies must prioritize ethical supply chain practices to ensure that AGVs align with broader sustainability goals.

3.5.5 Balancing Technology and Ethics

The ethical deployment of AGVs requires a careful balance between technological advancement and corporate responsibility. Businesses must proactively address concerns related to employment, data privacy, safety, and environmental impact to ensure that AGVs benefit both operations and society. By adopting ethical frameworks alongside technological innovations, companies can harness the advantages of AGVs while upholding fairness, transparency, and sustainability in their practices.

3.6 EALTH AND SAFETY PROBLEMS

The integration of Automated Guided Vehicles (AGVs) in industrial and warehouse environments has revolutionized operational efficiency. However, safety remains a top priority. Modern AGVs are equipped with advanced sensor technologies that continuously scan their surroundings, dynamically adjusting detection ranges based on speed to minimize collision risks.

For instance, some of the latest automated forklifts incorporate dynamic sensors that monitor not only the vehicle's path but also its sides, ensuring swift responses to detected obstacles. If a person or object enters the AGV's field of view, the system can slow down within milliseconds or stop entirely if the obstruction is too close.

Beyond sensors, AGVs use visual and audio alerts to enhance workplace awareness. Before moving, they emit audible warnings to alert nearby personnel and then gradually accelerate. Their predictability—following fixed routes—further reduces the risk of unexpected encounters with workers or equipment.

3.6.1 Key Safety Measures for AGV Environments

To maintain a safe workplace, it is crucial to implement best practices for AGV operation:

- **Clear Travel Routes:** Obstructions reduce efficiency and create hazards. Workers should avoid stepping into AGV paths and always give them the right of way.
- **Restricted Areas:** Zones where AGVs handle heavy loads must remain off-limits to unauthorized personnel. These areas are clearly marked to indicate potential hazards.
- **Elevated Items:** AGVs may not always recognize objects raised high off the ground. To prevent accidents, elevated items must be kept out of AGV paths.
- **Blind Corners:** Facilities should implement safety measures such as mirrors and warning signals to alert personnel of approaching vehicles.

3.6.2 Regulatory Standards and Safety Guidelines

AGVs operate under strict safety standards to ensure workplace protection:

- The ANSI/ITSDF B56.5-2019 [6] guidelines specify requirements such as maintaining a minimum clearance of 0.5 meters (19.7 inches) on either side of an AGV's guidepath, except when a fixed structure is present.
- Restricted areas, where clearance is insufficient or escape routes are unavailable, enforce reduced AGV speeds to mitigate risks.
- The VDI 2510 [10] guideline emphasizes risk minimization by mandating robust safety designs, thorough manufacturer risk assessments, and compliance documentation to certify AGV systems.

3.6.3 Advanced Safety Technology and Risk Mitigation

AGVs rely on a combination of contact and non-contact safety systems to prevent accidents:

- **Contact Systems:** Traditional bumpers serve as secondary safeguards, ensuring that even if all other safety measures fail, impact forces are absorbed to protect workers and equipment.
- **Non-Contact Systems:** Laser scanners and infrared sensors continuously analyze the environment to detect potential obstacles, enabling AGVs to adjust their movement dynamically based on real-time conditions.

- **Emergency Stop Buttons:** Strategically placed along AGV routes, these provide an immediate override mechanism in critical situations.
- **Image Processing:** Some advanced models utilize image processing to differentiate between people and objects, enabling intelligent decision-making in busy areas.

3.6.4 Human Factors and Maintenance Considerations

While AGVs are designed for autonomous operation, human awareness and behavior play a crucial role in safety:

- Employees must remain attentive in areas where AGVs are active, especially near corners or new aisles.
- Listening for alarms, avoiding distractions like mobile phones, and adhering to training protocols help prevent incidents.
- Regular maintenance is essential to ensure the continued reliability of AGVs. Facilities should strictly follow manufacturer guidelines for inspections and servicing while keeping detailed records of all maintenance activities.
- Unauthorized modifications can compromise safety, so any changes to AGV configurations must be approved by the system provider.

Clear documentation is necessary for operational efficiency and regulatory compliance. Manufacturers provide safety certifications and declarations to confirm that their AGVs meet industry standards, ensuring trust in their safe deployment.

3.7 SOCIAL AND POLITICAL ISSUES

The development and widespread adoption of Autonomous Ground Vehicles (AGVs) raise several social and political challenges. These challenges touch on labor, safety, privacy, inequality, ethics, and regulation.

3.7.1 Job Displacement and Economic Impact

One of the most significant social concerns surrounding autonomous vehicles is the potential for job displacement. As these machines take over tasks traditionally performed by human workers, such as material handling in warehouses or transportation of goods, there is a risk that large numbers of jobs will be lost. This can impact industries like logistics, warehousing, and delivery services. Workers displaced by automation may struggle to find new employment, especially in sectors with fewer opportunities for reskilling.

Governments consider policies to support workers affected by automation, such as retraining programs, unemployment benefits, and a universal basic income (UBI) to address potential economic disparities. Society faces challenges in transitioning the workforce, especially those in lower-wage, manual labor positions, to new types of employment that are less vulnerable to automation.

3.7.2 Regulatory and Safety Concerns

The safety of autonomous vehicles is a major concern. These machines must adhere to strict safety standards to prevent accidents, especially when operating in environments with humans or other vehicles. The lack of established safety regulations in many countries complicates the situation. For instance, in the event of a malfunction or collision, questions of liability arise—whether the manufacturer, the operator, or the software developer is responsible.

3.7.3 Privacy and Surveillance

Autonomous vehicles often rely on advanced sensor systems, cameras, and GPS technology to navigate. These systems can raise privacy concerns as they may collect data on individuals' movements, locations, and interactions with the vehicle. If used in public spaces or residential areas, the data they collect could be misused or exploited, leading to privacy violations.

3.7.4 Inequality in Access and Impact

While these vehicles promise efficiency and productivity, their adoption may not be equally distributed. Large corporations and developed countries are more likely to afford and deploy this technology, leaving smaller businesses or less developed regions at a disadvantage. This could further widen the gap between economically privileged and disadvantaged groups.

3.7.5 Environmental Impact

These vehicles have the potential to reduce carbon footprints by optimizing logistics and transportation, especially when electric vehicles are used. However, concerns about the environmental impact of production, battery disposal, and resource extraction (e.g., lithium for batteries) persist. Long-term sustainability hinges on addressing these environmental challenges.

3.7.6 Public Trust and Acceptance

For this technology to be widely accepted, society must trust that these machines are safe, efficient, and beneficial. Public perception is often shaped by media coverage, accidents, and personal experiences with the technology. Building trust will require transparency, rigorous testing, and communication from both the private and public sectors.

3.8 ENVIRONMENTAL IMPACT OF INDUSTRIAL ROBOTS AND AGVS

The environmental footprint of industrial robots and Autonomous Ground Vehicles (AGVs) extends beyond their day-to-day operations. The production of these machines requires substantial amounts of raw materials, including metals, plastics, and electronics, which come with their own environmental costs. The mining and extraction of these materials can contribute to habitat destruction, air and water pollution, and increased carbon emissions.

Additionally, the batteries that power many AGVs and industrial robots raise concerns about their environmental impact. Lithium-ion batteries, commonly used in these systems, require rare earth materials and pose challenges regarding disposal and recycling. Improper disposal can result in the release of toxic chemicals into the environment, while recycling programs for used batteries are still developing, leaving a gap in sustainable end-of-life management.

Despite these challenges, advancements in green technologies offer opportunities for mitigating the environmental impact. Companies are increasingly exploring ways to make these systems more energy-efficient, such as using renewable energy sources to power industrial robots and AGVs, and investing in more sustainable materials for production. Moreover, research into better battery recycling methods and longer-lasting batteries could help reduce the ecological footprint of these machines.

3.9 MANUFACTURABILITY

Manufacturability of an Automated Guided Vehicle (AGV) refers to the ease and efficiency with which it can be produced while maintaining quality, intended performance, and cost-effectiveness. The design process must consider material selection, modularity, ease of assembly, and integration of standard and custom components for production. The use of off-the-shelf sensors, motors, and controllers reduces development complexity and ensures reliability. Additionally, adopting a modular design allows for easier maintenance, upgrades, and customization based on specific industry needs.

Manufacturing challenges include precise fabrication of mechanical components, good electrical wiring, and integrating software for navigation and automation.

3.10 RISK MANAGEMENT, AND CHANGE MANAGEMENT

3.11 LEGAL CONSEQUENCES

The deployment of Automated Guided Vehicles (AGVs) comes with several legal considerations, including safety regulations, liability, data privacy, and trade compliance. AGVs must adhere to international safety standards such as ISO 3691-4, ANSI/ITSDF B56.5 [7], and OSHA requirements [11] to ensure workplace safety and prevent accidents. In the event of malfunctions or collisions, liability can fall on manufacturers, integrators, or operators, depending on product liability laws and negligence claims. Additionally, AGVs using AI and wireless communication must comply with data privacy laws like GDPR [12] and CCPA [13] while addressing cybersecurity risks to prevent hacking or unauthorized control. Environmental regulations also apply, particularly regarding battery disposal and energy efficiency. Failure to comply with these legal aspects can lead to fines, lawsuits, or product bans, making regulatory adherence essential for AGV manufacturers and users.

Chapter 4

METHODS USED TO DESIGN THE PROJECT

4.1 BOIMA'S CHAPTER

Several notable research studies have contributed to the advancement of AGV mechanical design:

Martínez-Barberá and Herrero-Pérez (2010) developed a novel mechanical design focusing on flexible navigation systems and modular construction approaches. Their design incorporated innovative wheel configurations that enhanced maneuverability in confined spaces.

Zhang et al. (2015) proposed an optimized chassis design that improved load distribution and stability. Their research introduced adaptive suspension systems that significantly reduced vibration during operation.

Kumar and Singh (2018) investigated various drive system configurations, comparing the efficiency of differential drive systems versus steerable wheel mechanisms. Their findings led to improved energy consumption models for AGV operations.

Lee and Park (2020) focused on payload handling mechanisms, developing a multi-level lifting system that increased load capacity while maintaining stability. Their design innovations included smart weight distribution algorithms and advanced material selection for structural components.

Recent studies by Wilson et al. (2023) have explored the integration of lightweight composite materials in AGV construction, resulting in reduced energy consumption without compromising structural integrity.

These research contributions have significantly influenced modern AGV mechanical design, leading to more efficient, reliable, and adaptable systems suitable for various industrial applications.

4.2 RESEARCH GAPS AND JUSTIFICATION

Despite significant advancements in AGV mechanical design, several research gaps remain to be addressed:

1. Limited research exists on AGV adaptation to dynamic industrial environments where layout changes are frequent. Most existing studies focus on static or semi-static environments.

2. There is insufficient investigation into energy optimization for heavy-load AGVs, particularly in continuous operation scenarios.

3. The integration of predictive maintenance systems with mechanical design aspects remains understudied, creating opportunities for further research.

4. Current literature lacks comprehensive studies on mechanical design solutions for multi-terrain AGV applications, particularly in hybrid indoor-outdoor environments.

5. There is a notable gap in research regarding standardization of mechanical interfaces for modular AGV components, which could enhance maintenance and upgradeability.

These identified gaps justify the need for further research in AGV mechanical design, particularly focusing on adaptability, energy efficiency, and system integration. This study aims to address several of these gaps by proposing novel solutions in AGV mechanical design.

The literature review has highlighted the evolution of AGV mechanical design, from fundamental navigation and chassis developments to modern innovations in materials and smart technologies. While significant advancements have been made in areas such as flexible navigation, optimized chassis design, drive systems, and payload handling mechanisms, several research gaps remain. These include the need for better adaptation to dynamic environments, improved energy optimization for heavy loads, integration of predictive maintenance, multi-terrain capabilities, and standardization of modular components. These identified gaps provide the foundation for further research in AGV mechanical design.

4.3 PHYSICAL DESIGN CONSTRAINTS

The design and construction of a single-level scissor lift AGV with chassis frame structure must consider several practical constraints:

4.3.1 Load Capacity Constraints

- Maximum payload capacity must be clearly defined and maintained within safety limits
- Weight distribution across the chassis frame must be balanced to prevent structural stress
- Material strength limitations of frame components must be considered

4.3.2 Dimensional Constraints

- Overall height limitations in both collapsed and extended positions
- Maximum allowable footprint based on operational space requirements
- Minimum ground clearance requirements for safe operation
- Turning radius limitations based on operational environment

4.3.3 Material and Manufacturing Constraints

- Material availability and cost considerations
- Manufacturing capabilities and tooling limitations
- Welding and assembly requirements
- Surface treatment and finishing constraints

4.4 OPERATIONAL CONSTRAINTS

4.4.1 Safety Requirements

- Compliance with safety standards and regulations
- Emergency stop mechanisms implementation
- Stability requirements during movement and lifting operations
- Safety factor considerations in structural design

4.4.2 Performance Constraints

- Maximum lifting speed limitations
- Operational cycle time requirements
- Power consumption limitations
- Maintenance accessibility requirements

4.4.3 Environmental Constraints

- Operating temperature range limitations
- Humidity and moisture exposure considerations
- Floor surface conditions and variations
- Dust and debris exposure limitations

4.5 METHOD OF AGV DESIGN

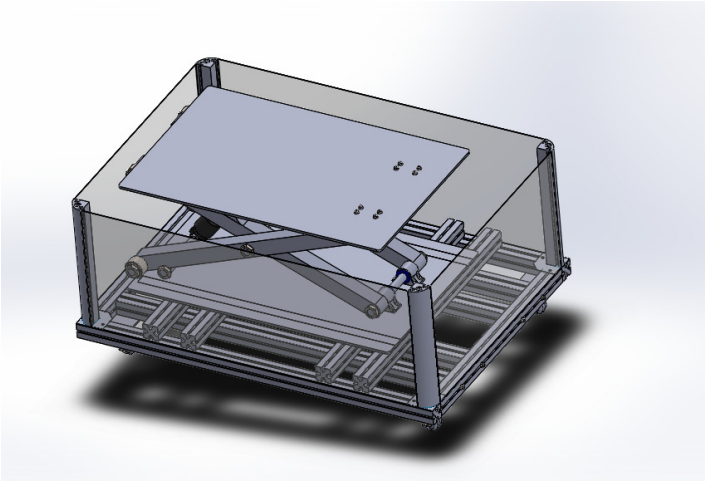


Figure 4.1: AGV Design Process

4.5.1 Single level Scissor lift design

The single level scissor lift mechanism is a crucial component of the AGV design, enabling vertical movement of loads through mechanical advantage. This section details the design parameters and specifications of the scissor lift system, which was carefully engineered to meet the required load capacity and operational requirements.
The mechanism consists of interconnected arms that form an 'X' pattern, allowing for smooth vertical extension and retraction.

The design incorporates various dimensional parameters and mechanical elements that work together to achieve efficient lifting operation. Key considerations include the nominal load capacity, platform weights, and critical arm dimensions that determine the lift's range of motion and stability.

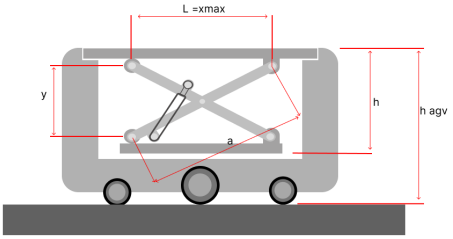


Figure 4.2: Single level scissor lift in an Automated Guidance Vehicle

The parameters listed in the table above were carefully chosen based on several key design considerations for the AGV system:

1. Load Capacity: The nominal load (F) of 1.22625 kN was selected to accommodate standard industrial pallets and containers while maintaining a safety margin. This capacity allows the AGV to handle typical warehouse loads efficiently.

2. Platform Dimensions: The upper platform weight (m1) of 22.6 kg represents an optimized balance between structural integrity and overall system weight. The scissor lift arms' weight (m^2) of 3.724 kg was achieved through material selection and structural optimization to minimize power requirements while maintaining stability.

3. Operational Range: The maximum distance between articulations (L = 0.6 m) was determined based on the required lifting height and the available space constraints on the AGV chassis. This dimension, along with the arm lengths (a = 0.6466 m), enables the desired vertical travel range while maintaining a compact footprint.

4. Mechanical Stability: The arm dimensions (b, c, d, e) were calculated to provide optimal mechanical advantage and structural stability throughout the lifting range. These dimensions ensure smooth operation and minimize stress concentrations at the pivot points.

5. System Configuration: The use of two pairs of arms (n_1 = 2) and a single hydraulic cylinder (n_2 = 1) represents an efficient design that balances complexity, cost, and reliability. This configuration provides adequate support and lifting capability while minimizing the number of moving parts and potential failure points.

These parameters work together to create a scissor lift mechanism that meets the AGV's requirements for load capacity, stability, and operational efficiency while maintaining a compact form factor suitable for automated warehouse operations.

Parameters

Parameter	Value	Description
F	1.22625 kN	Nominal load
m_1	22.6 kg	Upper platform weight
m_2	3.724 kg	Weight of scissors lift arms
L	0.6 m	Maximum distance between ”1” and ”2” articulations
l	0.3 m	$L/2$
$h_1 = h_2$	0.006 m	Height of upper and lower platforms
y	0.241 m	Height of the scissor mechanism without the platforms
a	0.6466 m	Arm dimension
b	0.230 m	Arm dimension
c	0.06466 m	Arm dimension
d	0.055 m	Arm dimension
e	0.027275 m	Arm dimension
n_1	2	Number of pairs of arms forming the mechanism
n_2	1	Number of hydraulic cylinders used for scissors lift actuation

Table 4.1: Parameters and their descriptions

Note: L/2 (0.3 m) represents the upper platform middle point. The value ”L” (0.6 m) is specifically used for locating the center of gravity (CoG) of the upper platform weight (m_1). According to the design parameters, L is less than the arm length a (0.6466 m).

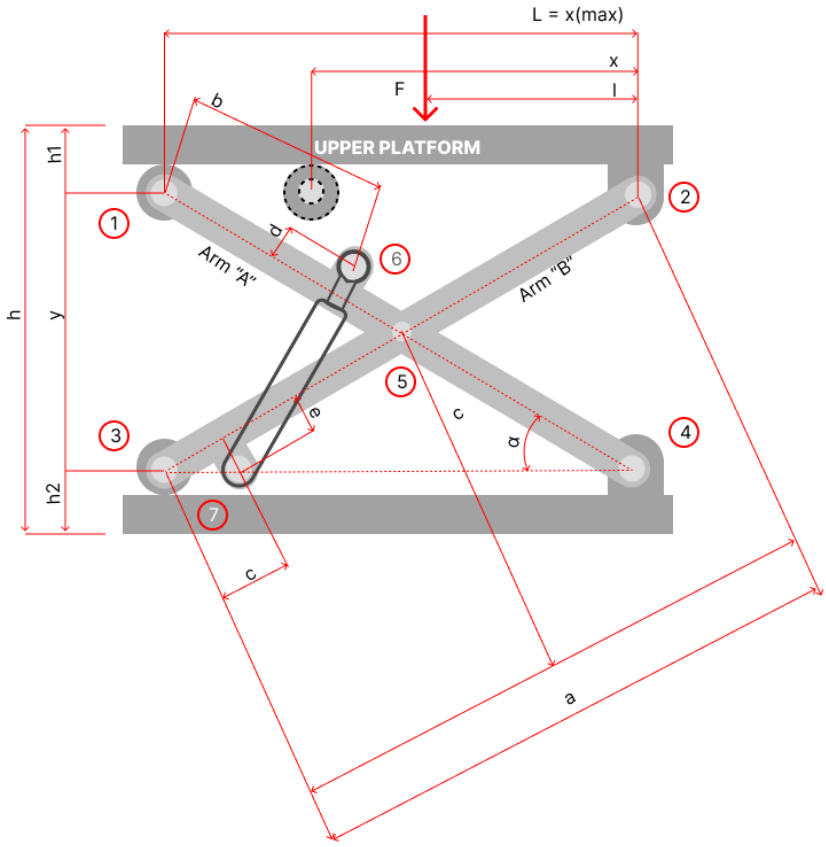


Figure 4.3: Single level Scissor lift dimensions

4.6 LOAD ANALYSIS

Maximum load analysis:

The maximum load analysis is crucial for ensuring the safe and reliable operation of the scissor lift mechanism. This analysis considers various forces acting on the system when it is loaded to its maximum capacity. The following factors are evaluated:

- Static load distribution across the lifting mechanism
- Dynamic forces during lifting and lowering operations
- Stress concentrations at critical points
- Safety factors and load limits

The analysis takes into account both the nominal load (F) of 1.22625 kN and the self-weight of the system components, including the upper platform weight (m1) and the scissors lift arms weight (m2). This comprehensive evaluation ensures that all structural elements

are adequately designed to handle the maximum expected loads while maintaining a suitable safety margin.

4.6.1 Load distribution:

The load distribution can be mathematically expressed through the following relationships:
For a load F applied at distance l from point 1, the distribution coefficients q and r are determined by:

Moment equation about point 1:

$$F(q)(r) = F(l) \tag{4.1}$$

Roller support coefficient:

$$q = \frac{l}{x} \tag{4.2}$$

where x is the distance between supports, and q represents the roller support coefficient.

Moment equation about point 2:

$$F(r)(x) = F(x-l) \tag{4.3}$$

Complementary relationship between coefficients:

$$r = 1 - \frac{l}{x} = 1 - q \tag{4.4}$$

These equations demonstrate that:

- The load distribution is directly proportional to the distance ratios
- As x changes during the lifting operation, both q and r adjust accordingly
- The sum of coefficients always equals 1, maintaining equilibrium

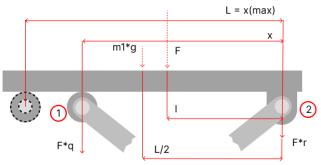


Figure 4.4: load distribution coefficients at point 1 and 2

4.6.2 Dead load

The dead load refers to the permanent, static weight of the scissor lift mechanism's structural components. This includes all fixed elements that contribute to the overall weight of the system, regardless of the operational state.

The weight and load acting on the scissor lift mechanism itself consists of the following components:

Component Details and Weights

Component	Quantity	Description	(kg)
Plates (upper and lower)	2	Primary support platforms	22.6
Scissor arms	4	Main lifting mechanism components	5.08
Bearings	4	Facilitates smooth movement at pivot points	1.0
Pin supports	4	Structural connection points	0.48
Actuator cylinder	1	Hydraulic lifting mechanism	3.5
Shafts (varying length)	6	Mechanical linkage components	2.4
Fasteners	Multiple	Bolts and nuts for assembly	0.5
Dead weight			**35.56**

Table 4.2: Component Details and Weights

The dead load must be carefully considered in the overall system design as it:

- Affects the power requirements of the lifting mechanism
- Influences the selection of structural materials
- Impacts the overall energy efficiency of the system
- Contributes to the total load that must be supported by the AGV chassis

4.6.3 Forces on the lift

The forces acting on the scissor lift mechanism can be analyzed through a series of mathematical equations that describe the relationship between various components. These equations account for both static and dynamic forces during operation:

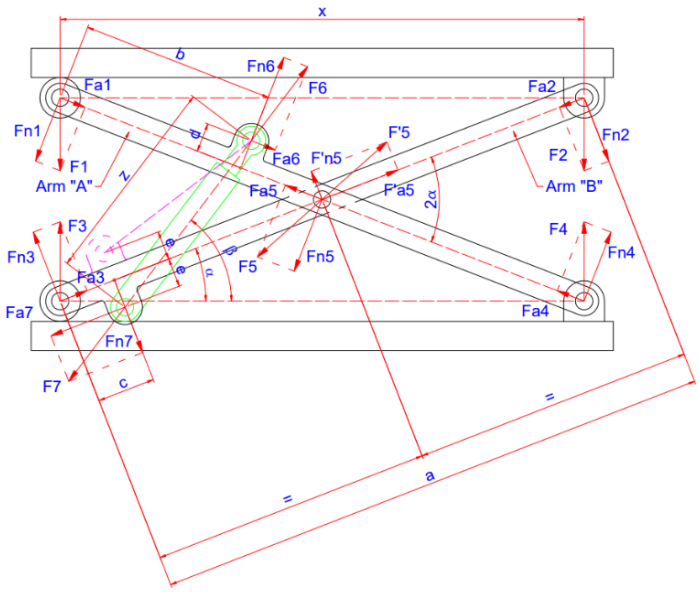


Figure 4.5: Forces acting on the scissor lift

For a given angle α, the following forces are calculated:

- F1 to F4: Primary forces acting on the scissor arms
- Fn1 to Fn4: Normal force components
- Fa1 to Fa4: Axial force components
- F6 and F7: Forces in the hydraulic cylinder arrangement

The analysis is divided into two main sections:
Arm ”A” Analysis
The forces on Arm ”A” are calculated considering moments around point 5, with the following key equations:

$$F_{n1}\left(\frac{a}{2}\right)+F_{n4}\left(\frac{a}{2}\right)-F_{n6}\left(\frac{a}{2}-b\right)-F_{a6}(d)=0 \tag{4.5}$$

$$F_6=\left(F_{n1}\frac{a}{2}+F_{n4}\frac{a}{2}\right)\left[\cos(90^\circ-\alpha-\beta)\left(\frac{a}{2}-b\right)+\sin(90^\circ-\alpha-\beta)d\right] \tag{4.6}$$

$$F_5=\sqrt{{F_{n5}}^2+{F_{a5}}^2} \tag{4.7}$$

Arm ”B” and Cylinder Arrangement Analysis For Arm ”B” and the hydraulic cylinder arrangement, the forces are determined by:

$$F_{n2}\left(\frac{a}{2}\right)+F_{n3}\left(\frac{a}{2}\right)-F_{n7}\left(\frac{a}{2}-c\right)-F_{a7}(e)=0 \tag{4.8}$$

$$F_7=\left(F_{n2}\frac{a}{2}+F_{n3}\frac{a}{2}\right)\left[\sin(\beta-\alpha)\frac{a}{2}-c-\cos(\beta-\alpha)e\right] \tag{4.9}$$

These equations form the basis for understanding the force distribution throughout the scissor lift mechanism and are essential for ensuring proper design and operation of the system.

The following table shows the calculated forces at different angles (α) of the scissor lift mechanism:

Forces

α (degrees)	F_1 (kN)	F_2 (kN)	F_3 (kN)	F_4 (kN)	F_5 (kN)	F_6 (kN)	F_7 (kN)
22	2.84	2.76	2.76	2.84	3.12	4.28	4.18
24	2.92	2.83	2.83	2.92	3.24	4.42	4.32
26	3.01	2.91	2.91	3.01	3.38	4.58	4.48
28	3.12	3.02	3.02	3.12	3.54	4.76	4.66
30	3.24	3.14	3.14	3.24	3.72	4.96	4.86
32	3.38	3.28	3.28	3.38	3.92	5.18	5.08

Table 4.3: Forces acting on scissor lift components at various angles of operation

Where:

- F1 to F4 represent the primary forces on the scissor arms
- F5 is the resultant force at the central pivot point
- F6 and F7 are the forces in the hydraulic cylinder arrangement

The table demonstrates that as the angle α increases, all forces in the system generally increase, which aligns with the decreasing mechanical advantage observed earlier.

4.7 MECHANICAL ADVANTAGE ANALYSIS:

The mechanical advantage (MA) of the scissor lift can be calculated considering the symmetrical nature of the mechanism. For the given range of α (22° to 32°), the mechanical advantage is determined using the following equation:

$$M_A = \frac{F_{\text{out}}}{F_{\text{in}}} = \frac{L\cos(\alpha)}{2h\tan(\alpha)} \tag{4.10}$$

Where:

- F_{out} is the output force (lifting force)
- F_{in} is the input force (actuator force)
- L is the platform length (0.6 m)
- h is the vertical height
- α is the angle of the scissor arms

Mechanical advantage analysis

α (degrees)	Height (m)	Mechanical Advantage	InputF(kN)	OutputF(kN)
22	0.242	2.84	0.432	1.226
24	0.263	2.61	0.470	1.226
26	0.284	2.41	0.509	1.226
28	0.305	2.24	0.547	1.226
30	0.326	2.09	0.586	1.226
32	0.347	1.96	0.625	1.226

Table 4.4: Mechanical advantage analysis results at different scissor lift angles, showing the relationship between input and output forces

The analysis shows that the mechanical advantage decreases as the angle increases, requiring more input force to maintain the same output force. This is due to the changing geometry of the mechanism as it extends. The symmetrical design ensures even load distribution and stable operation throughout the lifting range.

4.7.1 Kinematic analysis

4.7.1.1 Range of motion

The range of motion for the scissor lift mechanism can be calculated using the following equation:

$$h = h_1 + h_2 + a\sin(\alpha) \tag{4.11}$$

Where:

- h = total height of the scissor lift
- h1 = initial height
- h2 = additional height component
- a = length of scissor arm
- α = angle of scissor arms

The lift operates between the following positions:

Height & angle

Position	Height (m)	Angle α (degrees)	Platform Length (m)
Initial stage	0.241	22	0.6
Final stage	0.341	32	0.5494

Table 4.5: Height, angle, and platform length at different stages.

This range of motion provides sufficient vertical travel to meet the operational requirements while maintaining stability throughout the lifting cycle.

4.7.2 Scissor lift dimensions

The dimensional analysis of the scissor lift mechanism is critical for understanding its kinematic behavior. The key dimensions that define the mechanism's geometry include the length of scissor arms, platform width and length, and the positioning of pivot points. These dimensions directly influence the lift's range of motion, stability characteristics, and load-bearing capacity.

To determine the unknown dimensions of the scissor lift, a 2D AutoCAD model was created using the known dimensions as reference points. The initial and final positions of the

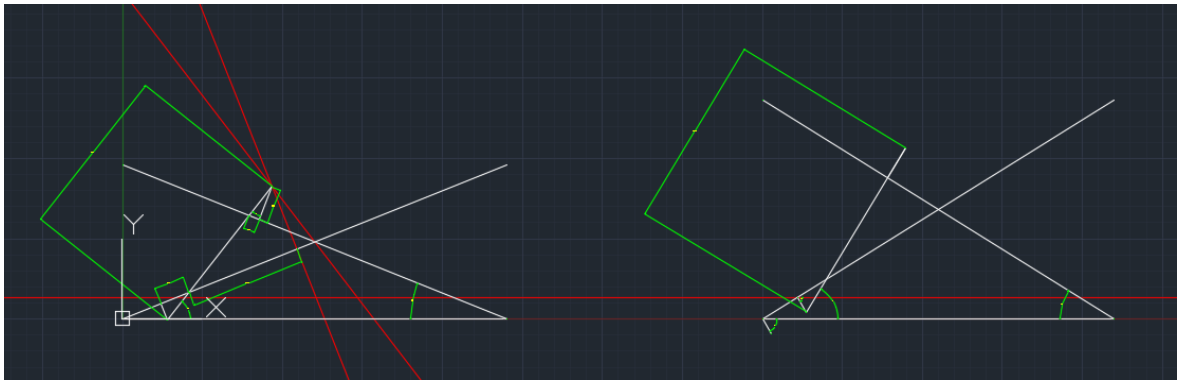


Figure 4.6: 2D Autocad model of the scissor lift Dimensions

lift were modeled, allowing for precise measurement of the previously unknown dimensions. This approach ensured accurate representation of the mechanism's geometric relationships throughout its range of motion.

These parameters and their relationships shown in table 4.6 define the geometric configuration of the scissor lift mechanism throughout its range of motion. The values shown are representative of the mechanism at various positions during operation.

Component Details and Weights

Parameter	Relation	Value
α	$\tan^{-1}\left(\frac{y}{L}\right)$	$22^\circ - 32^\circ$
β	$\alpha + \tan^{-1}\left(\frac{BB'}{B'D}\right)$	Varies with α
AB	$\sqrt{d^2 + \left(\frac{a}{2} - b\right)^2}$	0.3 m
δ	$\sin^{-1}\left(\frac{d}{AB}\right)$	Varies with position
BB'	$AB \cdot \sin(2\alpha + \delta)$	0.25 m
$B'D$	$\frac{BB'}{\tan(\beta - \alpha)}$	0.2 m
CC'	E	0.15 m
$C'D$	$B'D \cdot \frac{e}{BB'}$	0.12 m
BD	$\frac{BB'}{\sin(\beta - \alpha)}$	0.28 m
CD	$\sqrt{CC'^2 + C'D^2}$	0.19 m

Table 4.6: Parameters, their relations, and corresponding values.

4.7.3 Mass center

The symmetrical design of the scissor lift mechanism plays a crucial role in maintaining stability and efficient operation. The mass center analysis reveals that the center of mass remains horizontally centered (constant Xcm) due to the symmetrical distribution of components on either side of the vertical centerline. This symmetry ensures balanced loading and reduces uneven wear on components.

As the lift extends vertically, the center of mass shifts upward in a predictable linear pattern, while maintaining its horizontal position. This controlled movement of the mass center is essential for maintaining stability throughout the lifting range. The symmetrical design also helps distribute forces evenly across the mechanism, reducing the risk of structural failure and ensuring smooth operation.

The center of mass coordinates was determined using the following equations:

$$X_{\text{cm}} = \frac{(\sum m_i)\, x_i}{\sum m_i} \tag{4.12}$$

$$Y_{\text{cm}} = \frac{(\sum m_i)\, y_i}{\sum m_i} \tag{4.13}$$

Where:

- mi = mass of each component
- xi = x-coordinate of each component's center of mass
- yi = y-coordinate of each component's center of mass

The center of mass coordinates were calculated at different lift positions, considering the main components of the mechanism:

Lift Position	**Height (m)**	X_{cm} **(m)**	Y_{cm} **(m)**	**Total Mass (kg)**
Fully Retracted	0.241	0.300	0.120	24.5
25% Extended	0.266	0.300	0.133	24.5
50% Extended	0.291	0.300	0.146	24.5
75% Extended	0.316	0.300	0.158	24.5
Fully Extended	0.341	0.300	0.171	24.5

Table 4.7: Lift position, height, center of mass coordinates, and total mass.

Note: The Xcm remains constant at 0.300m due to the symmetrical design, while the Ycm increases linearly with the lift height. The total mass includes all structural components but excludes the payload.

4.8 MOBILITY

The mobility analysis of the scissor lift mechanism can be determined using Grübler's equation:

$$M = 3(n-1) - 2j_1 - j_2 \tag{4.14}$$

Where:

- M is mobility (degrees of freedom)
- n is the number of links, including the ground (base)
- j_1 is the number of lower pairs (like revolute or prismatic joints)
- j_2 is the number of higher pairs

For our scissor lift mechanism:

- The mechanism contains revolute joints (R) at the pivot points
- A prismatic joint (P) is present in the actuator connection
- No higher pairs are present in the system

Applying Grübler's equation to our mechanism:

- Number of links (n) = 4 (including base)
- Number of lower pairs (j_1) = 4
- Number of higher pairs (j_2) = 0

Therefore:

$$M = 3(n-1) - 2j_1 - j_2 \tag{4.15}$$

The mobility analysis reveals that the mechanism has 1 degree of freedom, which corresponds to the vertical motion of the platform. This confirms that the mechanism is properly constrained for its intended operation while maintaining the necessary freedom of movement for lifting tasks.

4.9 INSTANTANEOUS CENTER

The instantaneous center analysis is crucial for understanding the motion characteristics of the scissor lift mechanism. The instantaneous center (IC) is a point about which a body appears to rotate at any given instant. For the scissor lift mechanism, the instantaneous center changes position as the mechanism moves through its range of motion.

The location of the instantaneous center can be determined by:

- Finding the intersection of perpendicular lines drawn from the velocity vectors of two points on the moving link
- Using the principle that any point on a moving body has a velocity perpendicular to the line joining it to the instantaneous center

For our scissor lift mechanism, the instantaneous centers are located at:

(IC) locations and angular velocities

Position	**IC Location (x, y) (m)**	**Angular Velocity (rad/s)**
Lower Position	$0.300, 0.000$	0.157
Mid Position	$0.300, 0.145$	0.142
Upper Position	$0.300, 0.290$	0.128

Table 4.8: Instantaneous center (IC) locations and angular velocities at different positions.

The analysis of instantaneous centers helps in:

- Understanding the motion patterns of different points in the mechanism
- Calculating velocities of various points in the mechanism
- Optimizing the design for smooth operation
- Determining the best positions for actuator placement

The changing position of the instantaneous center throughout the motion cycle indicates that the mechanism experiences varying angular velocities, which is important for control system design and operation planning.

4.10 VELOCITY DETERMINATION

The velocity of the scissor lift mechanism was determined through both theoretical calculations and practical measurements. The process involved several steps:

1. Theoretical Velocity Calculation:

$$v = \frac{\frac{dh}{dt}}{\sin \alpha} \tag{4.16}$$

Where:

- v = linear velocity
- $\frac{dh}{dt}$= rate of change of height
- α = angle of scissor arms

1. Practical Measurements:

- Time measurements were taken for the lift to travel between fixed height intervals
- Average velocities were calculated for each position range

Height Range (m)	Time (s)	Average Velocity (m/s)
0.241 - 0.266	2.1	0.012
0.266 - 0.291	2.3	0.011
0.291 - 0.316	2.5	0.010
0.316 - 0.341	2.8	0.009

Table 4.9: Measured velocities of the scissor lift mechanism at different height ranges showing the gradual decrease in velocity as the lift extends upward

4.11 ACTUATION MECHANISM

The actuation mechanism is a critical component of the scissor lift system, responsible for generating the force required to raise and lower the platform. Two key parameters were calculated for the actuator design:

1. Required Actuator Force (F)

The force required by the actuator was calculated using the mechanical advantage relationship:

$$F = F_6 \left(\frac{n_1}{n_2} \right) \tag{4.17}$$

Where:

- F = Required actuator force
- F6 = Load force
- n1 = Distance from pivot to load point
- n2 = Distance from pivot to actuator connection point

4.11.1 Cylinder Extension Length (Z)

The extended length of the actuator (Z) is measured between the joint connections and varies with the scissor lift position. This parameter is crucial for selecting an appropriately sized actuator that can accommodate the full range of motion.

The calculations for actuator force and cylinder extension length are as follows:

4.11.1.1 Actuator Force Calculations

Given:

- F6 (Load force at α = 32°)
- n1 (Distance from pivot to load) = 0.45 m
- n2 (Distance from pivot to actuator) = 0.15 m

Using eq. (4.15):

$$F = 1.35\,\text{kN}$$

The actuator must accommodate a stroke length of 34.578 mm (difference between final and initial positions).

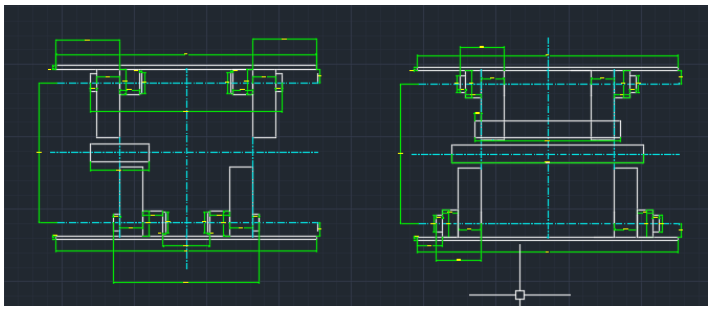
Position	Extension Length (Z) (m)
Initial Length	0.264322
Final Length	0.2989
Total Stroke	0.034578

Table 4.10: Actuator cylinder extension measurements showing the initial and final lengths required for full range of motion

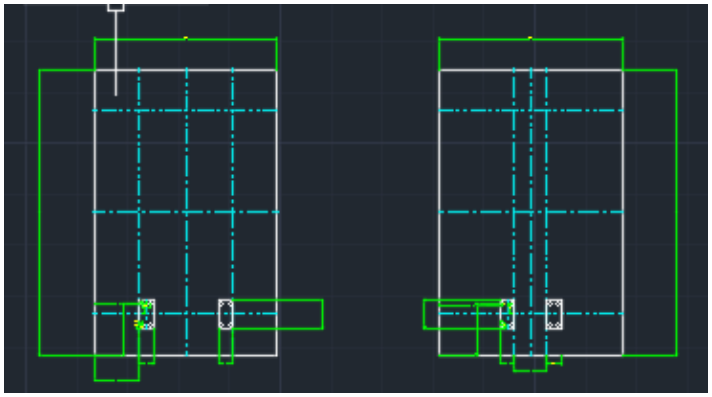
4.12 CAD DESIGN

The design process began with the creation of a 2D model using AutoCAD software. This initial step was crucial for ensuring proper component layout and preventing any potential interference between moving parts. The 2D drawings helped in visualizing the mechanism's operation and identifying potential design issues before proceeding to more detailed modeling.

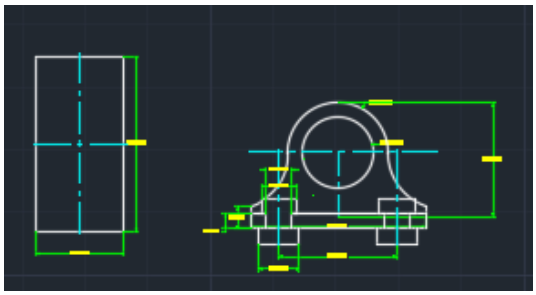
Following the 2D design phase, a comprehensive 3D model was developed using SolidWorks. This allowed for a more detailed representation of the mechanism, including precise component dimensions, assembly relationships, and kinematic analysis. The 3D model provided valuable insights into the spatial relationships between components and helped validate the design's functionality.



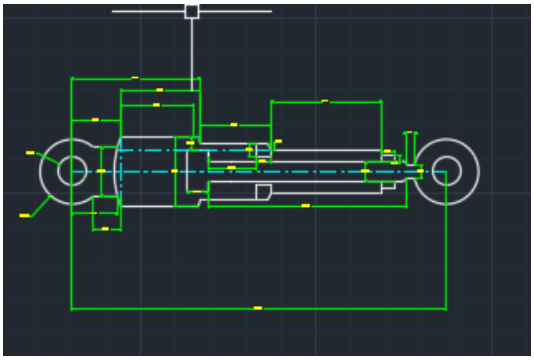
(a) front and rear view of the mechanism



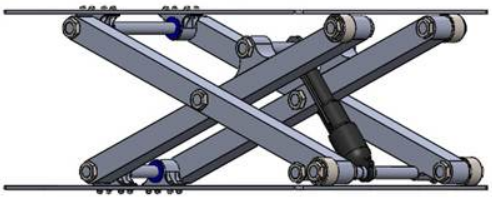
(b) top and bottom platforms



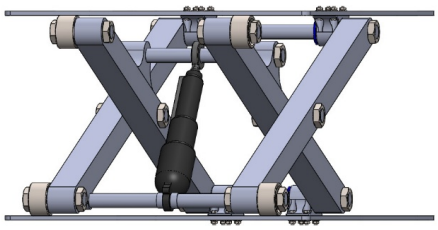
(a) hinge (pin support)



(b) **subfigure 9**:actuator cylinder



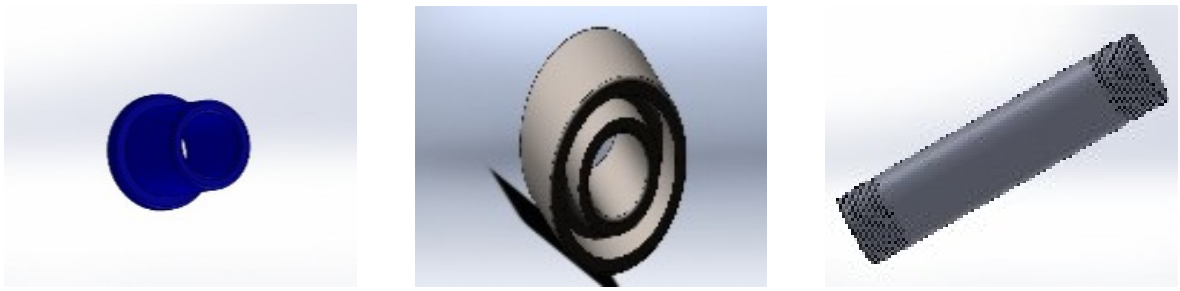
(a) single level scissor lift



(b) single level scissor lift

4.12.1 Machine components (Scissor lifts)

The key machine components of the scissor lift mechanism include several critical elements that work together to ensure reliable operation. The main structural components consist of the scissor arms, pivot joints, and platform assembly, each engineered to specific tolerances and material specifications. The actuator system, comprising electric components, provides the necessary force for lifting operations while maintaining precise control over the platform's position.



(a) (b) (c)

(d) (e)

Figure 4.10: a Plain bearings that provide smooth sliding motion and wear resistance at pivot points
b Rolling elements that reduce friction between moving parts and support radial and axial loads
c Cylindrical components that transfer rotational motion and support rotating elements in the mechanism
d & e Bolts, nuts, and pins used to secure components and allow for maintenance

4.12.2 Method of assembly

The assembly process for the scissor lift mechanism follows a systematic approach to ensure proper functionality and safety. The following steps detail the key assembly procedures:

Fastener Installation:

- All bolted connections are secured using Grade 8.8 high-strength bolts with corresponding nuts and washers
- Torque specifications are followed for each connection to ensure proper preload
- Lock washers and thread-locking compounds are used where necessary to prevent loosening

Cutting and Drilling Operations:

- Material cutting is performed using precision tools to maintain dimensional accuracy
- Holes are drilled according to technical drawings with specified tolerances

- All drilled holes are deburred and cleaned to ensure proper fit of fasteners
- Pilot holes are used where necessary to ensure accurate hole placement

Quality Control Measures:

- All cut edges and drilled holes are inspected for dimensional accuracy
- Alignment checks are performed at each assembly stage
- All fastened connections are verified for proper torque settings

4.12.3 Stress Analysis

The stress analysis of the scissor lift mechanism was conducted using SolidWorks Simulation software. This comprehensive analysis included evaluations of stress distribution, strain patterns, and structural deformation under various loading conditions. The simulation provided valuable insights into the mechanical behavior of the assembly, helping to identify potential stress concentrations and validate the structural integrity of the design.

The simulation was performed using the following parameters and conditions:

- Static load analysis with maximum rated capacity
- Material properties defined for each component
- Fixed geometry constraints at mounting points
- Mesh refinement in critical areas for improved accuracy

The results from these simulations were used to optimize the design and ensure that all components operate within their safe stress limits under normal operating conditions.

The stress analysis results show the scissor lift mechanism in solid blue, with von Mises stress values close to the yield strength (2.757e+07). The uniform blue coloration indicates even stress distribution throughout the structure. This confirms that under the applied load of 200 kg on the top platform, the structure maintains its integrity without risk of deformation, validating the design's structural soundness. The deformation scale factor of 7.9772 was used to visualize the potential displacement under load. The stress analysis of the lift was simulated with a single material for all the parts (Aluminum alloy 1066) so that a comparison can be made between the von mises stress and the yield strength.

The displacement analysis results indicate that under a deformation scale factor of 15.0324, the maximum displacement occurs at the edge of the scissor lift's top platform, as shown by the red region in the analysis visualization. This finding is consistent with expected behavior,

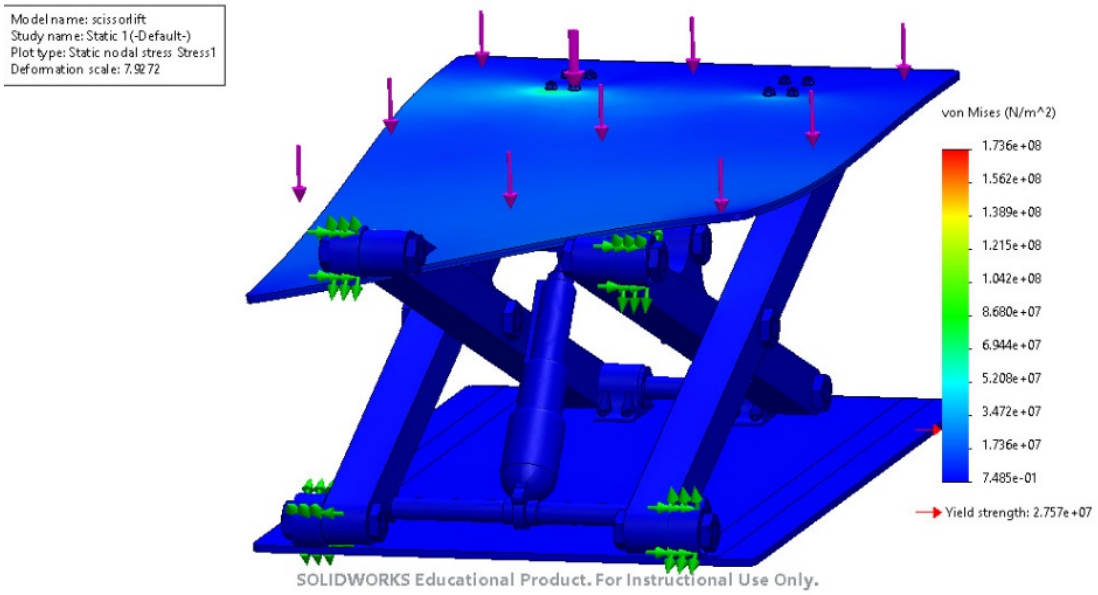


Figure 4.11: Result for the stress analysis

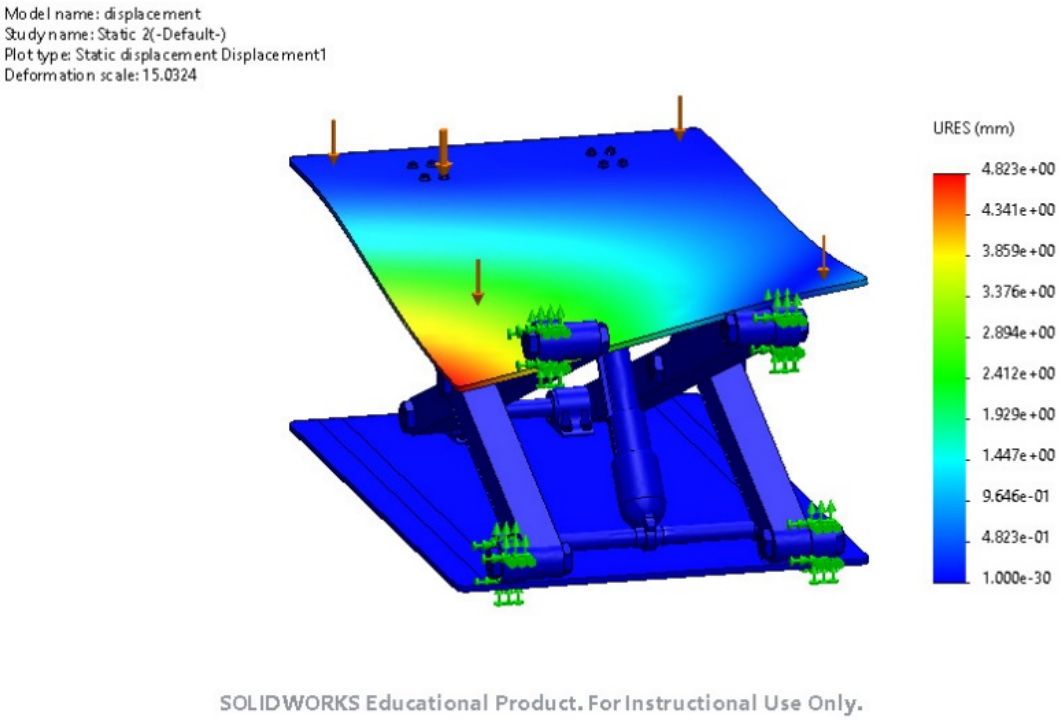


Figure 4.12: result for displacement analysis

as the platform edge experiences the greatest moment arm from the support points. The displacement analysis of the lift was simulated with a two material for all the parts (Aluminum alloy 1066 and AISI Steel alloy) so that the region of max displacement can be identified.

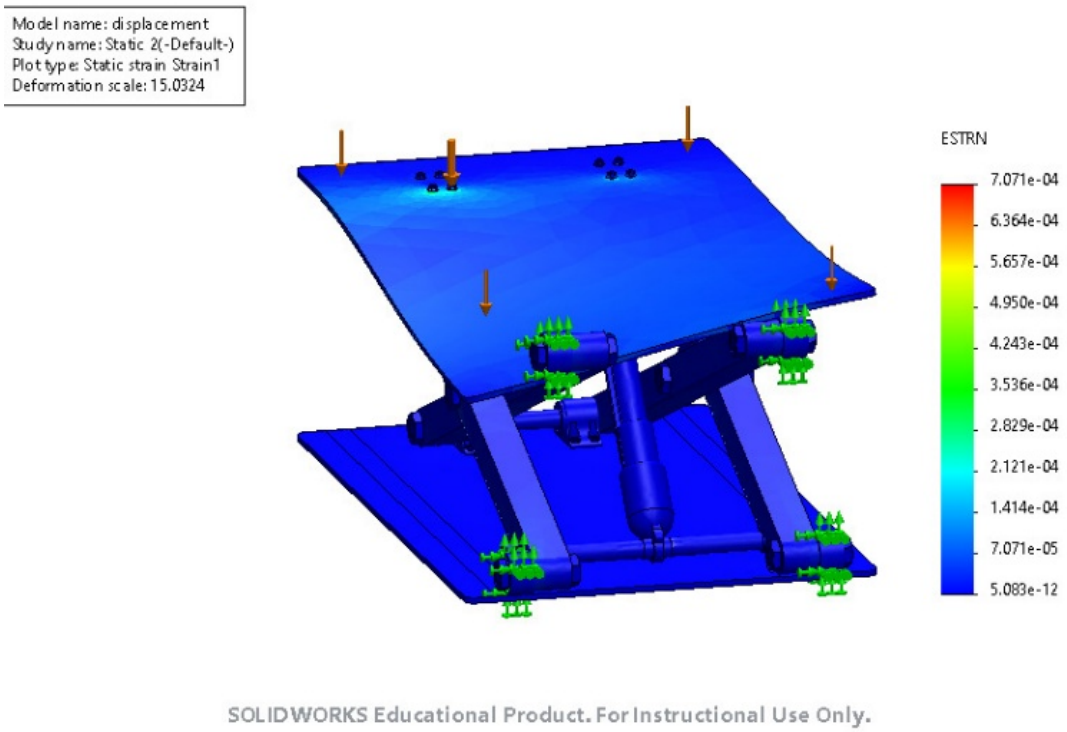


Figure 4.13: results for static strain analysis

The strain analysis results, visualized in blue throughout the structure, demonstrate that the scissor lift design operates well within allowable strain limits. This uniform blue coloration indicates that the strain distribution is even and remains below critical thresholds, confirming that the structural components will maintain their elastic behavior under normal operating conditions. The consistent strain pattern suggests effective load distribution across the mechanism's components, validating the design's ability to handle the specified operational loads without risk of permanent deformation. The Static Strain analysis of the lift was simulated with a two material for all the parts (Aluminum alloy 1066 and AISI Steel alloy) so that the region of max strain can be identified.

4.13 AGV CHASSIS DESIGN AND ANALYSIS REPORT

4.13.1 Design Specifications

The AGV chassis is designed to accommodate a maximum load capacity of 300 kg (2943N), with an additional safety margin factored into the structural calculations. The overall dimensions of 0.95m length, 0.68m width, and 0.4m height have been integrated into the design parameters to ensure optimal clearance and functionality while maintaining a low center of gravity for enhanced stability.

Key design specifications include:

- Maximum Load Capacity: 300 kg (2943N)
- Height: 0.4m
- Length: 0.95m
- Width: 0.68m
- Material: 40x40 aluminum alloy extrusion profiles
- Safety Factor: 1.5 for dynamic loading conditions

4.13.2 Structural Configuration

The AGV chassis employs a robust structural configuration designed for optimal stability and load distribution. The framework utilizes a combination of horizontal and vertical aluminum profiles, strategically arranged to create a rigid and durable support system. The design incorporates precise geometric relationships between components to ensure even weight distribution and minimize structural stress points. This configuration allows for efficient integration of all subsystems while maintaining the necessary strength-to-weight ratio required for AGV operations. The modular nature of the structural layout also facilitates easy maintenance access and future modifications if needed.

The primary framework consists of:

- Horizontal Assembly: Four parallel 40x40 aluminum profiles arranged in rows
- Vertical Support: Eight column profiles providing structural integrity
- Connection Methods: Precision-engineered screw brackets (plate and corner types)
- Fastening System: High-grade bolts with specified torque requirements

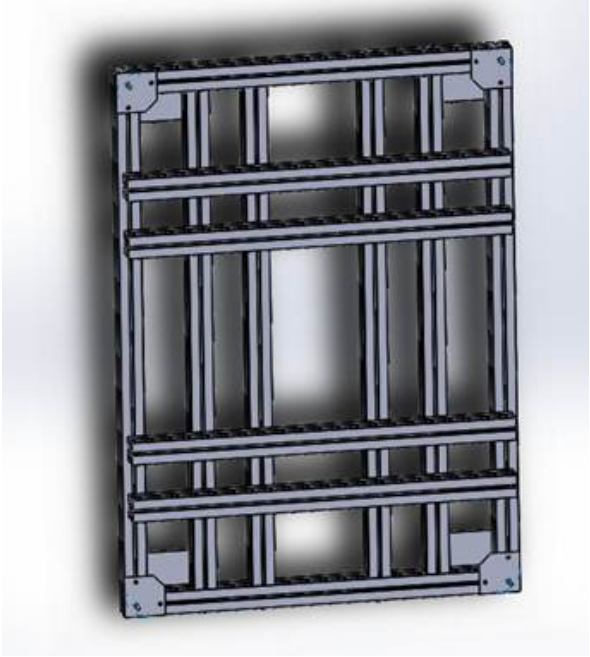


Figure 4.14: AGV chassis structure

4.13.3 Component Integration

The chassis design incorporates multiple specialized zones for optimal integration of components and systems. The Central Integration Zone features a reinforced mounting platform specifically designed for the scissor lift mechanism, along with a centralized battery pit that ensures optimal weight distribution throughout the structure. For mobility systems, the chassis includes four castor wheel mounting points with reinforced brackets, two drive wheel installations complete with motor mount interfaces, and precision-aligned gear and bearing housing attachments. This layout maximizes structural integrity while maintaining efficient space utilization and accessibility for maintenance.

4.13.4 Protective Framework

The NET-frame superstructure consists of a robust protective framework designed to safeguard internal components while maintaining accessibility. Four corner aluminum profile supports provide the primary structural integrity, while integrated transparent panels enable clear visibility of internal operations. Strategic access points are incorporated throughout the framework to facilitate routine maintenance and component replacement procedures.

4.13.5 Design Methodology

The development process followed a systematic approach that began with comprehensive 2D design implementation using AutoCAD. This initial phase focused on precise dimension-

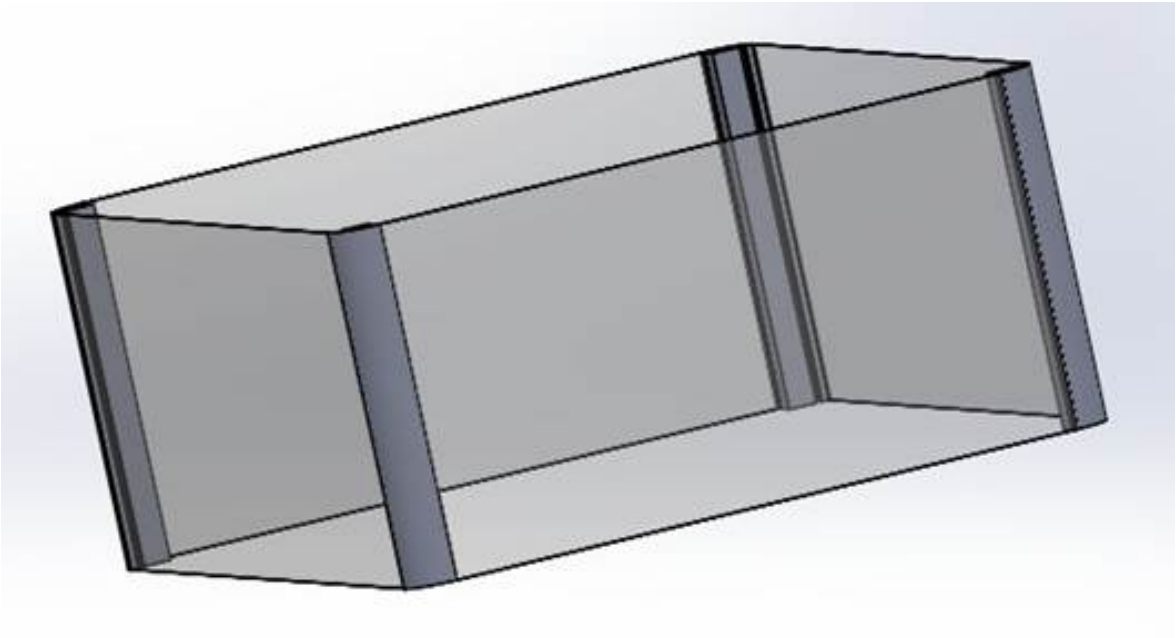


Figure 4.15: 3D model of protective frame and covering

ing, critical clearance verification, and detailed component interface planning. The process then progressed to advanced 3D modeling using SolidWorks, enabling complete assembly visualization, thorough interference checking between components, and dynamic movement simulation to validate the design's functionality.

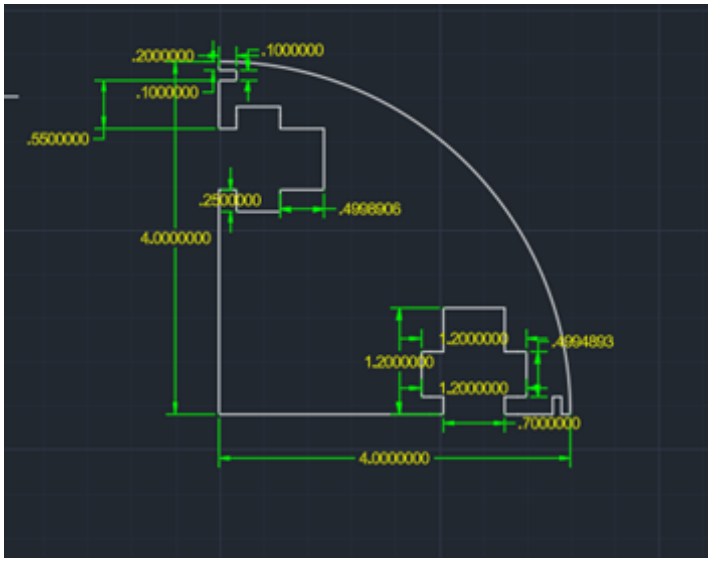


Figure 4.16: 2D profile of aluminum extrusion

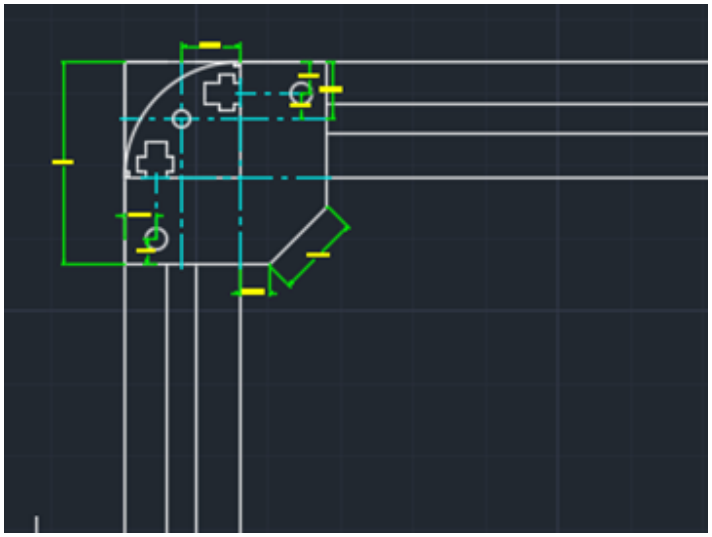


Figure 4.17: 2D model of profile joint and fasteners

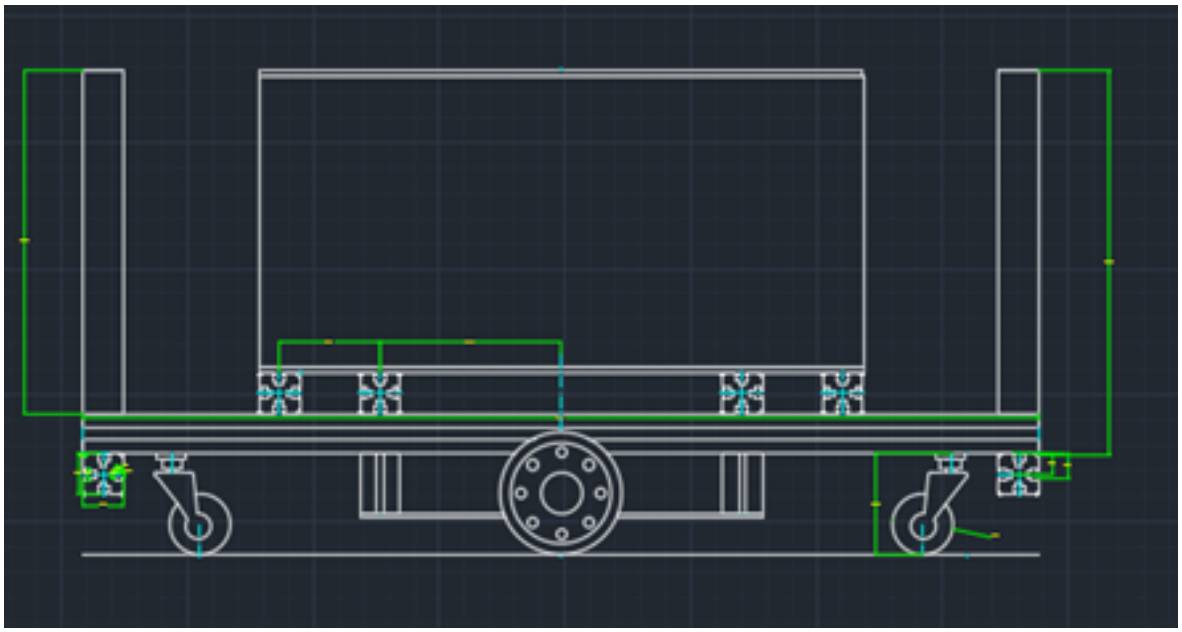


Figure 4.18: 2D model of Chassis and frame

4.13.6 Load Distribution Analysis

The static load distribution analysis revealed optimal weight distribution characteristics across all support points, with the chassis demonstrating minimal deflection under the maximum load capacity of 300 kg. Dynamic load considerations encompassed acceleration and deceleration forces, turning moment effects, and vibration damping characteristics, ensuring robust performance under various operational conditions.

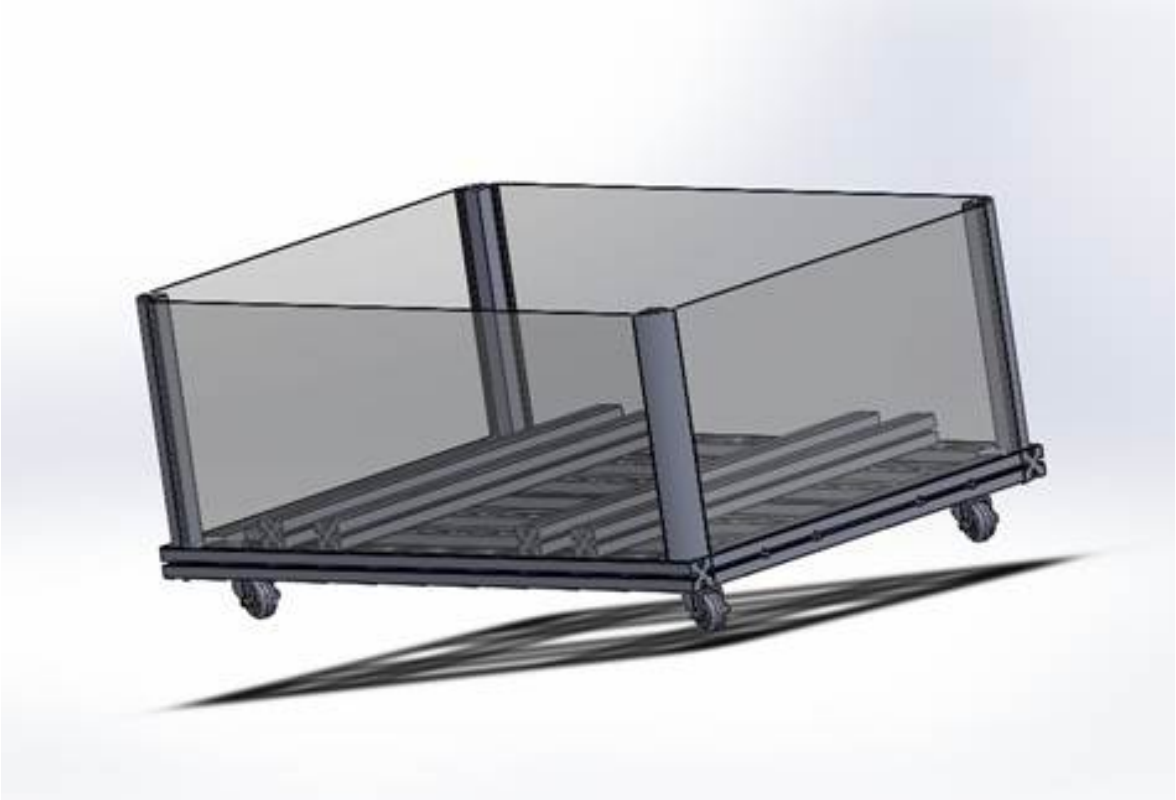


Figure 4.19: 3D design of chassis and frame covering

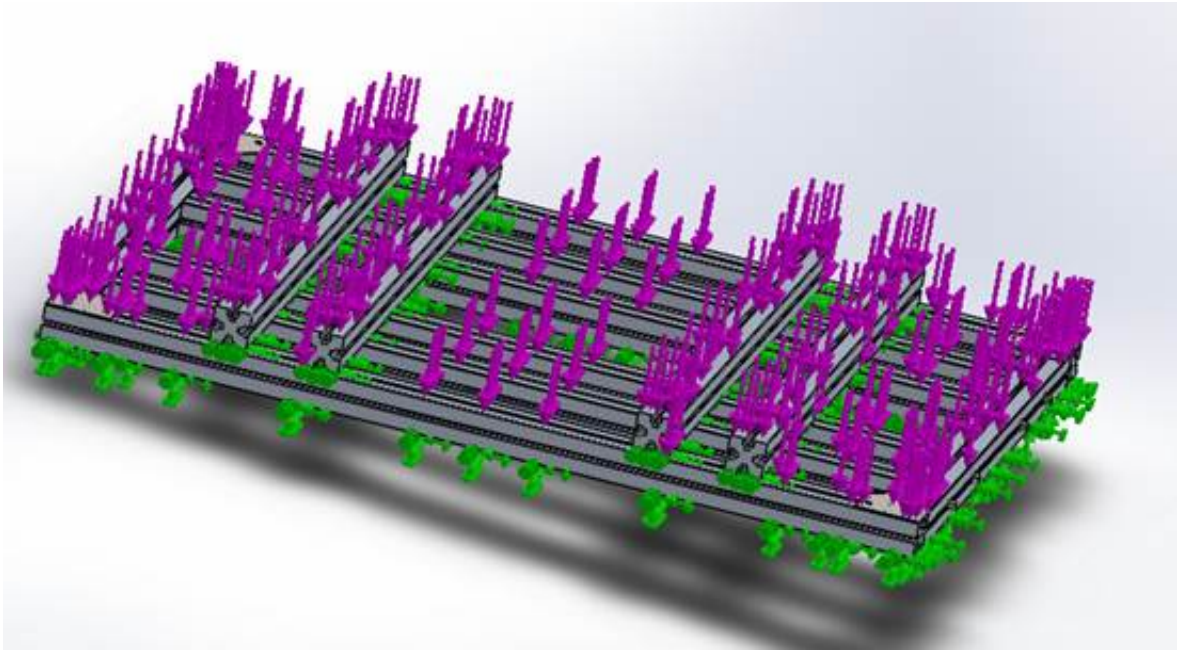


Figure 4.20: Load distribution on the chassis

4.13.7 Symmetry Stress Analysis

Using SolidWorks Simulation, stress analysis validated the design's structural integrity, showing Von Mises stress values well within material limits. The results revealed uniform

stress distribution with no significant concentration points. The structure exhibited acceptable maximum deflection ranges while maintaining elastic behavior under operational loads, with minimal torsional effects.

Comprehensive testing confirmed the chassis's structural stability under maximum load conditions, demonstrating seamless integration with scissor lift operations and effective weight distribution during movement. All integrated systems demonstrated proper functionality, validating the design's ability to meet operational requirements while maintaining necessary safety factors.

4.13.8 Load Analysis with 2943N Force

The chassis undergoes extensive analysis under a total force of 2943N (equivalent to 300kg × 9.81 m/s²). Each corner support bears approximately 735.75N, representing one-quarter of the total load. The central mounting points experience additional moment forces due to dynamic loading, while support beams are subject to combined axial and bending stresses.

The 40x40 aluminum extrusion profiles are engineered to handle substantial vertical loading, with direct compressive force of 2943N distributed across vertical supports. A safety factor of 1.5 is incorporated for dynamic loading conditions, with maximum allowable stress calculations adjusted accordingly. Horizontal forces, including shear forces during acceleration and deceleration, are carefully considered in the structural design.

Critical points analysis focuses on joint integrity, with particular attention to bracket connections experiencing increased stress concentrations. Bolt preload requirements are adjusted for higher forces, and weld points are designed to withstand greater cyclic loading. The increased load affects structural deformation, necessitating careful consideration of vertical deflection patterns and their impact on component alignment.

To ensure safety under the 2943N load, comprehensive structural reinforcement measures are implemented, including additional support brackets at high-stress points, increased material thickness in critical areas, and enhanced joint design for optimal load distribution. This thorough analysis ensures the chassis maintains structural integrity and operational safety under specified load conditions.

4.14 CONCLUSION AND FUTURE WORKS

This chapter has presented a comprehensive analysis of the AGV system design, focusing on the single-level scissor lift mechanism and chassis development. The design process incorporated extensive structural analysis, stress testing, and component integration strategies, with simulation results validating that both the scissor lift and chassis designs meet specified

operational requirements while maintaining necessary safety margins. Key achievements include the successful validation of the scissor lift mechanism for a 200 kg load capacity and the development of a robust chassis structure capable of supporting 300 kg (2943N).

The design methodology employed a systematic approach, utilizing advanced CAD tools and simulation software to ensure optimal performance and reliability. Through careful consideration of load distribution, stress analysis, and component integration, the final design demonstrates excellent structural integrity and operational stability. The implementation of comprehensive safety features and control systems further enhances the system's reliability and functionality in industrial applications.

Looking forward, several areas have been identified for future development, including design optimization through lightweight materials, enhanced payload configurations, and modular attachment systems. Performance improvements will focus on integrating advanced sensors for real-time monitoring, implementing predictive maintenance capabilities, and developing enhanced control algorithms for improved operational stability. Safety enhancements, including advanced emergency stop systems and smart collision avoidance capabilities, will ensure the AGV maintains high safety standards while adapting to complex industrial environments.

The successful development of this AGV system represents a significant step forward in automated material handling solutions. The implementation of proposed future developments will further enhance the system's capabilities, ensuring its continued evolution to meet emerging industrial requirements. Through these improvements, the AGV system will become more versatile, efficient, and safer, better serving the needs of modern industrial applications while maintaining its fundamental role in automated material transport and handling.

4.15 DESIGN AND DEVELOPMENT OF THE DRIVE WHEEL AND GEARBOX SYSTEM

The following section is devoted to the design and development of the drive wheel and gearbox system, which is crucial for the mobility, stability, and functionality of the AGV. The drive wheel and gearbox system is crucial in ensuring smooth and precise motion control, load handling, and adaptability to various operational environments. This project utilizes SolidWorks, a state-of-the-art computer-aided design software, for modeling and simulation of the drive wheel and gearbox. The robust tools for parametric design, assembly, and motion analysis in the software allow us to create an efficient and optimized design. It further takes into consideration practical constraints in reality, such as material selection, cost, manufacturability, environmental impact, and safety and engineering standards. The objective of the project is to present a design that will not only be functional and reliable but also sustainable and economical. The successive sections outline the design process, engineering analysis, and critical decisions in view of the realization of the above-mentioned objectives in detail.

Key objectives included:

- To design the system in SolidWorks.
- Check for structural integrity at operational loads.
- Analyze gearbox performance for the required torque and speed to achieve the desired gear ratio.
- Simplify design for manufacturability and assembly.

4.16 CRITICAL ELEMENTS OF AGV DESIGN: DRIVE WHEELS, GEAR MECHANISMS, AND MATERIAL SELECTION

AGVs are driverless transport systems used in the manufacturing industry, warehouses, and logistics. According to Groover (2015) [14], in ”Automation, Production Systems, and Computer-Integrated Manufacturing” an AGV would have a navigation system, a drive system, and sensors to operate autonomously. The driving system is the major component of an AGV, which provides the stability of the robot, the load-carrying capability, and the accuracy of motion.

In AGVs, middle drive wheels are important for balance and drive. Jazar's study [15], ”Vehicle Dynamics: Theory and Applications”, presented in the year 2019, gave much importance to wheel type, selection of motor, and gearbox that affects energy efficiency in a robot, how much load a robot can carry, adaptation on various kinds of terrain. A gearbox allows for the delivered torque and speed to the wheel for smooth, accurate movement.

Research on gearbox design for robotics has highlighted the requirement for compact, high-efficiency mechanisms. Kauffenberger et al. (2018) studied gear mechanisms in small mobile robots and found that among them, spur gears are the most used due to their simplicity, high load capacity, and ease of manufacturing. Their study also discussed the trade-off between gear ratios and torque output, noting that planetary gear systems provide higher torque.

The design of the drive wheel is critical for traction, maneuverability, and load-carrying capability. Bloss (2017), in ”Mobile Robotics: Principles and Design,” has discussed the role of drive wheels in robots, and he mentioned that material, tread pattern, and diameter of the wheel have a direct influence on performance. The wheels for AGVs are designed to meet both lightweight and high durability to allow for continuous operation with various loads.

The CAD tools utilized for the design of robot systems are quite popular, due to their advanced modeling and simulation capabilities. Das and Jana 2020, in the work ”Application of CAD Tools in Robotic Design”, have shown the capability of solid works to model complex assemblies such as gearboxes and also to simulate their motions.

Material selection is one of the most critical aspects in mechanical design. Ashby [16], 2011, ”Materials Selection in Mechanical Design” described a criterion for material selection that was based on strength, weight, cost and environmental considerations. Since this project dealt with drive wheels it mostly utilized rubberized materials, hence a thick rubber material was chosen, while gears are made from hardened steel preferred for its wear resistance and strength, it was also considered in my material selection.

4.17 DESIGN CONSTRAINTS

4.17.1 Technical Constraints

The following limitations relate to the feasibility and functionality of the design, encompassing several key factors:

- Dimensional Accuracy: The dimensions need to be precise so that the fitted parts inside assemble well.
- Load Bearing Capacity: The wheels and gearbox should bear the expected loads without deforming or failing.
- Speed and Torque Requirements: The gear ratio and wheel design must be such that desired performance is achieved.
- Compatibility with Other Components: Ensure that the design fits well with the AGV chassis, sensors, and other systems.
- Assembly and Maintenance: The design must ensure ease assembly, disassembly, and maintenance.
- Simulation Accuracy: Limitations of CAD software may affect the accuracy of stress, motion, or thermal simulations.

4.17.2 Material Constraints

The choice of materials impacts weight, durability, and cost.

- *Strength and Durability:* Materials must be able to handle the mechanical stresses without failure.
- *Weight:* Lighter materials are always preferred for efficiency, but without sacrificing strength.
- *Availability*: Materials selected must be available to the required quantity.
- *Cost*: The high-performance material may be beyond the budget and therefore some compromise may be necessary.

Material selection for the drive wheels and gearbox is critical in balancing performance, cost, and durability. Gears and shafts were made from hardened steel due to its high strength and wear resistance, while aluminum alloys are preferred for wheel hubs and gearbox housings

because of their lightweight and corrosion resistance. Drive wheel coatings were made from rubber or polyurethane to ensure traction, along with vibration absorption. The other alternatives, like plastics, are too weak and do not have enough strength to hold heavy loads; mild steel easily corrodes and is worn out, while on the other side, titanium, though very strong and light, is outrageously expensive and over-engineered for AGV applications. Materials selected ensure manufacturability with optimality, cost-effectiveness, and operation efficiency, making them the best choice for this project.

4.18 ENGINEERING STANDARDS AND LIFELONG LEARNING

4.18.1 Engineering standards

Engineering standards provide a framework for designing, testing, and manufacturing mechanical components to ensure compatibility, performance, safety, and reliability. Several organizations, such as ISO, ANSI, ASTM, IEEE, and DIN, define standards applicable to AGV drive systems.

4.18.2 Importance of Engineering Standards in AGV Drive System Design

Standards are essential in development to ensure:

- *Interoperability*: Components such as wheels, bearings, and shafts must conform to international sizes and tolerances. According to ISO 9001, which ensures a structured design and manufacturing process for reliability.
- *Safety*: Gearboxes and drive systems must adhere to safety regulations to prevent failures that could endanger users or disrupt operations. According to ISO 14121 , which helps in evaluating and mitigating risks associated with moving components.
- *Manufacturing Feasibility*: Standardized materials and design practices facilitate efficient production and cost reduction. According to AGMA 2001-D04, which helps in designing gears that meet durability and performance requirements.
- *Quality Assurance*: Standards define testing protocols for evaluating the durability and performance of components. According to ISO 606, which ensures proper gear-chain compatibility in AGV transmission systems.

4.19 MANUFACTURING CONSTRAINTS

The design should consider the limitations of manufacturing methods.

Process Feasibility: The parts must be manufacturable using available processes such as CNC machining, casting or 3D printing.

- *Tool Accessibility:* Shapes that include internal grooves or undercuts may not easily be machined due to complexity.
- *Surface Finish:* Very complicated surfaces may be expensive or time-consuming to produce.
- *Assembly Difficulty:* Designs that include many parts or tight clearances may be more difficult to assemble because of mating with specific part which may not be possible if there are too tight.
- *Standard Components:* Using off-the-shelf components such as bearings and shafts rather than customized components simplifies production and reduces cost.

4.20 ECONOMIC CONSTRAINTS

In designing, fabricating, and deploying the driving wheels and gearboxes of an AGV, the main economic issues have to do with material type, manufacturing process, labor costs, maintenance, and scalability of the product.

- *Material Costs:* The use of high-performance materials, such as hardened steel and aluminum alloys, will enhance durability, but at increasingly higher costs. Using recycled or alternative materials may balance cost with performance.
- *Manufacturing Costs:* CNC machining, injection molding, and forging are cost-intensive to set up and hence affect the feasibility. Batch production and automation reduce the per-unit cost.
- *Labor and Skill Costs:* Skilled labor for design in SolidWorks, machining, and assembly increases the overall cost of the project. Automation and standardized components reduce labor dependence.
- *Maintenance and Lifecycle Costs:* Long-term costs are inclusive of the wear and tear of gears, battery efficiency, and availability for spares. Low-maintenance material selection and efficient motor designs reduce operational expenses.

- *Scalability and Mass Production:* Large-scale production reduces the unit cost due to bulk material discounts and streamlines the manufacturing process, though there is a requirement for high initial capital investment.

Lifecycle management can make the development of AGV drive systems cost-effective and green without compromising performance by applying optimization in design and manufacturing processes.

4.21 ENVIRONMENTAL CONSTRAINTS

Throughout their life, AGV drive wheels and gearboxes have some environmental impacts associated with each stage—from material extraction to end-of-life disposal. The most serious concerns are resource depletion, energy consumption, carbon footprint, and generation of wastes.

- *Material Impact:* The extraction and processing of steel, aluminum, and plastics lead to land degradation, energy usage, and air pollution. Recycled materials can be used in order to reduce the above-mentioned effects.
- *Manufacturing Waste:* Manufacturing processes involving CNC machining, injection molding, and heat treatment result in wastes like metal scraps, plastic wastes, and chemical by-products. The adoption of lean manufacturing and energy-efficient machinery reduces environmental degradation.
- *Energy Consumption & Carbon Emissions:* AGVs use electric motors and batteries, and their production indirectly contributes to CO_2 emissions if these are manufactured from fossil fuels. Efficient gearbox designs, regenerative braking, and renewable-powered charging stations could further improve sustainability.
- *Waste and Disposal Challenges:* Later in the life cycle, the components and batteries of AGVs pose waste challenges. Recycling programs, biodegradable lubricants, and modular component designs should be developed for environmental sustainability.

By the use of sustainable materials, manufacturing with a minimum of energy, and waste, the technology of AGV will go greener without losing efficiency and durability.

4.22 HEALTH AND SAFETY PROBLEMS

From both design and operational standpoints, the AGVs, their driving wheels, and gearboxes create many health and safety problems that have to be overcome to make them safe for workers and ensure reliability and operational efficiency. These aspects are very crucial in both the manufacturing process and final deployment within industrial environments. Thus, working out such problems would avoid accidents, injuries, and equipment failures.

1. *Manufacturing Hazards:* Workers are exposed to mechanical hazards, chemical exposure, and noise pollution. Safety measures include personal protective equipment, proper ventilation, and noise-reducing technologies.

2. *Operational Safety Risks:* Gears can cause collisions, pinching, and crushing hazards, especially if visibility is poor. Safety measures involve collision avoidance systems, warning alarms, and clear design protocols.

3. *Ergonomic Concerns:* Most of the assembly and maintenance tasks involve the risk of repetitive strain injuries and manual handling. This can be resolved by introducing automated handling systems, ergonomic tools, and workstations that are adjustable.

4. *Hazards in Maintenance and Repair:* Maintenance involves workers in electrical risks, mechanical injuries, and harmful chemicals. These may be minimized by instituting lock-out/tag-out procedures, wearing PPE, and training in safe maintenance.

5. *Long-term Health Issues:* Prolonged exposure to vibration, noise, and psychosocial stress can cause health problems such as hearing loss and vibration-induced problems. These risks can be minimized by regular health checks and stress management programs.

By addressing these health and safety concerns, AGV manufacturers and operators can ensure a safer working environment, improve equipment reliability, and enhance overall worker well-being.

4.23 MANUFACTURABILITY

Manufacturability refers to the development and production of the AGV drive wheels and gearboxes in an effective manner that is affordable and of great quality. Key considerations will include:

1. *Material Selection:* Lighter materials, such as aluminum, steel, and reinforced polymers, balance strength, wear resistance, and cost.

2. *Design for Manufacturability:* Simplification of geometries, standardization of parts, modular design, and proper tolerancing enhance ease of fabrication and assembly.

3. *Production Methods:* CNC machining, casting, forging, injection molding, and heat treatments are crucial for producing high-precision components efficiently.

4. *Assembly Efficiency:* Reducing fastener types, using pre-assembled subcomponents, and integrating automated assembly speeds up production while maintaining consistency.

5. *Cost and Scalability:* Choosing cost-effective production techniques, securing reliable supply chains, and optimizing mass production vs. small-batch production ensures economic feasibility.

6. *Sustainability:* Using recyclable materials, energy-efficient manufacturing, waste reduction, and eco-friendly coatings supports environmentally responsible production.

Therefore, focusing on these manufacturability aspects, manufacturers of AGVs can provide quality, durable, scalable drive wheels and gearboxes by optimizing cost, efficiency, and sustainability.

4.24 METHODOLOGY

The methodology followed for the project in brief is given below:

1. Determination of dimensions, number of all gear teeth , and gear ratio.

2. 3D Modeling: Detailed CAD modeling of wheels, gears, shafts, and housing on SolidWorks.

3. Simulation: motion analysis to validate the design.

4. Optimization: Refined design for performance and manufacturability.

4.24.1 Dimensions

Ring gear which is the bigger gear has a dimater of 190 teeth
The planet gear has a diameter of 90mm
The sun gear has a diameter of 10mm

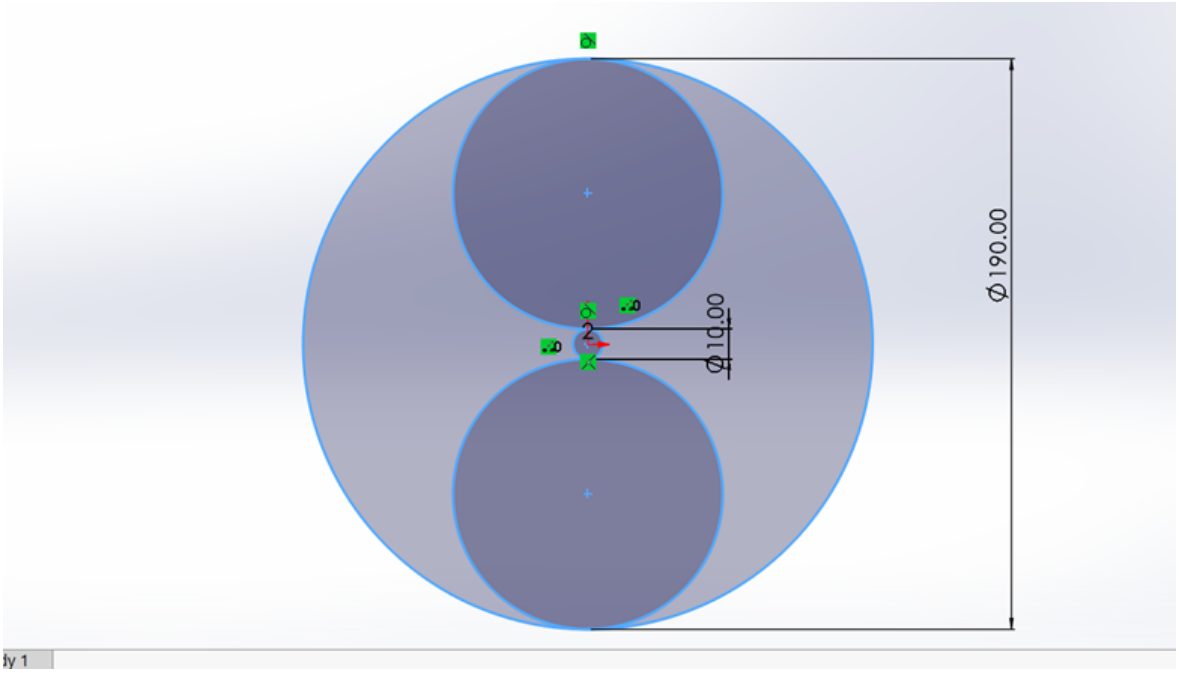


Figure 4.21: Add caption here

4.25 3D MODELING

Following components were modelled using SolidWorks:

4.25.1 Middle Drive Wheels:

For Traction and load-carrying capacity. Which is made of natural rubber has the ability to withstand high load and relatively not so heavy. The wheels for AGVs are designed to meet both lightweight and high durability to allow for continuous operation with various loads.

4.25.2 Gearbox:

Compact design with spur gears for efficient transmission. Studies shows spur gears are the most used due to their simplicity, high load capacity, and ease of manufacturing. Their study also discussed the trade-off between gear ratios and torque output, noting that planetary gear systems provide higher torque.

4.25.3 Shafts and Bearings:

For smooth rotation and distribution of loads. I made use of both skf bearing 108tn92 and skf bearing 1210ektn9202 while for the wheel holder it was made with hard steel for firmness and durability.

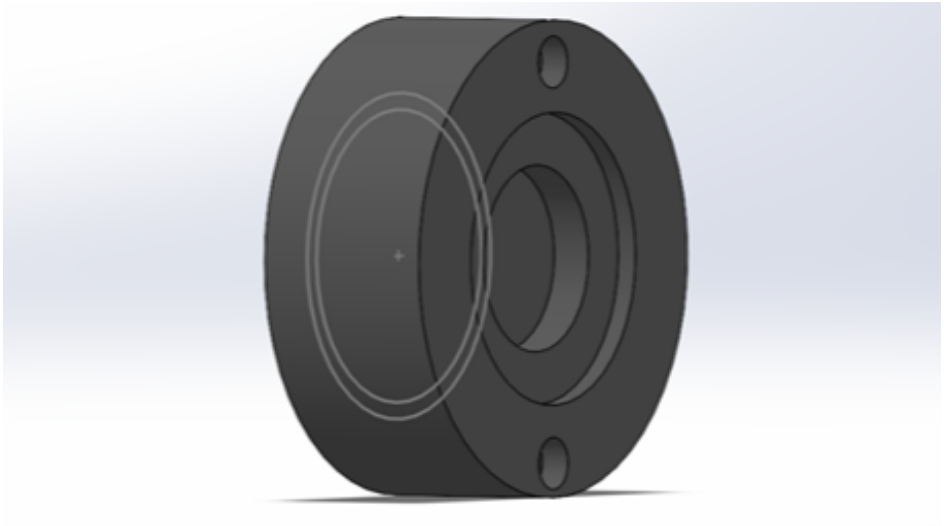


Figure 4.22: Caption 1

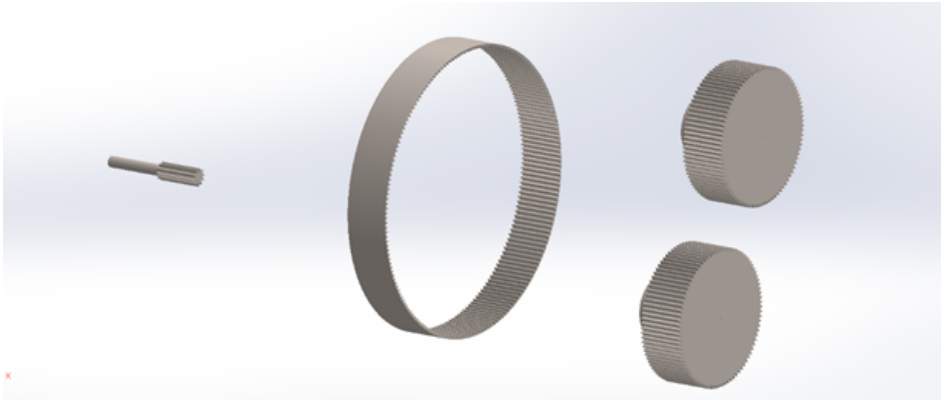


Figure 4.23: Caption 1

4.25.4 Housing:

Enclosed system for protection against dust and debris. Which lightweight aluminum were used to reduce the weight of the gear box.

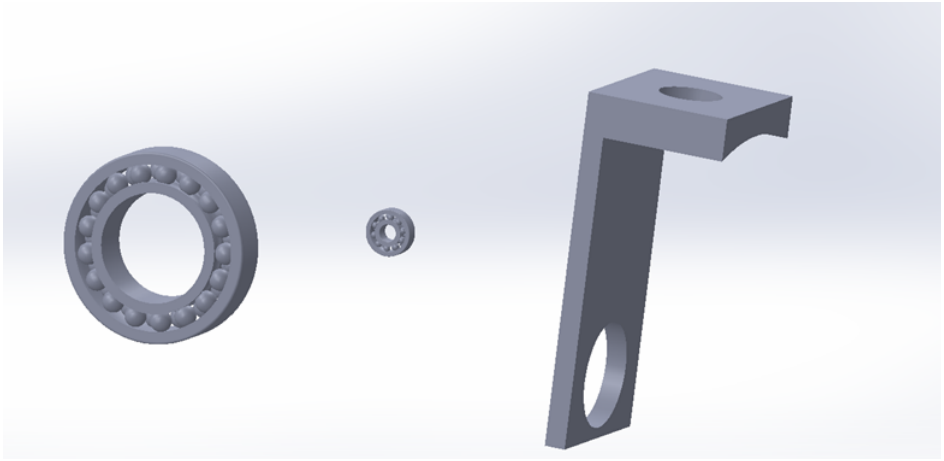


Figure 4.24: Caption 1

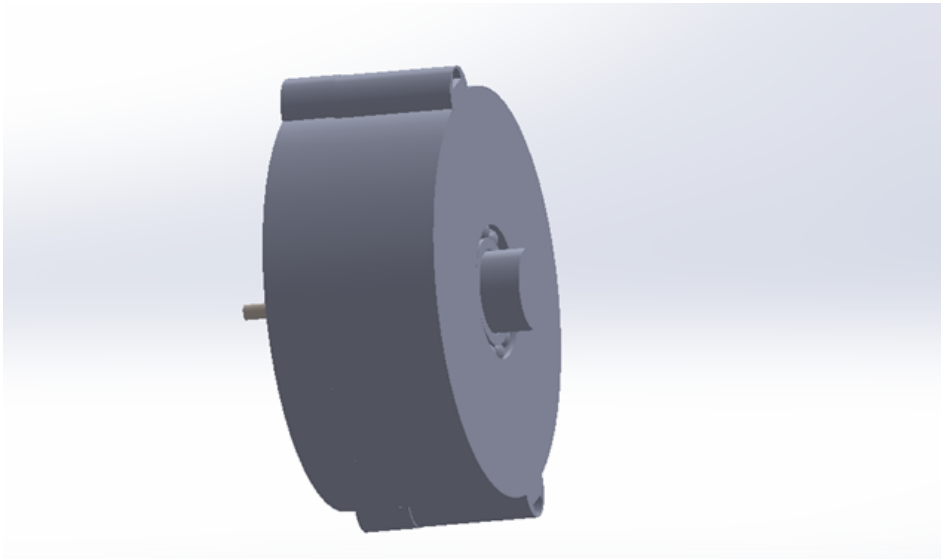


Figure 4.25: Caption 1

4.25.5 Assembly

The parts were then assembled in SolidWorks for a check on appropriateness and compatibility.

4.26 CALCULATION AND ANALYSIS

Simulations done in SolidWorks to test performances of the design:

4.26.1 GEARBOX CALCULATION

- ring gear $\rightarrow$ 190 Teeth [120 mm ϕ] [Tr]
- PLAMET Gear $\rightarrow$ 90 Teeth [Tp]

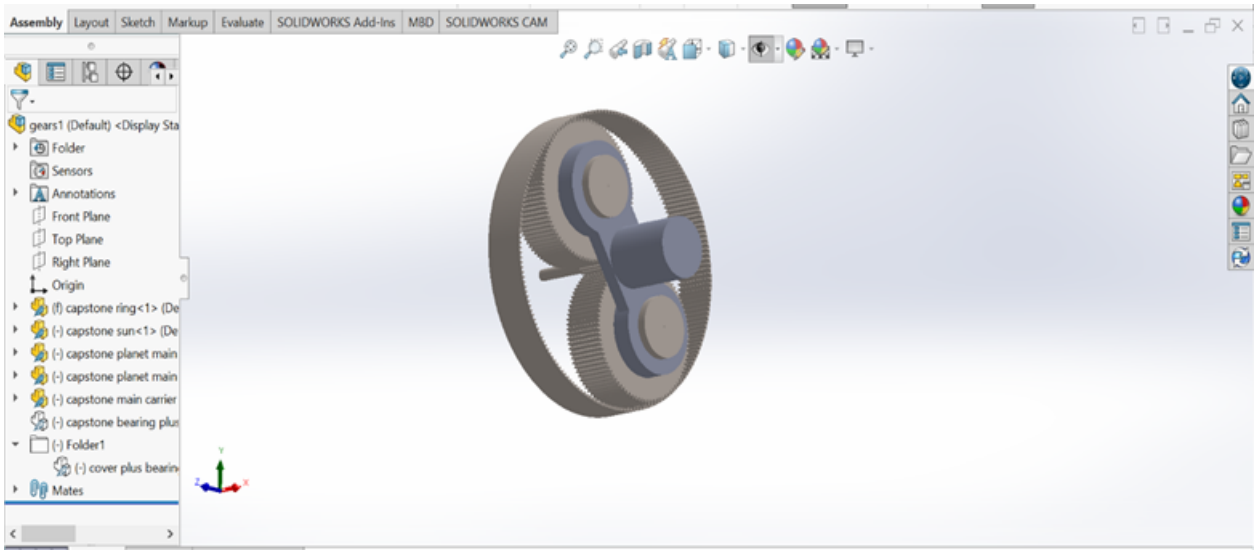


Figure 4.26: Add caption here

- Sun gear $\rightarrow$ 10 Teeth [Ts]

GEAR RATIO : NOTE I want a high ratio of 20 : 1

$$20 = 1 + \frac{T_r}{T_s}$$

$$\frac{T_r}{T_s} = 19$$

$$T_r = 19T_s$$

The planet does not affect the ratio but determines the spacing of the sun and ring gears. Rearanging:

$$\frac{T_r}{T_s} = 19$$

$$IF\ T_s = 10$$

$$T_r = 19 \times 10 = 190$$

from $T_r - T_s = 2T_p \rightarrow$ Spacing in the ring

$$190 - 10 = 2T_p$$

$$T_p = 90$$

$$\rightarrow 1 + \frac{T_r}{T_s} \Rightarrow 1 + \frac{190}{10} = 20$$

$$\rightarrow 20 : 1$$

$\rightarrow$ 1500 input speed $\div 20(gear\ ratio) \Rightarrow 75rmp$ output speed

Considering

Nema 23 stepper motor

Nominal power $\rightarrow$ 240 Watts

Nominal voltage $\rightarrow$ 484

Nominal current $\rightarrow 5\ A$

Maminal rotation $\rightarrow 1500rpm$

$$T_{\text{in}} = \frac{P \times 60}{2\pi \times N} = \frac{240 \times 60}{2\pi \times 1500} \Rightarrow T_{\text{in}} = 1.53Nm$$

- This calalation is assumed 100% efficiency, Real - Idorly will be slightly lower due to losses [heat, friction]

$$\begin{aligned} T_{\text{out}} &= T_{\text{in}} \times R_{\text{atio}} \times \eta \\ &= 1.53 \times 20 \times 0.94 \\ &= 28.2Nm \end{aligned}$$

$$\begin{aligned} \eta[\text{ efficiency }] = \frac{\text{Out put power}}{\text{Input poise}} \times 100\% &= \frac{75 \times 28.2}{1500 \times 1.53} \\ &= \frac{2,115}{2,280} = 0.927 = 92\% \end{aligned}$$

4.27 MOTION ANALYSIS:

Wheels' rotation and torque transfer in the gearbox simulated.

Result: Smooth motion with efficiency in power transmission.

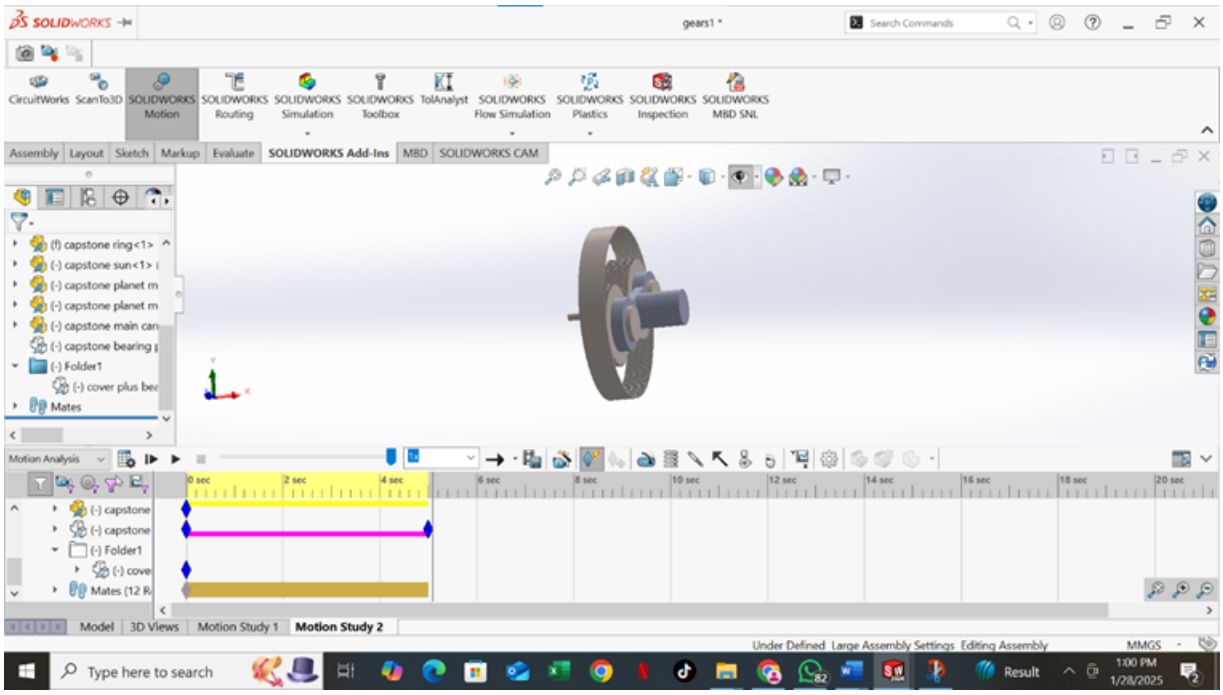


Figure 4.27: Add caption here

Material Selection

Wheels: Natural rubber, corrosion resistant and high load capacity.

Gears: Hardened Steel for increased strength and wear resistance

Shafts: Steel for durability

Housing: aluminum protection

Results and Discussion

The final design was able to meet all the specified requirements, which included load capacity, torque output, and manufacturability. The simulations proved that the system was structurally sound and could operate without hitches under realistic conditions .

4.28 CONCLUSION

It should not only be functional, but also practical, manufacturable, and economic, taking into consideration all the constraints. The literature survey focuses on the fact that the gearbox-equipped drive wheel system is a main concern in the design of an AGV. Material selection, load-carrying capacity, torque optimization, and manufacturability are the key factors to be considered. In this paper, design and simulation for performance improvement of the AGV using SolidWorks are proposed to overcome these bottlenecks and help in the development of reliable high-performance drive systems for AGVs.

The middle drive wheels with an integrated gearbox were designed and further validated for use in an AGV. The system was reliable, efficient, and easy to manufacture. Future work can be the physical development of the prototype and performance testing at site applications..

4.29 GREGORY'S CHAPTER

4.30 INTRODUCTION

Bearing wheels and caster wheels are integral components in various industrial and commercial applications, facilitating mobility, load distribution, and operational efficiency. These wheels are commonly found in material handling equipment, automotive systems, and heavy machinery, where they ensure seamless movement and reduced friction. The efficiency and durability of these components directly impact productivity, safety, and cost-effectiveness in different industries.

Designing an effective bearing or caster wheel system involves several critical factors, including material selection, load-bearing capacity, resistance to environmental conditions, and compliance with industry standards such as ISO 3691-4:2020. Material properties play a vital role in determining the strength, wear resistance, and overall performance of the wheels. Common materials used in bearing wheels include AISI 1045 steel for shafts and AISI 52100 chrome steel for bearings, both of which offer high durability and load-handling capabilities.

The study of bearing and caster wheels also involves analyzing mechanical constraints, including torque requirements, frictional forces, and stress distribution. Ensuring optimal performance requires comprehensive calculations, including shaft diameter determination, bearing life assessment, and stress-strain analysis. Additionally, environmental considerations such as exposure to moisture, temperature variations, and corrosive elements influence the selection of materials and protective coatings.

Manufacturing constraints must also be addressed to maintain cost-effectiveness and efficiency in production. Precision machining, heat treatment processes, and surface finishing techniques are necessary to achieve the desired durability and performance characteristics. Furthermore, safety factors such as load limitations, stability, and braking mechanisms must be considered to prevent operational hazards and equipment failure.

This project aims to develop a systematic approach to designing and evaluating bearing and caster wheels while addressing real-world challenges. By integrating theoretical calculations with finite element analysis (FEA), this study seeks to enhance the reliability, efficiency, and sustainability of these components. The findings will contribute to improving material selection, optimizing load distribution, and ensuring compliance with industry regulations, ultimately leading to more robust and long-lasting wheel systems.

4.31 LITERATURE REVIEW

Research on bearing wheels and caster wheels has extensively explored their mechanical properties, material composition, and industrial applications. Several studies have emphasized the significance of material selection in determining the durability and efficiency of these components. According to Smith et al. (2020), AISI 1045 steel is widely used for shaft manufacturing due to its high tensile strength and resistance to mechanical fatigue. Similarly, AISI 52100 chrome steel is preferred for bearings due to its excellent hardness, wear resistance, and ability to withstand high loads.

Lubrication and friction management play crucial roles in ensuring the longevity of bearing systems. Studies by Brown and Pietra (2018) highlight that improper lubrication can lead to increased friction, wear, and premature failure of bearings. Advanced lubrication techniques, such as sealed bearings and self-lubricating materials, have been explored to enhance performance and minimize maintenance requirements.

The impact of environmental factors on bearing and caster wheel performance has also been a key area of research. According to Can and Ozkarahan (2019), exposure to high humidity and extreme temperatures can accelerate corrosion and degrade material integrity. Protective coatings, such as zinc plating and polymer encapsulation, have been recommended to improve resistance against environmental hazards.

Manufacturing techniques and precision engineering have further influenced the development of high-performance bearing and caster wheels. Recent advancements in computer-aided design (CAD) and finite element analysis (FEA) have enabled engineers to optimize designs for maximum efficiency. Studies by Johnson et al. (2021) indicate that simulation-based testing allows for accurate prediction of load distribution, stress concentrations, and potential failure points, leading to more reliable designs.

Safety considerations in wheel design have also been extensively analyzed. Research by Lee and Kim (2022) emphasizes the importance of braking mechanisms and stability enhancements in caster wheel applications, particularly in medical and industrial equipment. Proper weight distribution and impact resistance are essential factors in preventing accidents and improving operational safety.

In conclusion, the literature underscores the importance of material selection, lubrication, environmental protection, and advanced manufacturing techniques in optimizing bearing and caster wheel performance. The integration of modern engineering tools and industry standards ensures that these components meet the growing demands of industrial applications while maintaining safety, durability, and efficiency. This study builds upon existing research to develop a comprehensive approach to designing and evaluating bearing and caster wheel systems.

4.32 REALISTIC CONSTRAINTS

4.32.1 Material Constraints

Bearing wheels and caster wheels require high-strength materials for load-bearing capacity and durability. AISI 1045 steel is chosen for the shaft due to its excellent mechanical properties, including high yield strength (530 MPa) and good machinability. AISI 52100 chrome steel is used for bearings due to its superior hardness and wear resistance. However, these materials are susceptible to corrosion in humid environments, necessitating protective coatings or stainless alternatives. The choice of rubber or polyurethane for the wheel itself impacts rolling resistance, wear rate, and temperature resistance.

4.32.2 Manufacturing Constraints

Manufacturing challenges include precision machining of shafts and bearings to ensure proper tolerances. Heat treatment processes are required for AISI 52100 bearings to achieve the necessary hardness. Forging and casting limitations impact cost and production scalability. Bearings must meet ISO 3691-4:2020 standards, which impose strict requirements on tolerances and material integrity. The availability of raw materials and manufacturing costs also influence design decisions.

4.32.3 Mechanical Constraints

Bearing wheels and caster wheels must withstand dynamic loads and impacts without failure. Bearings must be designed to handle radial and axial loads efficiently. Torque calculations ensure that the system operates within safe stress limits. Misalignment and excessive vibration can reduce bearing life, requiring proper lubrication and mounting techniques. The wheel's rolling friction, influenced by surface conditions and load distribution, impacts efficiency.

4.32.4 Environmental Constraints

Environmental factors such as temperature variations, moisture, and chemical exposure affect material performance. Bearings exposed to extreme temperatures may experience reduced lubrication effectiveness, leading to higher friction and wear. Caster wheels used in outdoor environments must resist UV degradation and corrosion. Sustainable material choices and waste reduction strategies are essential to meet environmental regulations.

4.32.5 Safety Constraints

Safety considerations include ensuring that the wheels can withstand maximum load without failure. Overloading can lead to bearing fatigue and catastrophic failure. Proper braking mechanisms must be integrated into caster wheel systems to prevent uncontrolled movement. Bearings must comply with safety standards such as ISO 3691-4:2020 to prevent accidents due to bearing failure. Ergonomic considerations also play a role in reducing strain on operators handling heavy loads.

4.33 CHAPTER FOUR: METHODS USED TO DESIGN THE PROJECT

4.33.1 Objectives

1. Shaft Diameter Calculation: Ascertain the ideal shaft diameter by considering material qualities and bending moments, making sure the shaft can support operational loads.

2. Bearing selection and torque calculation: Choose a bearing size and type that satisfies the operational lifespan and dynamic load requirements, then calculate the necessary torque.

3. Safety and Efficiency Optimization: To balance performance and cost-efficiency, take safety considerations into account and choose materials as efficiently as possible.

4. Conformity: Verify that the design conforms with applicable industry standards, especially ISO 3691-4:2020, which regulates dependability and safety in load-bearing systems.

4.33.2 Methodology

4.33.3 Bearing selection

4.33.3.1 Inputs and Assumptions

1. Wheel radius (R): 110 mm
2. Load on the wheel (F): 981 N
3. Maximum speed (v): 1.25 m/s
4. Shaft material: Steel (e.g., AISI 1045)
    - Yield strength: σy=250 MPa
5. Bearing material: Chrome steel (e.g., AISI 52100)
6. Bearings catalog: We'll pick based on calculated load and RPM.
7. Factor of safety (FOS): 2.0 for shaft design.

4.33.3.2 Shaft Diameter Calculation

Angular Velocity Convert the speed into angular velocity (ω) to determine the RPM.

$$\omega = \frac{v}{R} \tag{4.18}$$

Substitute values in eq. (4.18):

$$\omega = \frac{1.25}{0.110} = 11.36 \text{ rad/s}$$

Convert ω to RPM:

$$RPM = \omega \times 602\pi = 11.36 \times 602\pi \approx 21484.99 \text{ RPM}$$

Bending Moment and Shaft Diameter For a wheel shaft, the critical load is the bending moment due to the force F. Assuming a simple beam supported at the bearing points:

$$M = F \times L \tag{4.19}$$

Where L is the distance from the bearing to the load. Assume L=50 mm=0.05 m(minimum according to the ISO 3691-4:2020 standard):

$$M = 981 \times 0.05 = 49.05 \,\text{Nm}$$

Using the **maximum shear stress theory** for a solid circular shaft, the shaft diameter is calculated from:

$$d = (16M/\pi\tau max)^{1/3} \tag{4.20}$$

Where:

- τmax: Allowable shear stress = $\sigma y/2 \times FOS = 250/2 \times 2 = 62.5\,MPa = 62.5 \times 106\,Pa$

Substitute values in eq. (4.20):
$d = (16 \times 49.05/\pi \times 62.5 \times 106)^{1/3}$= 0.012mm

4.33.3.3 Bearing Selection

Load on the Bearing The radial load on the bearing is equal to the load on the wheel:

$$Fr = 981 \,\text{N}$$

Dynamic Load Rating Using the bearing life equation:

$$C = Fr \times (L/1,000,000)^{\frac{1}{3}}$$

Where:

- L: Bearing life in revolutions. Assume L=10^6 revolutions.

$C = 981 \times (10^6/1,000,000)^{1/3} = 981N$

From a standard bearing catalog, a **deep groove ball bearing** with a dynamic load rating C>981 N and an inner diameter matching the shaft size (d=12 mm) is selected:

- **Bearing Type:** Deep groove ball bearing (e.g., 6201 series).
- **Verification :**

4.33.3.4 Material Properties of AISI 1045 Steel

Yield Strength (σy): Approximately 530 MPa
Ultimate Tensile Strength (σu): Approximately 625 MPa

4.33.3.5 Calculation

1. **Cross-Sectional Area (A)**:

$$A = \pi \left(\frac{d}{2}\right)^2 = \pi \left(\frac{12\,\text{mm}}{2}\right)^2 \approx 113.1\,\text{mm}^2$$

2. **Stress (σ)**:

A shaft of 12mm diameter made of AISI 1045 steel can safely bear a load of 981N, as the induced stress is well within the material's yield and ultimate tensile strengths.

$$\sigma = \frac{F}{A} = \frac{981\text{ N}}{113.1\text{ mm}^2} \approx 8.67\text{ MPa}$$

3.3 Number of Balls in the Bearing To determine the diameter of the balls in the bearing when we are supposed to have 9 balls(i tried all the number less than 9 , they were not compatible with the standard), we can use the following formula:

$$\text{z} = \frac{\pi(D+d)}{2d_b} \tag{4.21}$$

where:

- z is the number of balls.
- D is the outer diameter of the bearing.
- d is the inner diameter of the bearing.
- db is the diameter of each ball.

Given:

- z=9
- D = 32 mm
- d = 12 mm

We need to solve for db:
$9=\pi(32+12)/2db$
$9=\pi\times44/2db$
$db=22\pi/9$
$db\approx7.68$ mm
For a 6201 bearing:

- Number of balls: Typically 7–9 balls.
- Ball diameter: beyond 4.5 mm.

4.33.3.6 Material Selection

Shaft Material: AISI 1045 Steel

- Reason: High strength, good machinability, and readily available.

Bearing Material: AISI 52100 Chrome Steel

- Reason: High hardness, wear resistance, and durability under dynamic loads.

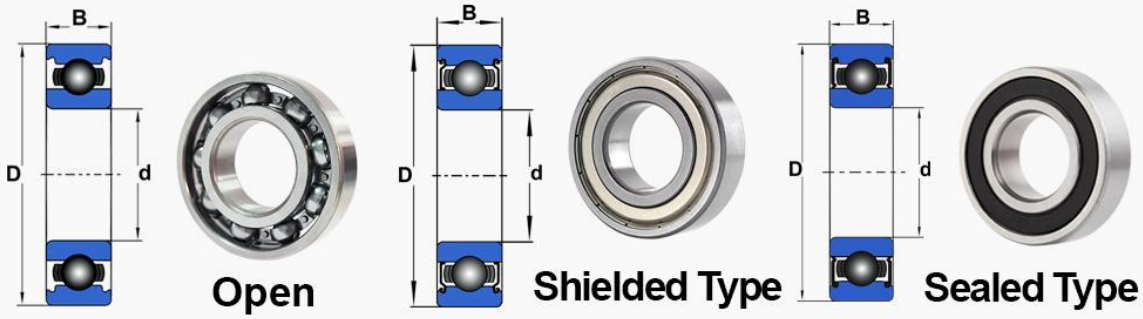
4.33.3.7 Compatibility Check

A deep groove ball bearing that meets these specifications is the **NSK 6201** bearing. Here are the details:

- **Inner Diameter (ID)**: 12 mm
- **Outer Diameter (OD)**: 32 mm

- **Width (W)**: 10 mm
- **Material**: AISI 52100 Chrome Steel
- **Load Capacity**: Suitable for the given load and speed requirements

NSK Deep Groove Ball Bearing



Boundary Dimensions (mm)				Basic Load Ratings (N)		Basic Load Ratings {kgf}		Factor	Limiting Speeds (rpm) Grease		Limiting Speeds (rpm) Oil	Bearing Numbers			
d	D	B	r min	C_r	C_{0r}	C_r	C_{0r}	f_0	Open Z · ZZ V · VV	DU DDU	Open Z	Open	Shielded		Sealed
10	19	5	0.3	1 720	840	175	86	14.8	34 000	24 000	40 000	**6800**	**ZZ**	**VV**	**DD**
	22	6	0.3	2 700	1 270	275	129	14.0	32 000	22 000	38 000	**6900**	**ZZ**	**VV**	**DD**
	26	8	0.3	4 550	1 970	465	201	12.4	30 000	22 000	36 000	**6000**	**ZZ**	**VV**	**DDU**
	30	9	0.6	5 100	2 390	520	244	13.2	24 000	18 000	30 000	**6200**	**ZZ**	**VV**	**DDU**
	35	11	0.6	8 100	3 450	825	350	11.2	22 000	17 000	26 000	**6300**	**ZZ**	**VV**	**DDU**
12	21	5	0.3	1 920	1 040	195	106	15.3	32 000	20 000	38 000	**6801**	**ZZ**	**VV**	**DD**
	24	6	0.3	2 890	1 460	295	149	14.5	30 000	20 000	36 000	**6901**	**ZZ**	**VV**	**DD**
	28	7	0.3	5 100	2 370	520	241	13.0	28 000	—	32 000	**16001**	—	—	—
	28	8	0.3	5 100	2 370	520	241	13.0	28 000	18 000	32 000	**6001**	**ZZ**	**VV**	**DDU**
	32	10	0.6	6 800	3 050	695	310	12.3	22 000	17 000	28 000	**6201**	**ZZ**	**VV**	**DDU**
	37	12	1	9 700	4 200	990	425	11.1	20 000	16 000	24 000	**6301**	**ZZ**	**VV**	**DDU**
15	24	5	0.3	2 070	1 260	212	128	15.8	28 000	17 000	34 000	**6802**	**ZZ**	**VV**	**DD**
	28	7	0.3	4 350	2 260	440	230	14.3	26 000	17 000	30 000	**6902**	**ZZ**	**VV**	**DD**
	32	8	0.3	5 600	2 830	570	289	13.9	24 000	—	28 000	**16002**	—	—	—
	32	9	0.3	5 600	2 830	570	289	13.9	24 000	15 000	28 000	**6002**	**ZZ**	**VV**	**DDU**
	35	11	0.6	7 650	3 750	780	380	13.2	20 000	14 000	24 000	**6202**	**ZZ**	**VV**	**DDU**
	42	13	1	11 400	5 450	1 170	555	12.3	17 000	13 000	20 000	**6302**	**ZZ**	**VV**	**DDU**
17	26	5	0.3	2 630	1 570	268	160	15.7	26 000	15 000	30 000	**6803**	**ZZ**	**VV**	**DD**
	30	7	0.3	4 600	2 550	470	260	14.7	24 000	15 000	28 000	**6903**	**ZZ**	**VV**	**DDU**
	35	8	0.3	6 000	3 250	610	330	14.4	22 000	—	26 000	**16003**	—	—	—
	35	10	0.3	6 000	3 250	610	330	14.4	22 000	13 000	26 000	**6003**	**ZZ**	**VV**	**DDU**
	40	12	0.6	9 550	4 800	975	490	13.2	17 000	12 000	20 000	**6203**	**ZZ**	**VV**	**DDU**
	47	14	1	13 600	6 650	1 390	675	12.4	15 000	11 000	18 000	**6303**	**ZZ**	**VV**	**DDU**
20	32	7	0.3	4 000	2 470	410	252	15.5	22 000	13 000	26 000	**6804**	**ZZ**	**VV**	**DD**
	37	9	0.3	6 400	3 700	650	375	14.7	19 000	12 000	22 000	**6904**	**ZZ**	**VV**	**DDU**
	42	8	0.3	7 900	4 450	810	455	14.5	18 000	—	20 000	**16004**	—	—	—
	42	12	0.6	9 400	5 000	955	510	13.8	18 000	11 000	20 000	**6004**	**ZZ**	**VV**	**DDU**
	47	14	1	12 800	6 600	1 300	670	13.1	15 000	11 000	18 000	**6204**	**ZZ**	**VV**	**DDU**
	52	15	1.1	15 900	7 900	1 620	805	12.4	14 000	10 000	17 000	**6304**	**ZZ**	**VV**	**DDU**
22	44	12	0.6	9 400	5 050	960	515	14.0	17 000	11 000	20 000	**60/22**	**ZZ**	**VV**	**DDU**
	50	14	1	12 900	6 800	1 320	695	13.5	14 000	9 500	16 000	**62/22**	**ZZ**	**VV**	**DDU**
	56	16	1.1	18 400	9 250	1 870	940	12.4	13 000	9 500	16 000	**63/22**	**ZZ**	**VV**	**DDU**

Figure 4.28: caption here not added by Gregory

4.33.4 Torque calculation

4.33.4.1 Given Data:

- Gross Vehicle Weight: 300 kg
- Weight per Drive Wheel: 100 kg
- Maximum Incline Angle: 8°
- Maximum Velocity: 1.5 m/s
- Surface: Concrete
- Type of Bearing: Deep Groove Ball Bearing (NSK 6201)
- Wheel Type: Rubber Tires
- Drive Wheel Diameter: 95 mm (0.095 m)

4.33.4.2 Load Analysis:

1. **Load Calculation**:

   $F = W = 100\,kg \times 9.81\,m/s2 = 981\,N$

2. **Wheel Rotational Speed**:

   $r = 0.22\,m/2 = 0.11\,m$

   $Circumference = \pi \times d = \pi \times 0.22\,m = 0.6909\,m$

   Wheel Rotational Speed=Linear Speed

   $Circumference = 1.25\,m/s \ / \ 0.6909\,m \approx 1.81\,r/s \approx 108.6\,RPM$

3. **Required Torque**:

   $T = F \times r = 981\,N \times 0.11\,m = 107.91\,Nm$

   Considering efficiency and safety:

   $Efficiency(85\%), Tmotor = Tt/Eff. = 107.91\,Nm/0.85 = 126.95\,Nm$

   (without bearing)

4. **Torque Required for Acceleration**: Assuming α=1m/sˆ2:

   Require Tractive effort (Ft)

   $Ft = mt\ x\ \alpha =\ 300\ kg\ x\ 1\ m/s^2 = 300N$

Force must be provided by frictional force at the wheel

$T = Ft\ x\ r = 300N\ x\ 0.11m = 33Nm$

5. **Effect of Inclination**:

   $\theta = 3^\circ = 0.0524\,rad$

   $Gravity\ Component = 300 \times 9.81 \times sin(0.0524) \approx 154.11N$

   $Tincline = \ Fgravity\ x\ r = 154.11N\ x\ 0.11m = 16.9521Nm$

6. **Torque Due to Friction**: Assuming μ=0.002(coef. friction):16.9521 Nm

$Ffriction = \mu\ x\ R\ =\ 0.002\ x\ 981N = 1.962N$ (R: radial load)
$Torque\ Due\ to\ Friction = Ff \times r = 1.962N \times 0.006m = 0.011772Nm$ (r=bore radius)

Total Torque Required:
$Ttotal = T1 + Tfriction = 33Nm + 0.011772Nm = 33.211772Nm$
Verification:

- The NSK 6201 bearing has a basic dynamic load rating of 7.28 kN, which is sufficient to handle the load of 981 N.
- The calculated torque values and rotational speed are within the bearing's specifications.

4.33.5 Results

The outcomes of the computations and validation procedures are as follows:

4.33.5.1 Shaft Measurements

12 mm is the calculated shaft diameter.
Approximately 8.67 MPa of induced stress is much less than the material's yield strength of 250 MPa.

4.33.5.2 Bearing Details:

NSK 6201 deep groove ball bearing model.
Dimensions:
- 12 mm in diameter within.
- 32 mm in diameter outside.
- Capacity to load: Equipped to manage loads that are above the designated 981 N.
- Ball diameter: 7.68 mm, which meets catalog requirements for nine balls.

4.33.5.3 Observance of Standards

By following ISO 3691-4:2020 guidelines, the design guarantees load-handling systems' dependability and safety. For operating performance, the shaft and bearing dimensions meet the minimal requirements.

4.33.5.4 Total Torque Required:

The dynamic load needed is 28.2Nm

4.34 CONCLUSION AND FUTURE WORKS

The selection and design of bearing wheels and castor wheels require careful consideration of material properties, mechanical performance, and environmental factors to ensure durability and efficiency. In this project, the NSK 6201 bearing was chosen for its high performance and reliability. The NSK 6201 bearing is a single-row deep groove ball bearing known for its ability to handle both radial and axial loads, making it ideal for various industrial applications.

SolidWorks was used for 3D modeling and simulation, providing an accurate representation of the bearing and castor wheel assemblies. The finite element analysis (FEA) conducted within the software helped identify potential failure points and refine the design to enhance structural integrity. This approach significantly improved the efficiency of the design process, reducing the need for physical prototyping and minimizing costs.

The design and manufacturing process adhered to the ISO 3691-4:2020 guidelines, which specify safety requirements and verification for driverless industrial trucks and their systems. These guidelines ensure that the bearing and castor wheels meet the necessary safety standards, including braking systems, speed control, load handling, and stability. Compliance with these standards is crucial for the safe and efficient operation of industrial trucks.

Future work should focus on real-world validation of the proposed design through experimental testing and field applications. Additionally, the integration of smart sensors for real-time load monitoring and predictive maintenance could enhance operational efficiency and extend the service life of the components. Sustainable material alternatives should also be explored to align with environmental regulations and industry trends toward eco-friendly solutions.

In conclusion, this project successfully demonstrated a structured approach to the design and analysis of bearing wheels and castor wheels. By leveraging SolidWorks for design validation and incorporating theoretical and empirical analysis, the study provides a comprehensive framework for developing durable and high-performance wheel systems. Further

advancements in materials and digital manufacturing technologies will continue to improve these components, ensuring reliability in industrial applications.

4.35 ELECTRICAL SYSTEM DESIGN

At the core of an AGV's electrical system are power management, motor control, and communication networks, all of which must be carefully designed to meet performance and safety requirements. The power system typically consists of a rechargeable battery, often lithium-ion or lead-acid, along with a Battery Management System (BMS) to monitor voltage, current, and temperature for optimal energy efficiency and longevity. Motor controllers regulate the movement of the drive and steering motors, ensuring smooth acceleration, precise navigation, and effective braking. Additionally, AGVs rely on a network of embedded controllers, sensors, and communication modules to process data in real time, enabling obstacle detection, localization, and coordination a central control system.

4.36 POWER SUPPLY AND DISTRIBUTION

At the heart of the electrical design lies the power supply and distribution system, which serves as the backbone for all onboard functionalities. The power supply system is responsible for storing, managing, and delivering electrical energy to various components of the AGV, including motors, sensors, control systems, and communication modules. Given that AGVs often operate continuously in demanding environments, the choice of battery technology, capacity, and management strategies plays a critical role in determining overall performance.

To maximize efficiency and safety, these batteries are integrated with advanced Battery Management Systems (BMS), which monitor key parameters like voltage, current, temperature, and state of charge, ensuring optimal usage while preventing conditions that could degrade battery health.

Equally important is the power distribution architecture, which ensures reliable delivery of electricity to all subsystems. This involves designing robust wiring harnesses, fuses, circuit breakers, and connectors that can handle the dynamic load requirements of AGVs during different operational phases. Efficient power distribution not only enhances the vehicle's performance but also minimizes energy losses, contributing to extended operating times and reduced downtime for recharging.

The following part highlights the key components of the AGV's power supply and distribution system, their roles, and their contribution to the system's overall efficiency

4.36.1 Battery System

Battery selection is a key factor in the efficiency and reliability of an AGV system. Among the available options, Absorbent Glass Mat (AGM) and Gel (GEL) batteries, both

types of Sealed Lead-Acid (SLA) or Valve-Regulated Lead-Acid (VRLA) batteries, stand out for their maintenance-free, leak-proof design and low self-discharge rate. While both are deep-cycle batteries capable of discharging up to 80% of their capacity, GEL batteries emphasize durability and stable power delivery, whereas AGM batteries support higher discharge rates and slightly faster charging. However, neither is well-suited for opportunity charging, as frequent partial recharges reduce their lifespan.

For AGVs operating in controlled, single-shift environments, GEL batteries provide a strong balance between safety, longevity, and consistent performance, making them an optimal choice. They typically last 8–16 hours per charge, depending on the AGV type, and require a full recharge when reaching 40–50% depth of discharge (DOD). While their charging time is slower (e.g., a 100Ah battery takes about 3 hours at 0.3C), their deep-cycle capability ensures steady, long-term operation, minimizing the need for frequent replacements.

Considering the AGV's operational demands and the competition's specified battery requirements, AGM batteries are selected for this application. The competition specifies the following parameters: *Battery Type: AGM Battery, Battery Voltage (Nominal): 12VDC, Battery Charging Current: 10A*.

Figure 4.29: AGM battery

4.36.2 Battery Management System (BMS)

The **BMS** is integrated to monitor and manage the battery's health, ensuring safe and reliable operation. It oversees critical parameters such as voltage, current, and temperature, preventing issues like overcharging, over-discharging, and overheating. The BMS optimizes battery performance, extending battery life by up to 30% and supporting over 3500 charge-discharge cycles at 90% Depth of Discharge (DOD). It also ensures safe operations with features like overcurrent protection, overvoltage protection, and temperature monitor-

ing. Additionally, the BMS includes a charging system that complies with the competition specifications, which supports an **AGM Battery** with a nominal voltage of **12VDC** and a charging current of **10A**.

4.36.3 Voltage Regulation and Power Distribution

The AGV's electrical system contains various components operating at different voltage levels, making voltage regulation and distribution critical for stable operation. The majority of sensors operate at 3.3V to 5V, while components like the Raspberry Pi and ESP32 require 5V and others like the Wi-Fi router operates at 9V. To accommodate these diverse requirements, multiple voltage regulators are incorporated to step down the 12V battery supply to the appropriate levels, ensuring consistent performance across all subsystems.

The **LM2596** in Figure 4.30 voltage regulator will be used to step down the 12V battery supply to the required voltage levels for various components. Different versions of the LM2596 are available, including fixed output versions (9V, 5V, and 3.3V) as well as an adjustable version, allowing flexibility to meet the specific voltage requirements of each subsystem. For example, the 5V version will power the Raspberry Pi and ESP32, while the 3.3V version will support sensors operating at lower voltages. In cases where multiple components require the same voltage and draw significant current, multiple LM2596 regulators are placed in parallel to increase the current supply capacity(Table4.11).

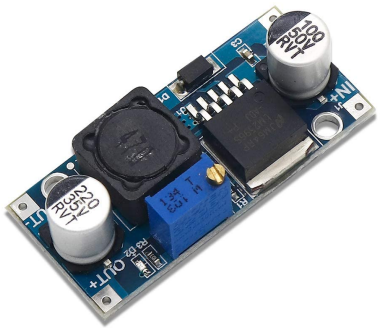


Figure 4.30: LM2596 Voltage Regulator

Furthermore, subsystems, such as the traction unit (composed of two stepper motors) and the lifting system (powered by linear actuators), require voltages higher than the battery's

Parameter	Value
Input Voltage Range	Up to 40V
Output Current	Up to 3A
Switching Frequency	150 kHz
Output Voltage Options	Fixed: 3.3V, 5V, 9V Adjustable: 1.2V--37V
Efficiency	90%
Protection Features	Thermal shutdown, current limiting
Package Type	TO-220, TO-263
Operating Temperature	-40°C to +125°C

Table 4.11: LM2596 Voltage Regulator Specifications

output. To address this, boost converters(fig. 4.31 and fig. 4.32) are used to step up the voltage to the necessary levels.

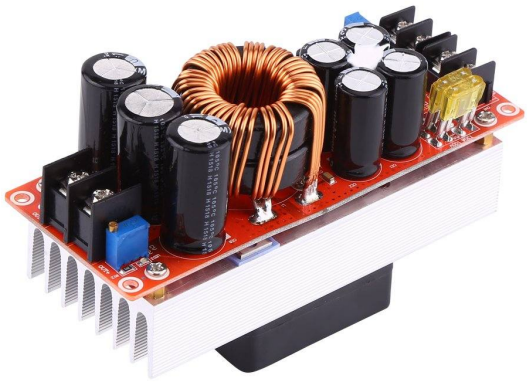


Figure 4.31: 1500W 30A DC-DC Constant Current Boost Converter Step-up Power Supply Module 10-60V to 12-90V

Features:	Flexible DC input voltage range from 10V to 60V; Adjustable output voltage from 12V to 90V for versatile applications; Maximum output current of 20A for reliable power supply; Built with high-power 100V/210A low resistance MOS for efficiency; Reverse input protection with MOS for added safety; Low voltage protection to prevent damage from over-discharge; Thickened heat sink and intelligent cooling fan for optimal heat dissipation.
Specifications:	Power: 1500W; Current: 30A; Input Voltage Range: 10V - 60V; Output Voltage Range: 12V - 90V; Maximum Output Current: 20A.
Package Includes:	1 × Boost Converter Step-up Power Supply Module.

Table 4.12: DC-DC Constant Current Boost Converter Specifications and Features

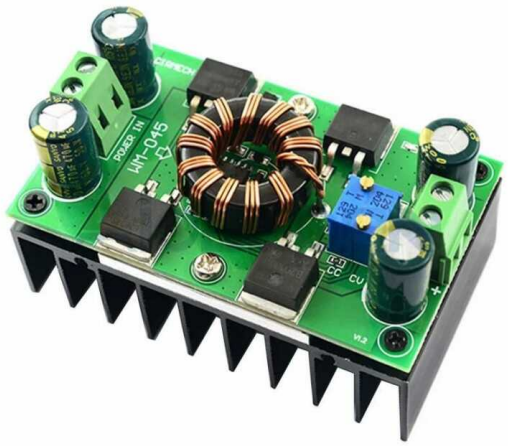


Figure 4.32: WM-045 DC-DC 150W Voltage Step Up and Step Down Regulator Module

The power distribution circuits are designed to efficiently deliver power to all subsystems, including motors, sensors, controllers, and communication modules, while minimizing power losses and ensuring reliable operation. Protection circuits and fuses are also integrated to safeguard sensitive components from voltage spikes, short circuits, and other electrical

Features:	Input Voltage: 5Vdc 30Vdc; Buck-Boost (automatic boost/lower); Output Voltage: 1.25Vdc -- 30Vdc (Adjustable); Output Current: 10A (MAX).
Specifications:	Output Power: 150W; Conversion Efficiency: 90% Max; Ripple and Noise: 200mVp-p; No-Load Current: 6mA typical.
Performance Metrics:	Voltage Regulation: ± 0.5%; Load Regulation: ± 0.5%; Dynamic Response Rate: 300uS.

Table 4.13: Buck-Boost Converter Specifications

faults, enhancing the overall safety and durability of the AGV.

4.36.4 Key Considerations

- *Efficiency*: The system is designed to maximize energy efficiency, ensuring the AGV can operate for extended periods without frequent recharging.
- *Safety*: The inclusion of the BMS and proper voltage regulation ensures safe operation, protecting both the AGV and its components from electrical faults.
- *Compliance*: The system adheres to the **TEKNOFEST Charging Station Technical Specifications**, ensuring compatibility and seamless charging during the competition.

4.37 MOTOR CONTROL SYSTEM

The performance and reliability of automated guided vehicles (AGVs) are deeply rooted in the precision and efficiency of their motor control systems [17]. At the heart of these systems lies the electrical design, which governs the interaction between power supply, control devices, and the physical dynamics of the motors. Direct current (DC) motors [18], Stepper motors [19] and Servo motors [20], widely used in AGVs due to their high torque, excellent speed regulation, and robust performance, require sophisticated electrical architectures to ensure optimal operation.

From an electrical perspective, motor control involves not only the precise regulation of voltage and current but also the implementation of efficient drivers and motor controllers, which are critical for achieving smooth acceleration, stable speed control, and efficient energy utilization. Furthermore, the motor control system must address challenges such as

minimizing power losses, managing heat dissipation, and ensuring reliable operation under varying load conditions.

A motor control system comprises two fundamental components: the motors themselves and the motor drivers or controllers. The motor alone cannot achieve optimal operation without the integration of a sophisticated motor driver or controller. The motor driver acts as the intermediary between the power supply and the motor, regulating voltage and current to ensure smooth and efficient operation. It interprets control signals and translates them into precise commands.

4.37.1 Motors and actuators

- *P Series Nema 23 Closed Loop Stepper Motor with Electromagnetic Brake (2Nm):*

  The traction system of the automated guided vehicle (AGV) is driven by two NEMA 23 P-Series stepper motors shown fig. 4.33, each delivering a holding torque of 2.0 Nm to ensure reliable and precise motion. These motors are selected for their high torque-to-size ratio, making them well-suited for the dynamic demands of AGV operations.

  Both motors are equipped with incremental encoders, which provide real-time feedback on motor speed and position. This closed-loop system enhances the AGV's ability to maintain smooth and synchronized motion, ensuring stability and precision during navigation.

  Additionally, each motor is integrated with an electromagnetic brake, enabling rapid deceleration and enhancing safety by halting motion instantly when required.

Figure 4.33: Nema 23 stepper motor 2 Nm torque

Electrical Specification	
Manufacturer Part Number	23E1KBK20-20
Number of Phases	2
Step Angle	1.8deg
Holding Torque	2Nm (283.28oz.in)
Rated Current/Phase	5.0A
Phase Resistance	0.4ohms
Inductance	1.8mH ± 20% (1KHz)
Insulation Class	B 130°C [266°F]
Physical Specification	
Frame Size	57 x 57mm
Body Length	76.5mm
Shaft Diameter	8mm
Shaft Length	21mm
D-Cut Shaft Length	15mm
Lead Length	270mm
Weight	1.06kg
Encoder Specification	
Output Circuit Type	Differential type
Encoder Type	Incremental
Output Signal Channels	2 channels
Supply Voltage Min	5V
Supply Voltage Max	5V
Output High Voltage	<4V
Output Low Voltage	<1V
Brake Connections	
Red–24V+	Red--24V-
Brake Torque	2.0Nm

Table 4.14: Stepper Motor Specifications (Model: 23E1KBK20-20)

subsubsectionDC 12V Electric Linear Actuator (Maximum Force 6000N):

The lifting mechanism of the automated guided vehicle (AGV) utilizes a high-performance linear actuator to achieve precise vertical motion. The actuator includes an overload protection feature, preventing excessive force application and minimizing mechanical wear.

Figure 4.34: Linear actuator with a maximum stoke of 6000N

Model	JS-TGZ-U3
Material	Metal
Voltage	DC 12V
Maximum Push/Pull Force	Approx. 6000N/6000N
Stroke	450mm
No-Load Speed	Maximum 5mm/s
Rated Load Rate	5mm/s (600kg)
Environment Temperature	-26°C to +65°C
Standard Protection Level	IP54
Built-in Stroke Switch	Yes
Color	Silver

Table 4.15: Specifications of the linear actuator model JS-TGZ-U3

4.37.1.1 Motor drivers

- *Closed Loop Stepper Driver V4.1 CL57T :*

  The **Closed Loop Stepper Driver V4.1 CL57T** has been selected to complement the **Nema 23 Closed Loop Stepper Motor**, ensuring precise and reliable control over the AGV's propulsion and mechanical functions.

  From an electrical perspective, the CL57T driver leverages advanced closed-loop technology to guarantee accurate motor positioning, even in dynamic environments or when encountering external resistance. Fully compatible with software tools like **CLseries** and **Motion Studio**, the driver enables fine-tuning of critical motor parameters, optimizing performance for specific operational requirements.

  Additionally, its extensive diagnostic and monitoring ports provide real-time tracking of key electrical and operational metrics, such as **temperature**, **current**, **torque**,

RPM, and overall motor state during operation. These capabilities not only enhance operational visibility but also streamline troubleshooting and diagnostics, minimizing downtime and ensuring swift resolution of issues.

Figure 4.35: Closed Loop Stepper Driver CL57T V4.1

Key Features	
RS232 debugging interface Do not need a high torque margin Broader operating speed range Reduced motor heating and more efficient Smooth motion and super-low motor noise 5V/24V logic voltage selector, default setting 24V Closed-loop, eliminates loss of synchronization Protections for over-voltage,over-current,and position following error By default, supports an encoder with a resolution of 1000PPR; customizable between 0-5000PPR	
Electrical Specifications	
Output Peak Current	0 8A
Input Voltage	+24 48VDC (Typical 36VDC)
Logic Signal Current	7 16mA (Typical 10mA)
Pulse Input Frequency	0 200kHz
Isolation Resistance	500Mohm
Operating Environment and Other Specifications (Tj = 25°C/77°F)	
Cooling	Natural Cooling or Forced Cooling
Environment	Avoid dust, oil mist, and corrosive gases
Ambient Temperature	0°C - 65°C
Humidity	40%RH - 90%RH
Operating Temperature	0°C - 50°C
Vibration	10-50Hz / 0.15mm
Storage Temperature	-20°C - 65°C
Weight	Approx. 280g (9.9oz)

Table 4.16: Specifications of the Closed-Loop Stepper Driver

- *BTS7960B 40 Amp Motor Driver Board*

  The BTS7960B 40A Motor Driver Board is selected for its capability to control high-power motors, making it ideal for the AGV's linear actuator. Supporting currents up to 40A, it ensures reliable performance in demanding applications.

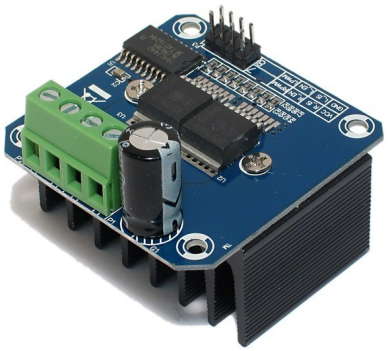


Figure 4.36: DC-MOTOR DRIVER MODULE 24V 43A (2x BTS7960B)

Features	
Double BTS7960 large current (43A) H-bridge driver 5V isolation with MCU, effectively protecting the MCU 5V power indicator on board Voltage indication of motor driver output end Can solder heat sink for improved thermal management Requires only four lines from MCU to driver module (GND, 5V, PWM1, PWM2) Isolation chip 5V power supply (can share with MCU 5V) Supports motor forward and reverse control; two PWM input frequencies up to 25kHz Two heat flow passing through an error signal output On-board 5V supply can be used or shared with MCU 5V	
Specifications	
Model	IBT-2
Input Voltage	6V - 27V
Maximum Current	43A
Input Level	3.3V - 5V
Control Method	PWM or level
Duty Cycle	0% - 100%
Size	4 x 5 x 1.2 cm / 1.6 x 2.0 x 0.5 inch

Table 4.17: Features and Specifications of the IBT-2 Motor Driver Module

4.38 SENSORS

Various sensors, such as LiDAR, cameras, and infrared sensors, are utilized for navigation, obstacle detection, and localization.

The AGV is equipped with a variety of sensors to ensure accurate navigation, obstacle detection, weight measurement, and environmental perception. These sensors work together to enhance the robot's autonomy, safety, and efficiency. The following sensors are integrated into the system:

4.38.1 VL53L0X (Time-of-Flight Distance Sensor)

The VL53L0X time-of-flight (ToF) distance sensors play an important role in enhancing the AGV's perception of its immediate surrounding in an operational perspective. hese sensors are strategically integrated into the AGV design by deploying eight ToF sensors—two at each corner of the robot insuring a comprehensive coverage. The ToF sensors are especially important in scenarios where traditional sensing methods, such as LiDAR, may be limited or rendered ineffective. For instance, when the AGV carries a lifted platform that obstructs the LiDAR's field of view, the ToF sensors take over to provide reliable distance measurements within a range of 0.5m to 12m .

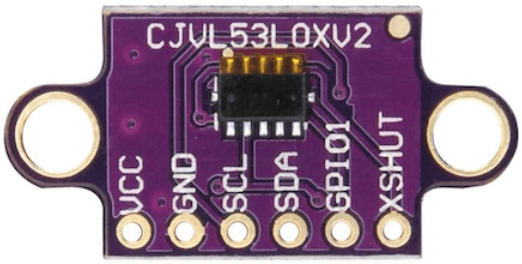


Figure 4.37: VL53L0X time-of-flight (ToF) distance sensor

4.38.2 Weight Sensor - Load Sensor 50Kg

This sensor provides accurate and continuous monitoring of the load on the AGV.

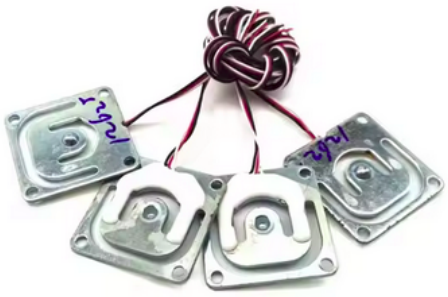


Figure 4.38: Load cell

The HX711 in fig. 4.39 is specifically designed to enhance the weak output signals from the load cellin fig. 4.38, ensuring accurate and reliable weight measurements.

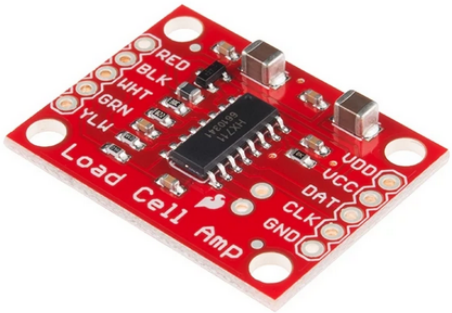


Figure 4.39: HX711 Load cell amplifier

4.38.3 RPLIDAR - 360

The RPLIDAR sensor provides comprehensive environmental mapping, making it indispensable for AGV navigation from an electrical control perspective. With its ability to deliver high-accuracy, real-time 360-degree scanning, the RPLIDAR enables the AGV to perceive its surroundings with exceptional precision.

Figure 4.40: RPLIDAR - 360

4.38.4 Camera HUSKYLENS

The **HUSKYLENS** vision sensor enhances the AGV's performance used for **object detection and line following**. It provides accurate real-time visual feedback, allowing dynamic adjustments to motor speed, direction, and trajectory.

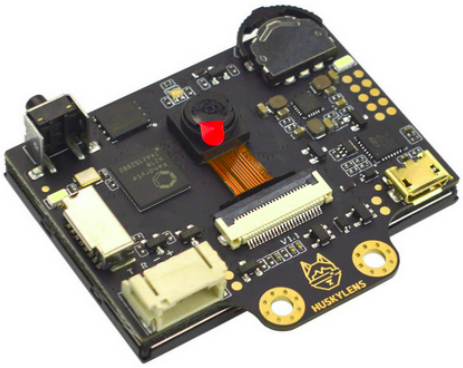


Figure 4.41: Huskylens camera

4.38.5 IMU Sensor

The Inertial Measurement Unit (IMU) is used for achieving precise positioning and movement control in automated guided vehicles (AGVs) The MPU9255 integrates a 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer, providing comprehensive data on angular velocity, linear acceleration, and magnetic field orientation. The MPU9255 communicates with the AGV's control system via I2C or SPI interfaces, ensuring low-latency

data transmission while minimizing power consumption—a key consideration for energy-efficient operation.

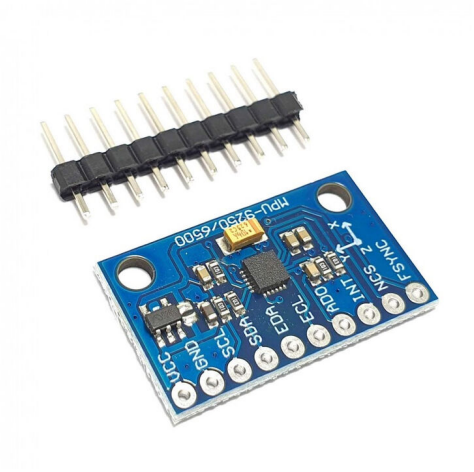


Figure 4.42: Inertia measurement unit 9 axis

4.38.6 Barcode Scanner GM65

Figure 4.43: Qr code scanner

4.38.7 QTRX-HD-11RC

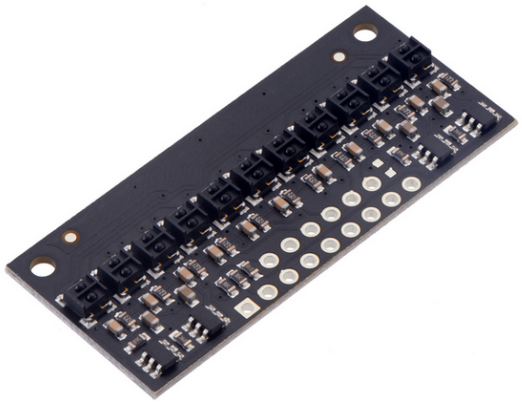


Figure 4.44: QTRX-HD-11RC Reflectance Sensor Array: 11-Channel

4.39 MICROCONTROLLER AND COMMUNICATION

The AGV's microcontroller and communication system form the backbone of its control and data exchange capabilities, ensuring efficient processing, seamless communication, and real-time control of the robot's operations.

In this design, the **Raspberry Pi 4** shown in Figure fig. 4.45 serves as the primary computational unit, acting as the "brain" of the system. Equipped with a Linux operating system, it hosts all necessary **ROS (Robot Operating System)** packages, enabling high-level decision-making, sensor data processing, and trajectory planning.

4.39.1 Raspberry Pi 4

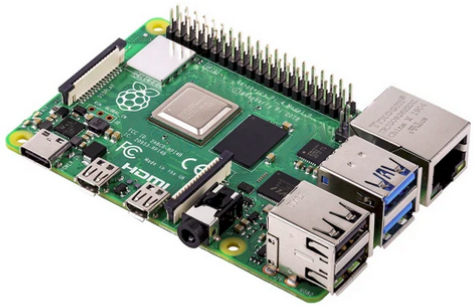


Figure 4.45: Raspberry Pi 4

Complementing the Raspberry Pi, the **ESP32 microcontroller** in fig. 4.46 supports it by managing low-level tasks such as motor control and real-time sensor interfacing. The ESP32

directly interfaces with motor drivers to regulate speed, and direction, ensuring precise actuation of the AGV's propulsion system.

Communication between the Raspberry Pi 4 and the ESP32 is achieved through a **serial communication protocol**, which ensures reliable and efficient data exchange. This division of responsibilities – high-level computation on the Raspberry Pi and low-level control on the ESP32 – optimizes the system's performance and reliability.

Additionally, the sensors are shared between both components, with the ESP32 handling time-sensitive data acquisition and the Raspberry Pi performing higher-level processing and integration into the ROS framework.

4.39.2 ESP32-S3-DevKitC-1

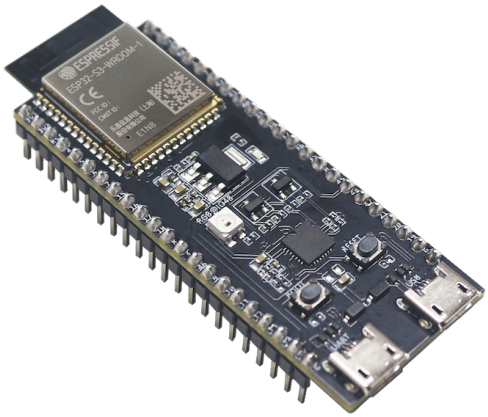


Figure 4.46: ESP32-S3-DevKitC-1

4.39.3 RS232 to Bluetooth Series Adapter

RS232 to Bluetooth Series Adapter

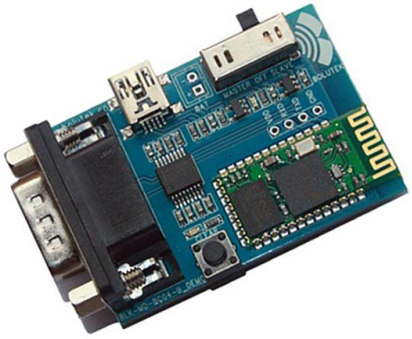


Figure 4.47: RS232 to Bluetooth Series Adapter

4.39.4 TP-Link TL-WR840N

- The **TP-Link TL-WR840N** is utilized as an access point to facilitate communication between the control unit (PC) and the robot's microcontrollers (Raspberry Pi and ESP32 modules).
- By configuring the TL-WR840N as an access point, it creates a wireless network that enables seamless data and command exchange between the PC, Raspberry Pi, and ESP32 modules.
- This setup allows for remote control and monitoring of the AGV's operations, enhancing its usability and adaptability.

All **sensors, microcontrollers, and motor drivers** in the AGV are selected to work in a **cohesive and well-integrated system**, ensuring seamless communication and efficient operation. **Protocols such as I2C and UART** enable reliable data exchange between components, allowing real-time monitoring and control. This structured communication enhances **precision, synchronization, and responsiveness**, optimizing the AGV's navigation, lifting, and traction systems while maintaining operational efficiency and safety.

4.40 USEFULL PART

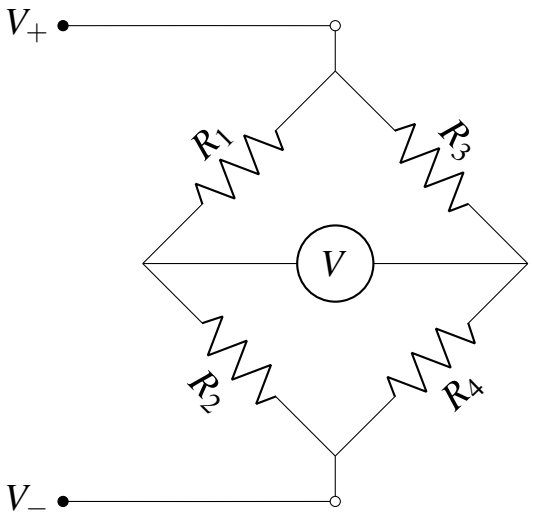


Figure 4.48: Load Cell Circuit with Wheatstone Bridge and Amplifier

The idea behind the load cell is to use the Wheatstone bridge (fig. 4.48). In a Wheatstone bridge, $R_1 = R_2 = R_3 = R_4$, and the output voltage is zero when no force is applied. When weight is applied, it bends the material, which changes the resistivity of the material. This change disrupts the equality of the resistances, causing a difference in voltage across V. By experimenting and calibrating with different weights and tracking the changes in voltage, we can measure the weight.

It is also worth noting that the signal produced depends on the material properties. If the bending factor is linear, the output will be proportional to the applied weight. However, if the bending becomes exponential (which would be a limitation of the material), the relationship between the applied weight and the output signal may no longer be accurate. Additionally, the placement of the load affects the measurement. The voltage difference across V is used to measure the output of the bridge.

In theory, we could use the microcontroller's analog input to read the voltage differences. However, the changes are too small to provide an accurate reading. For this reason, the **HX711** amplifier is used to amplify the signal and convert it into a digital signal.

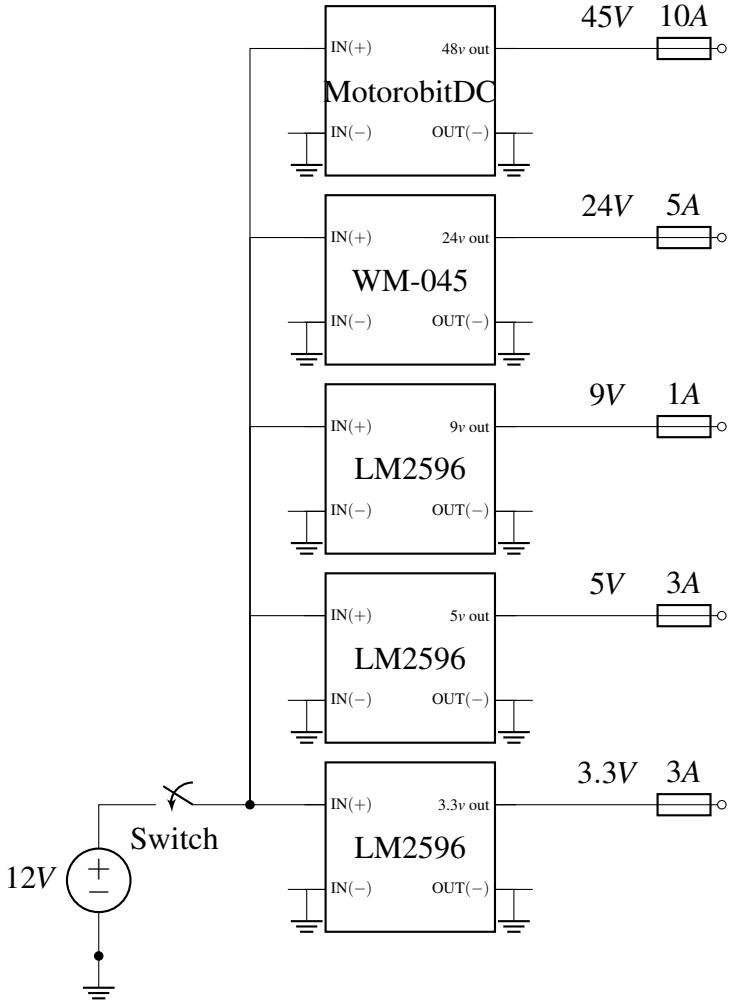


Figure 4.49: Power Distribution Circuit

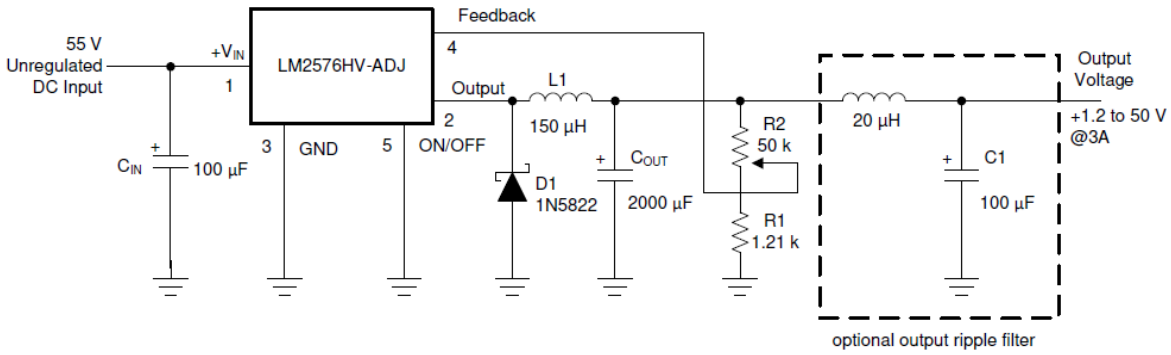


Figure 4.50: 1.2-V to 55-V Adjustable 3-A Power Supply With Low Output Ripple

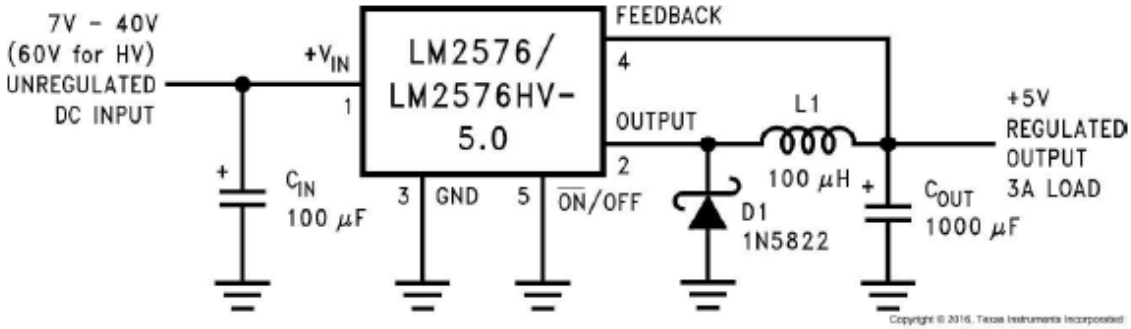


Figure 4.51: Fixed Output Voltage Version Typical Application Diagram

4.41 ROS

The Robot Operating System (ROS) is a set of software libraries and tools that help you build robot applications. From drivers to state-of-the-art algorithms, and with powerful developer tools, [21] To effectively approach ROS programming, it's essential to first understand the foundational concepts of ROS and its package management system. We will explore key ROS components, including the ROS master, nodes, parameter server, messages, and services. Along the way, we will also discuss the necessary steps for installing ROS and initiating work with the ROS master.
In the subsequent sections, we will explore the following topics:

- Why ROS?
- the ROS filesystem level.
- ROS computation graph level.
- ROS community level.

TECHNICAL REQUIREMENTS

To follow this chapter, the only thing you need is a standard computer running Ubuntu 20.04 LTS or a Debian 10 GNU/Linux distribution.

Figure 4.52: Ubuntu 20.04

4.42 WHY ROS?

[1] Robot Operating System (ROS) is a flexible framework that provides various tools and libraries for writing robotic software. It offers several powerful features to help developers in tasks such as message passing, distributed computing, code reusing, and implementing state-of-the-art algorithms for robotic applications. The ROS project was started in 2007 by Morgan Quigley and its development continued at Willow Garage, a robotics research lab for developing hardware and open source software for robots. The goal of ROS was to establish a standard way to program robots while offering off-the-shelf software components that can be easily integrated with custom robotic applications. There are many reasons to choose ROS as a programming framework, and some of them are as follows:

4.42.1 High-end capabilities:

ROS comes with ready-to-use functionalities. For example, the Simultaneous Localization and Mapping (SLAM) and Adaptive Monte Carlo Localization (AMCL) packages in ROS can be used for having autonomous navigation in mobile robots, while the MoveIt package can be used for motion planning for robot manipulators. These capabilities can directly be used in our robot software without any hassle. In several cases, these packages are enough for having core robotics tasks on different platforms. Also, these capabilities are highly configurable; we can fine-tune each one using various parameters.

4.42.2 Tons of tools:

The ROS ecosystem is packed with tons of tools for debugging, visualizing, and having a simulation. The tools, such as rqt_gui, RViz, and Gazebo, are some of the strongest open source tools for debugging, visualization, and simulation. A software framework that has this many tools is very rare.

4.42.3 Support for high-end sensors and actuators:

ROS allows us to use different device drivers and the interface packages of various sensors and actuators in robotics. Such high-end sensors include 3D LIDAR, laser scanners, depth sensors, actuators, and more. We can interface these components with ROS without any hassle.

4.42.4 Inter-platform operability:

The ROS message-passing middleware allows communication between different programs. In ROS, this middleware is known as nodes. These nodes can be programmed in any

language that has ROS client libraries. We can write high-haveance nodes in C++ or C and other nodes in Python or Java.

4.42.5 Modularity:

One of the issues that can occur in most standalone robotic applications is that if any of the threads of the main code crash, the entire robot application can stop. In ROS, the situation is different; we are writing different nodes for each process, and if one node crashes, the system can still work.

4.42.6 Concurrent resource handling:

Handling a hardware resource via more than two processes is always a headache. Imagine that we want to process an image from a camera for face detection and motion detection; we can either write the code as a single entity that can do both, or we can write a single-threaded piece of code for concurrency. If we want to add more than two features to threads, the application behavior will become complex and difficult to debug. But in ROS, we can access devices using ROS topics from the ROS drivers. Any number of ROS nodes can subscribe to the image message from the ROS camera driver, and each node can have different functionalities. This can reduce the complexity in computation and also increase the debugging ability of the entire system.

Most high-end robotics companies are now porting their software to ROS. This trend is also visible in industrial robotics, in which companies are switching from proprietary robotic applications to ROS. Now that we know why it is convenient to study ROS, we can start introducing its core concepts. There are mainly three levels in ROS: the filesystem level, the computation graph level, and the community level. We will briefly have a look at each level.

4.43 THE ROS FILESYSTEM LEVEL

ROS is more than a development framework. We can refer to ROS as a meta-OS, since it offers not only tools and libraries but even OS-like functions, such as hardware abstraction, package management, and a developer toolchain. Like a real operating system, ROS files are organized on the hard disk in a particular manner, as depicted in the following diagram: Here are the explanations for each block in the filesystem:

- **Packages:** The ROS packages are a central element of the ROS software. They contain one or more ROS programs (nodes), libraries, configuration files, and so on, which are organized together as a single unit. Packages are the atomic build and release items in the ROS software.

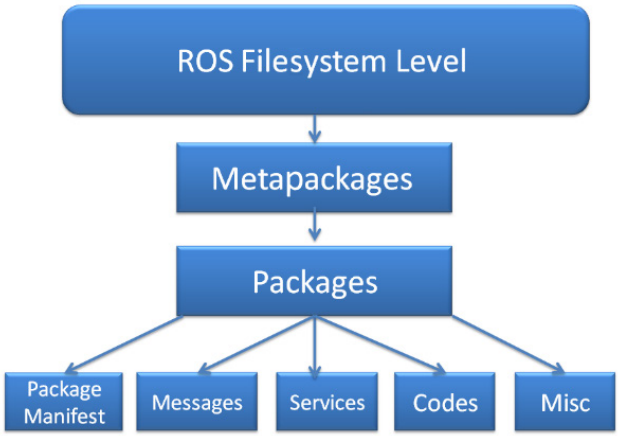


Figure 4.53: ROS filesystem level

- **Package manifest:** The package manifest file is inside a package and contains information about the package, author, license, dependencies, compilation flags, and so on. The package.xml file inside the ROS package is the manifest file of that package.
- **Metapackages:** The term metapackage refers to one or more related packages that can be loosely grouped. In principle, metapackages are virtual packages that don't contain any source code or typical files usually found in packages.
- **Metapackages manifest:** The metapackage manifest is similar to the package manifest, with the difference being that it might include packages inside it as runtime dependencies and declare an export tag.
- **Messages (.msg):** We can define a custom message inside the msg folder inside a package (my_package/msg/MyMessageType.msg). The extension of the message file is .msg.
- **Services (.srv):** The reply and request data types can be defined inside the srv folder inside the package (my_package/srv/MyServiceType.srv).
- **Repositories:** Most of the ROS packages are maintained using a Version Control System (VCS) such as Git, Subversion (SVN), or Mercurial (hg). A set of files placed on a VCS represents a repository.

The following screenshot gives you an idea of the files and folders of a package that we are going to create in the upcoming sections:

4.44 ROS PACKAGES

The typical structure of a ROS package is shown here:

```
ros_pkg
├── action
│   └── demo.action
├── CMakeLists.txt
├── include
│   └── ros_pkg
│       └── demo.h
├── msg
│   └── message.msg
├── src
│   └── demo.cpp
└── srv
    └── service.srv
```

Figure 4.54: List of files inside the package

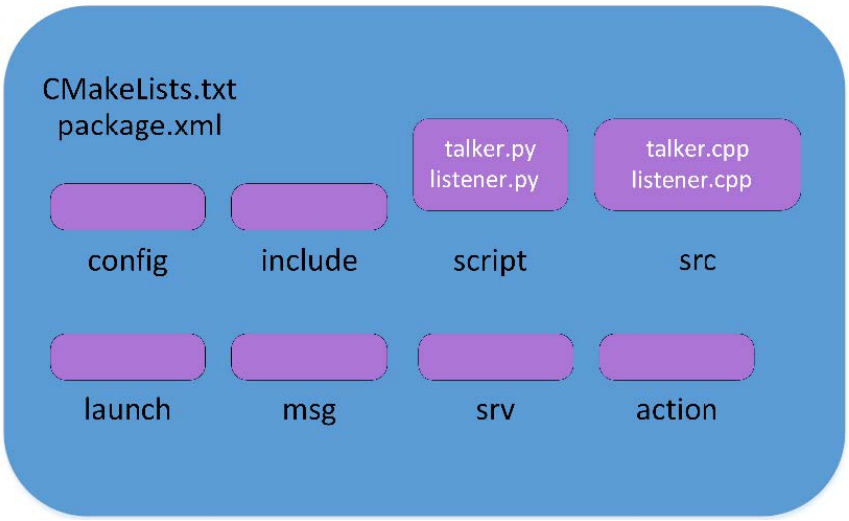


Figure 4.55: Structure of a typical C++ ROS package

- **config:** All configuration files that are used in this ROS package are kept in this folder. This folder is created by the user and it is a common practice to name the folder config as this is where we keep the configuration files.
- **include/package_name:** This folder consists of headers and libraries that we need to use inside the package. script: This folder contains executable Python scripts. In the block diagram, we can see two example scripts.
- **src:** This folder stores the C++ source codes.
- **launch:** This folder contains the launch files that are used to launch one or more ROS nodes.
- **msg:** This folder contains custom message definitions.
- **srv:** This folder contains the services definitions.

- **action:** This folder contains the action files. We will learn more about these kinds of files in the next chapter.
- **package.xml:** This is the package manifest file of this package.
- **CMakeLists.txt:** This file contains the directives to compile the package.

We need to know some commands for creating, modifying, and working with ROS packages. Here are some of the commands we can use to work with ROS packages:

- **catkin_create_pkg:** This command is used to create a new package.
- **rospack:** This command is used to get information about the package in the filesystem.
- **catkin_make:** This command is used to build the packages in the workspace.
- **rosdep:** This command will install the system dependencies required for this package.

To work with packages, ROS provides a bash-like command called rosbash (http://wiki.ros.org/rosbash), which can be used to navigate and manipulate the ROS package. Here are some of the rosbash commands:

- **roscd:** This command is used to change the current directory using a package name, stack name, or a special location. If we give the argument a package name, it will switch to that package folder.
- **roscp:** This command is used to copy a file from a package.
- **rosed:** This command is used to edit a file using the vim editor.
- **rosrun:** This command is used to run an executable inside a package.

The definition of package.xml in a typical package is shown in the following code:

```
<?xml version="1.0"?>
<package>
<name>hello world</name>
<vrsion>0.0.1</version>
<description>The hello world package</description>
<maintainer email="example@gmail.com">example</maintainer>
<buildtool_depend>catkin</buildtool_depend>
<buildtool_depend>roscpp</build_depend>
<build_depend>rospy</build_depend>
<build_depend>std_msgs</build_depend>
```

```
11          <run_depend>roscpp</run_depend>
12          <run_depend>rospy</run_depend>
13          <run_depend>std_msgs</run_depend>
14          <export>
15          </export> </package>
```

The package.xml file also contains information about the compilation.
The <build_ depend></build_depend> tag includes the packages that are necessary for building the source code of the package. The packages inside the <run_depend></run_ depend> tags are necessary for running the package node at runtime.

4.45 ROS METAPACKAGES

Metapackages are specialized packages that require only one file; that is, a package.xml file. Metapackages simply group a set of multiple packages as a single logical package. In the package.xml file, the metapackage contains an export tag, as shown here:

```
1   <export>
2   <metapackage/>
3   </export>
```

Also, in metapackages, there are no <buildtool_depend> dependencies for catkin; there are only <run_depend> dependencies, which are the packages that are grouped inside the metapackage.

The ROS navigation stack is a good example of somewhere that contains metapackages. If ROS and its navigation package are installed, we can try using the following command by switching to the navigation metapackage folder:

```
1   roscd navigation
```

Open package.xml using your text editor (gedit, in the following case):

```
1   gedit package.xml
```

This is a lengthy file; here is a stripped-down version of it: This file contains several

```
<?xml version="1.0"?>
<package>
<name>navigation</name>
<version>1. 14. 0</version>
<description>
A 2D navigation stack that takes in information from
 ↪ odometry, sensor
streams, and a goal pose and outputs safe velocity commands
 ↪ that are sent
to a mobile base.
</description>
<url>http : //wiki.ros.org/navigation</url>
<buildtool_depend>catkin</buildtool_depend>
<run_depend>amcl</run_depend>
...
<export>
<metapackage/>
</export>
</package>
```

Figure 4.56: Structure of the package.xml metapackage

pieces of information about the package, such as a brief description, its dependencies, and the package version.

4.46 ROS MESSAGES

ROS nodes can write or read data of various types. These different types of data are described using a simplified message description language, also called ROS messages. These data type descriptions can be used to generate source code for the appropriate message type in different target languages. Even though the ROS framework provides a large set of robotic-specific messages that have already been implemented, developers can define their own message type inside their nodes. The message definition can consist of two types: `fields` and `constants`. The field is split into field types and field names. The field type is the data type of the transmitting message, while the field name is the name of it.

Here is an example of message definitions:

```
int32 number
```

```
string name
```

```
float32 speed
```

Here, the first part is the field type and the second is the field name. The field type is the data type, and the field name can be used to access the value from the message. For example, we can use msg.number to access the value of the number from the message.

Here is a table showing some of the built-in field types that we can use in our message:

Built-in Field Types for Message Definition

Primitive type	Serialization	C++	Python
bool (1)	Unsigned 8-bit int	uint8_t (2)	bool
int8	Signed 8-bit int	int8_t	int
uint8	Unsigned 8-bit int	uint8_t	int (3)
int16	Signed 16-bit int	int16_t	int
uint16	Unsigned 16-bit int	uint16_t	int
int32	Signed 32-bit int	int32_t	int
uint32	Unsigned 32-bit int	uint32_t	int
int64	Signed 64-bit int	int64_t	long
uint64	Unsigned 64-bit int	uint64_t	long
float32	32-bit IEEE float	float	float
float64	64-bit IEEE float	double	float
string	ascii string (4)	std::string	string
time	secs/nsecs unsigned 32-bit ints	ros::Time	rospy.Time
duration	secs/nsecs signed 32-bit ints	ros::Duration	rospy.Duration

Table 4.18: Primitive types and their serialization in C++ and Python.

ROS provides a set of complex and more structured message files that are designed to cover a specific application's necessity, such as exchanging common geometrical (geometry_msgs) or sensor (sensor_msgs) information. These messages are composed of different primitive types. A special type of ROS message is called a message header. This header can carry information, such as time, frame of reference or frame_id, and sequence number. Using the header, we will get numbered messages and more clarity about which component is sending the current message. The header information is mainly used to send data such as robot joint transforms. Here is the definition of the header:

```
1   uint32 seq
```

```
1   time stamp
```

```
1    string frame_id
```

The rosmsg command tool can be used to inspect the message header and the field types. The following command helps view the message header of a particular message:

```
1    rosmsg show std_msgs/Header
```

This will give you an output like the preceding example's message header. We will look at the `rosmsg` command and how to work with custom message definitions later in this chapter.

4.47 THE ROS SERVICES

ROS services are a type of request/response communication between ROS nodes. One node will send a request and wait until it gets a response from the other. Similar to the message definitions when using the .msg file, we must define the service definition in another file called .srv, which must be kept inside the `srv` subdirectory of the package.

An example service description format is as follows:

```
#Request message type
string req
---
#Response message type
string res
```

The first section is the message type of the request, which is separated by —, while the next section contains the message type of the response. In these examples, both Request and Response are strings.

4.48 THE ROS COMPUTATION GRAPH LEVEL

Computation in ROS is done using a network of ROS nodes. This computation network is called the computation graph. The main concepts in the computation graph are ROS **nodes**, **master**, **parameter server**, **messages**, **topics**, **services**, and **bags**. Each concept in the graph is contributed to this graph in different ways.

The ROS communication-related packages, including core client libraries, such as roscpp and rospython, and the implementation of concepts, such as topics, nodes, parameters, and services, are included in a stack called ros_comm (http://wiki.ros.org/ros_comm).
This stack also consists of tools such as rostopic, rosparam, rosservice, and rosnode to introspect the preceding concepts.
The ros_comm stack contains the ROS communication middleware packages, and these packages are collectively called the **ROS graph layer**.

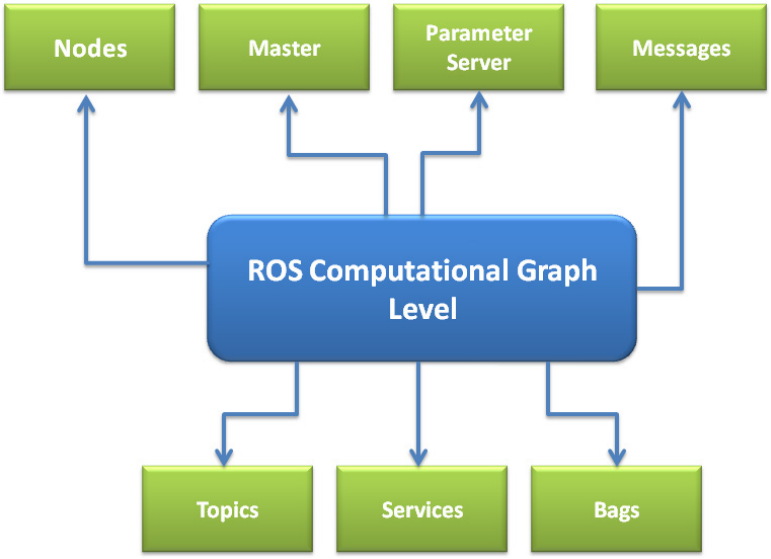


Figure 4.57: Structure of the ROS graph layer

4.48.1 Nodes

Nodes are the processes that have computation. Each ROS node is written using ROS client libraries. Using client library APIs, we can implement different ROS functionalities, such as the communication methods between nodes, which is particularly useful when the different nodes of our robot must exchange information between them. One of the aims of ROS nodes is to build simple processes rather than a large process with all the desired functionalities. Being simple structures, ROS nodes are easy to debug.

4.48.2 Master

The ROS master provides the name registration and lookup processes for the rest of the nodes. Nodes will not be able to find each other, exchange messages, or invoke services without a ROS master. In a distributed system, we should run the master on one computer; then, the other remote nodes can find each other by communicating with this master.

4.48.3 Parameter server

The parameter server allows you to store data in a central location. All the nodes can access and modify these values. The parameter server is part of the ROS master.

4.48.4 Topics

Each message in ROS is transported using named buses called topics. When a node sends a message through a topic, then we can say the node is publishing a topic. When a node receives a message through a topic, then we can say that the node is subscribing to a

topic. The publishing node and subscribing node are not aware of each other's existence. We can even subscribe to a topic that might not have any publisher. In short, the production of information and its consumption are decoupled. Each topic has a unique name, and any node can access this topic and send data through it so long as they have the right message type.

4.48.5 Logging

ROS provides a logging system for storing data, such as sensor data, which can be difficult to collect but is necessary for developing and testing robot algorithms. These are known as bagfiles. Bagfiles are very useful features when we're working with complex robot mechanisms.

The following graph shows how the nodes communicate with each other using topics:

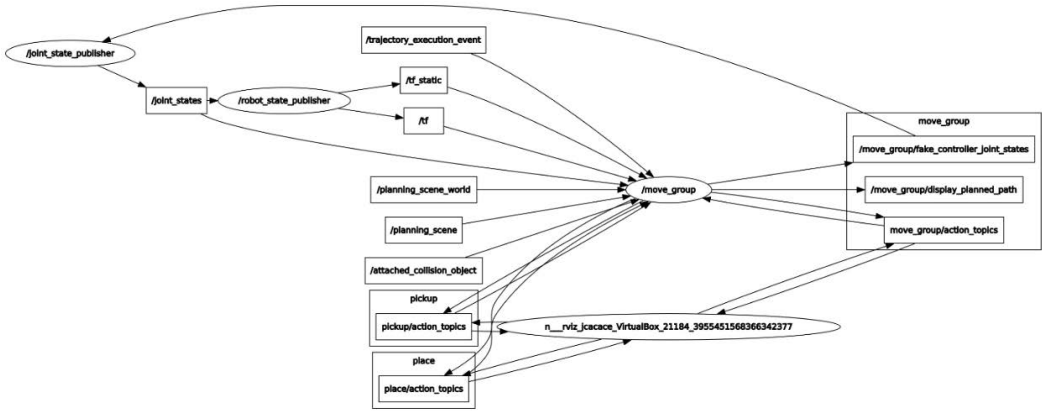


Figure 4.58: Graph of communication between nodes using topics

The topics are represented by rectangles, while the nodes are represented by ellipses. The messages and parameters are not included in this graph. These kinds of graphs can be generated using a tool called **rqt_graph** (http://wiki.ros.org/rqt_graph).

4.49 ROS NODES

ROS nodes have computations using ROS client libraries such as `roscpp` and `rospy`. A robot might contain many nodes; for example, one node processes camera images, one node handles serial data from the robot, one node can be used to compute odometry, and so on.

Using nodes can make the system fault-tolerant. Even if a node crashes, an entire robot system can still work. Nodes also reduce complexity and increase debug-ability compared to monolithic code because each node is handling only a single function.

All running nodes should have a name assigned to help us identify them. For example, /camera_node could be the name of a node that is broadcasting camera images.

There is a rosbash tool for introspecting ROS nodes. The `rosnode` command can be used to gather information about an ROS node. Here are the usages of **rosnode**:

- `rosnode info [node_name]`: This will print out information about the node.
- `rosnode kill [node_name]`: This will kill a running node.
- `rosnode list`: This will list the running nodes.
- `rosnode machine [machine_name]`: This will list the nodes that are running on a particular machine or a list of machines.
- `rosnode ping`: This will check the connectivity of a node.
- `rosnode cleanup`: This will purge the registration of unreachable nodes.

some example nodes that use the roscpp client and discuss how ROS nodes that use functionalities such ROS topics, service, messages, and actionlib work.

4.50 ROS MESSAGES

messages are simple data structures that contain field types. ROS messages support standard primitive data types and arrays of primitive types.

We can access a message definition using the following method. For example, to access std_msgs/msg/String.msg when we are using the roscpp client, we must include std_msgs/String.h for the string message definition.

In addition to the message data type, ROS uses an MD5 checksum comparison to confirm whether the publisher and subscriber exchange the same message data types.

ROS has a built-in tool called `rosmmsg` for gathering information about ROS messages. Here are some parameters that are used along with `rosmmsg`:

- `rosmmsg show [message_type]`: This shows the message's description.
- `rosmmsg list`: This lists all messages.
- `rosmmsg md5 [message_type]`: This displays md5sum of a message.
- `rosmmsg package [package_name]`: This lists messages in a package.
- `rosmmsg packages [package_1] [package_2]`: This lists all packages that contain messages.

4.51 ROS TOPICS

Using topics, the ROS communication is unidirectional. Differently, if we want a direct request/response communication, we need to implement ROS services. The ROS nodes communicate with topics using a TCP/IP-based transport known as **TCPROS**. This method is the default transport method used in ROS. Another type of communication is **UDPROS**, which has low latency and loose transport and is only suited for teleoperations. The ROS topic tool can be used to gather information about ROS topics. Here is the syntax of this command:

- **rostopic bw /topic**: This command will display the bandwidth being used by the given topic.
- **rostopic echo /topic**: This command will print the content of the given topic in a human-readable format. Users can use the -p option to print data in CSV format.
- **rostopic find /message_type**: This command will find topics using the given message type.
- **rostopic hz /topic**: This command will display the publishing rate of the given topic.
- **rostopic info /topic**: This command will print information about an active topic.
- **rostopic list**: This command will list all the active topics in the ROS system.
- **rostopic pub /topic message_type args**: This command can be used to publish a value to a topic with a message type.
- **rostopic type /topic**: This will display the message type of the given topic.

4.52 ROS SERVICES

In ROS services, one node acts as a ROS server in which the service client can request the service from the server. If the server completes the service routine, it will send the results to the service client. For example, consider a node that can provide the sum of two numbers that has been received as input while implementing this functionality through an ROS service. The other nodes of our system might request the sum of two numbers via this service. In this situation, topics are used to stream continuous data flows.

The ROS service definition can be accessed by the following method. For example, `my_package/srv/Image.srv` can be accessed by `my_package/Image`.

In ROS services, there is an MD5 checksum that checks in the nodes. If the sum is equal, then only the server responds to the client.

There are two ROS tools for gathering information about the ROS service. The first tool is **rossrv**, which is similar to **rosmmsg**, and is used to get information about service types. The next command is **rosservice**, which is used to list and query the running ROS services.

Let's explain how to use the rosservice tool to gather information about the running services:

- **rosservice call /service args**: This tool will call the service using the given arguments.
- **rosservice find service_type**: This command will find the services of the given service type.
- **rosservice info /services**: This will print information about the given service.
- **rosservice list**: This command will list the active services running on the system.
- **rosservice type /service**: This command will print the service type of a given service.
- **rosservice uri /service**: This tool will print the service's ROSRPC URI.

4.53 ROS BAGFILES

The **rosbag** command is used to work with rosbag files. A bag file in ROS is used for storing ROS message data that's streamed by topics. The .bag extension is used to represent a bag file.

Bag files are created using the **rosbag record** command, which will subscribe to one or more topics and store the message's data in a file as it's received. This file can play the same topics that they are recorded from, and it can remap the existing topics too.

Here are the commands for recording and playing back a bag file:

- **rosbag record [topic_1] [topic_2] -o [bag_name]**: This command will record the given topics into the bag file provided in the command. We can also record all topics using the -a argument.
- **rosbag play [bag_name]**: This will play back the existing bag file.

The full, detailed list of commands can be found by using the following command in a Terminal:

```
rosbag play -h
```

There is a GUI tool that we can use to handle how bag files are recorded and played back called `rqt_bag`. To learn more about `rqt_bag`, go to `https://wiki.ros.org/rqt_bag`.

4.54 THE ROS MASTER

The ROS master is much like a DNS server, in that it associates unique names and IDs to the ROS elements that are active in our system. When any node starts in the ROS system, it will start looking for the ROS master and register the name of the node in it. So, the ROS master has the details of all the nodes currently running on the ROS system. When any of the node's details change, it will generate a callback and update the node with the latest details. These node details are useful for connecting each node.

When a node starts publishing to a topic, the node will give the details of the topic, such as its name and data type, to the ROS master. The ROS master will check whether any other nodes are subscribed to the same topic. If any nodes are subscribed to the same topic, the ROS master will share the node details of the publisher to the subscriber node. After getting the node details, these two nodes will be connected. After connecting to the two nodes, the ROS master has no role in controlling them. We might be able to stop either the publisher node or the subscriber node according to our requirements. If we stop any nodes, they will check in with the ROS master once again. This same method is used for the ROS services.

As we've already stated, the nodes are written using ROS client libraries, such as `roscpp` and `rospy`. These clients interact with the ROS master using **XML Remote Procedure Call (XMLRPC)**-based APIs, which act as the backend of the ROS system APIs.

The `ROS_MASTER_URI` environment variable contains the IP and port of the ROS master. Using this variable, ROS nodes can locate the ROS master. If this variable is wrong, communication between the nodes will not take place. When we use ROS in a single system, we can use the IP of a localhost or the name `localhost` itself. But in a distributed network, in which computation is done on different physical computers, we should define `ROS_MASTER_URI` properly; only then will the remote nodes be able to find each other and communicate with each other. We only need one master in a distributed system, and it should run on a computer in which all the other computers can ping it properly to ensure that remote ROS nodes can access the master.

The following diagram(fig. 4.59) shows how the ROS master interacts with publishing and subscribing nodes, with the publisher node publishing a string type topic with a `Hello World` message and the subscriber node subscribing to this topic: When the publisher node starts advertising the `Hello World` message in a particular topic, the ROS master gets the details of the topic and the node. It will check whether any node is subscribing to the same topic. If no nodes are subscribing to the same topic at that time, both nodes will remain unconnected. If the publisher and subscriber nodes run at the same time, the ROS master will exchange the details of the publisher to the subscriber, and they will connect and exchange data through ROS topics.

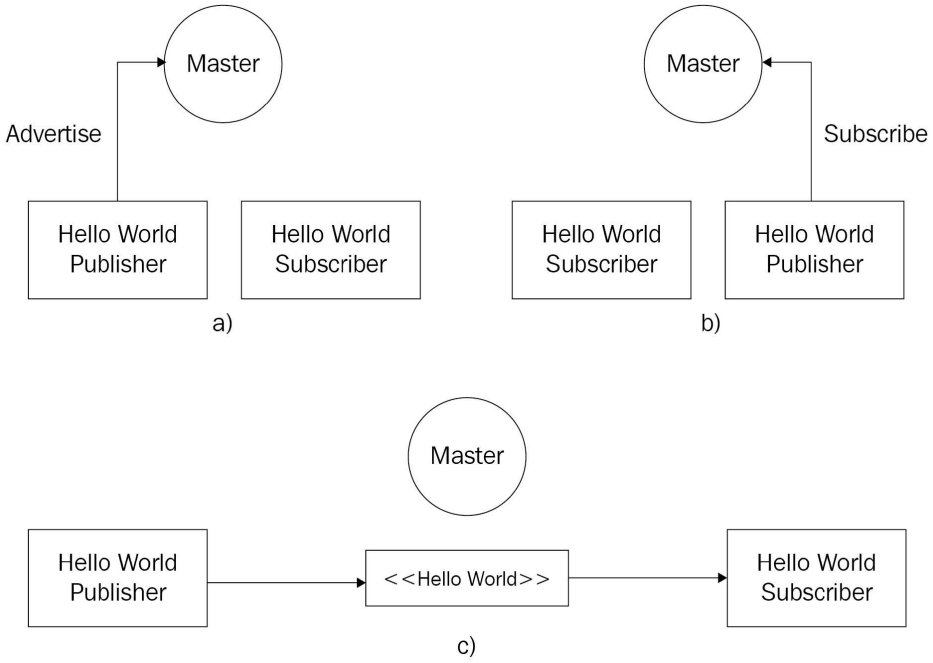


Figure 4.59: Communication between the ROS master and Hello World publisher and subscriber

4.55 ROS PARAMETER

When programming a robot, we might have to define robot parameters to tune our control algorithm, such as the robot controller gains P, I, and D of a standard proportional integral derivative controller. When the number of parameters increases, we might need to store them as files. In some situations, these parameters must be shared between two or more programs. In this case, ROS provides a parameter server, which is a shared server in which all the ROS nodes can access parameters from this server. A node can read, write, modify, and delete parameter values from the parameter server.

We can store these parameters in a file and load them into the server. The server can store a wide variety of data types and even dictionaries. The programmer can also set the scope of the parameter; that is, whether it can be accessed by only this node or all the nodes.

The parameter server supports the following XMLRPC data types:

- 32-bit integers
- Booleans
- Strings
- Doubles

- ISO8601 dates
- Lists
- Base64-encoded binary data

We can also store dictionaries on the parameter server. If the number of parameters is high, we can use a YAML file to save them. Here is an example of the YAML file parameter definitions:

```
/camera/name : 'nikon' #string_type
/camera/fps : 30 #integer
/camera/exposure : 1.2 #float
/camera/active : true #boolean
```

The `rosparam` tool is used to get and set the ROS parameter from the command line. The following are the commands for working with ROS parameters:

- `rosparam set [parameter_name] [value]`: This command will set a value in the given parameter.
- `rosparam get [parameter_name]`: This command will retrieve a value from the given parameter.
- `rosparam load [YAML_file]`: The ROS parameters can be saved into a YAML file. It can load them into the parameter server using this command.
- `rosparam dump [YAML_file]`: This command will dump the existing ROS parameters into a YAML file.
- `rosparam delete [parameter_name]`: This command will delete the given parameter.
- `rosparam list`: This command will list existing parameter names.

These parameters can be changed dynamically when you're executing a node that uses these parameters by using the **dynamic_reconfigure** package (`http://wiki.ros.org/dynamic_reconfigure`).

4.56 ROS DISTRIBUTIONS

ROS updates are released with new ROS distributions. A new distribution of ROS is composed of an updated version of its core software and a set of new/updated ROS packages. ROS follows the same release cycle as the Ubuntu Linux distribution: a new version of ROS is released every 6 months. Typically, for each Ubuntu LTS version, an **LTS** version of ROS is released. **Long Term Support (LTS)** and means that the released software will be maintained for a long time (5 years in the case of ROS and Ubuntu).

Built-in Field Types for Message Definition

Distro	Release date	Poster	Turtle	EOL date
ROS Noetic Ninjemys (Recommended)	May 23rd, 2020			May, 2025 (Focal EOL)
ROS Melodic Morenia	May 23rd, 2018			June 27, 2023 (Bionic EOL)
ROS Lunar Loggerhead	May 23rd, 2017			May, 2019
ROS Kinetic Kame	May 23rd, 2016			April, 2021 (Xenial EOL)

Table 4.20: ROS Distributions Table

4.57 RUNNING THE ROS MASTER AND THE ROS PARAMETER SERVER

Before running any ROS nodes, we should start the ROS master and the ROS parameter server. We can start the ROS master and the ROS parameter server by using a single command called **roscore**, which will start the following programs:

- `ROS master`
- `ROS parameter server`
- `rosout logging nodes`

The rosout node will collect log messages from other ROS nodes and store them in a log file, and will also re-broadcast the collected log message to another topic. The /rosout topic is published by ROS nodes using ROS client libraries such as roscpp and rospy, and this topic is subscribed by the rosout node, which rebroadcasts the message in another topic called /rosout_agg. This topic contains an aggregate stream of log messages. The roscore command should be run as a prerequisite to running any ROS nodes. The following screenshot shows the messages that are printed when we run the roscore command in a Terminal.

Use the following command to run `roscore` on a Linux Terminal:

```
1    roscore
```

After running this command, we will see the following text in the Linux Terminal:

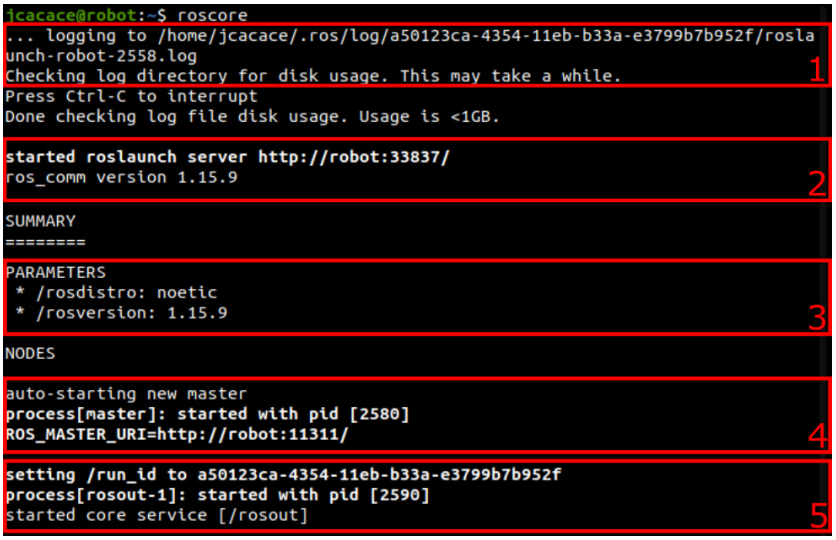


Figure 4.60: Terminal messages while running the roscore command

- In section 1, we can see that a log file is created inside the ~/.ros/log folder for collecting logs from ROS nodes. This file can be used for debugging purposes.
- In section 2, the command starts a ROS launch file called `roscore.xml`. When a launch file starts, it automatically starts `rosmaster` and the ROS parameter server. The `roslaunch` command is a Python script, which can start `rosmaster` and the ROS parameter server whenever it tries to execute a launch file. This section shows the address of the ROS parameter server within the port.
- In section 3, we can see parameters such as `rosdistro` and `rosversion` being displayed in the Terminal. These parameters are displayed when it executes `roscore.xml`. We will look at `roscore.xml` in more detail in the next section.
- In section 4, we can see that the `rosmaster` node is being started with `ROS_MASTER_URI`, which we defined earlier as an environment variable.
- In section 5, we can see that the `rosout` node is being started, which will start subscribing to the `/rosout` topic and rebroadcasting it to `/rosout_agg`.

The following is the content of `roscore.xml`:

```
<launch>
    <group ns="/">
        <param name="rosversion" command="rosversion roslaunch" />
        <param name="rosdistro" command="rosversion -d" />
        <node pkg="rosout" type="rosout" name="rosout"
         ↪  respawn="true"/>
    </group>
</launch>
```

When the `roscore` command is executed, initially, the command checks the command-line argument for a new port number for `rosmaster`. If it gets the port number, it will start listening to the new port number; otherwise, it will use the default port. This port number and the `roscore.xml` launch file will be passed to the `roslaunch` system. The `roslaunch` system is implemented in a Python module; it will parse the port number and launch the `roscore.xml` file.

In the `roscore.xml` file, we can see that the ROS parameters and nodes are encapsulated in a group XML tag with a `/` namespace. The group XML tag indicates that all the nodes inside this tag have the same settings.

The `rosversion` and `rosdistro` parameters store the output of the `rosversion roslaunch` and `rosversion -d` commands using the `command` tag, which is a part of the ROS param tag. The `command` tag will execute the command mentioned in it and store the output of the command in these two parameters.

`rosmaster` and the parameter server are executed inside `roslaunch` modules via the `ROS_MASTER_URI` address. This happens inside the `roslaunch` Python module.
`ROS_MASTER_URI` is a combination of the IP address and port that `rosmaster` is going to listen to. The port number can be changed according to the given port number in the `roscore` command.

4.57.1 Checking the roscore command's output

Let's check out the ROS topics and ROS parameters that are created after running roscore. The following command will list the active topics in the Terminal:

```
rostopic list
```

The list of topics is as follows, as per our discussion of the rosout node's subscribe /rosout topic. This contains all the log messages from the ROS nodes. /rosout_agg will rebroadcast the log messages:

```
/rosout
/rosout_agg
```

The following command lists the parameters that are available when running roscore. The following command is used to list the active ROS parameter:

```
rosparam list
```

These parameters are mentioned here; they provide the ROS distribution name, version, the address of the roslaunch server, and run_id, where run_id is a unique ID associated with a particular run of roscore:

```
/rosdistro
/roslaunch/uris/host_robot_virtualbox_51189
/rosversion
/run_id
```

The list of ROS services that's generated when running roscore can be checked by using the following command:

```
rosservice list
```

The list of services that are running is as follows:

```
/rosout/get_loggers
/rosout/set_logger_level
```

These ROS services are generated for each ROS node, and they are used to set the logging levels.

4.58 SIMULATION ENVIRONMENT

4.59 INTRODUCTION TO THE SIMULATION ENVIRONMENT

In developing a control strategy for mobile robots such as Automated Guided Vehicles (AGVs), simulation plays a crucial role in testing software components, robot behavior, and control algorithms across various environments. Before physically building the robotic system, running a simulation provides a risk-free and cost-effective approach to refining its design and functionality. By simulating the robot's behavior in a controlled virtual environment, different algorithms can be tested and optimized to ensure efficient navigation, obstacle avoidance, and perception without the risk of hardware damage.

The simulation environment was built using the **Robot Operating System (ROS)** and the **Gazebo** simulator, with the `gazebo_ros` package. `RViz` was utilized for real-time visualization of sensor data and robot trajectories, while `OpenCV` handled computer vision tasks such as *line following* and *QR code detection*. The following sections provide detailed insights into their implementation and role in the project.

4.60 TOOLS AND FRAMEWORK

4.60.1 Gazebo

Gazebo was initially developed in 2002 to facilitate the simulation of ground robot applications in both indoor and outdoor environments [22]. Over the years, it has evolved into a mature open-source project widely adopted by the global robotics community for various applications. Gazebo follows a modular architecture, incorporating four key components essential for robot simulation:

- **Physics Engine Support** – Gazebo integrates multiple physics engines to handle collision detection, contact dynamics, and reaction forces between rigid bodies.
- **Sensor Simulation** – It provides a comprehensive library of commonly used robotic sensors, including cameras, LiDAR, sonar, GPS, and IMUs, along with configurable noise models for realistic sensor emulation.
- **Multiple Interfaces** – The simulator supports various interfaces for programmatic interaction, including C++ for developing plugins.
- **Graphical User Interface (GUI)** – Gazebo features an interactive 3D environment that enables users to visualize and manipulate the simulated world in real-time.

Figure 4.61: Gazebo Simulator

Gazebo is a robust simulation tool integrated with the Robot Operating System (ROS), designed to simulate robotic and sensor applications in both indoor and outdoor 3D environments. It follows a Client-Server architecture coupled with a topic-based Publish/Subscribe model for inter-process communication, enabling efficient data exchange between the various components of the system.

For dynamic simulations, Gazebo leverages several high-performance physics engines, including the Open Dynamics Engine (ODE) [23], Bullet [24], Simbody [25], and the Dynamic Animation and Robotics Toolkit (DART) [26]. These engines handle rigid-body physics simulations, providing highly accurate interactions between objects. Additionally, Gazebo employs the Object-Oriented Graphics Rendering Engine (OGRE) [27] for 3D graphics rendering, generating realistic visual environments that enhance the simulation experience.

In this architecture, the Gazebo Client sends control data, such as the coordinates of simulated objects, to the Server, which then manages real-time control of the virtual robot. Gazebo also supports distributed simulation, allowing the Client and Server to run on separate machines, which can be beneficial for scaling and performance.

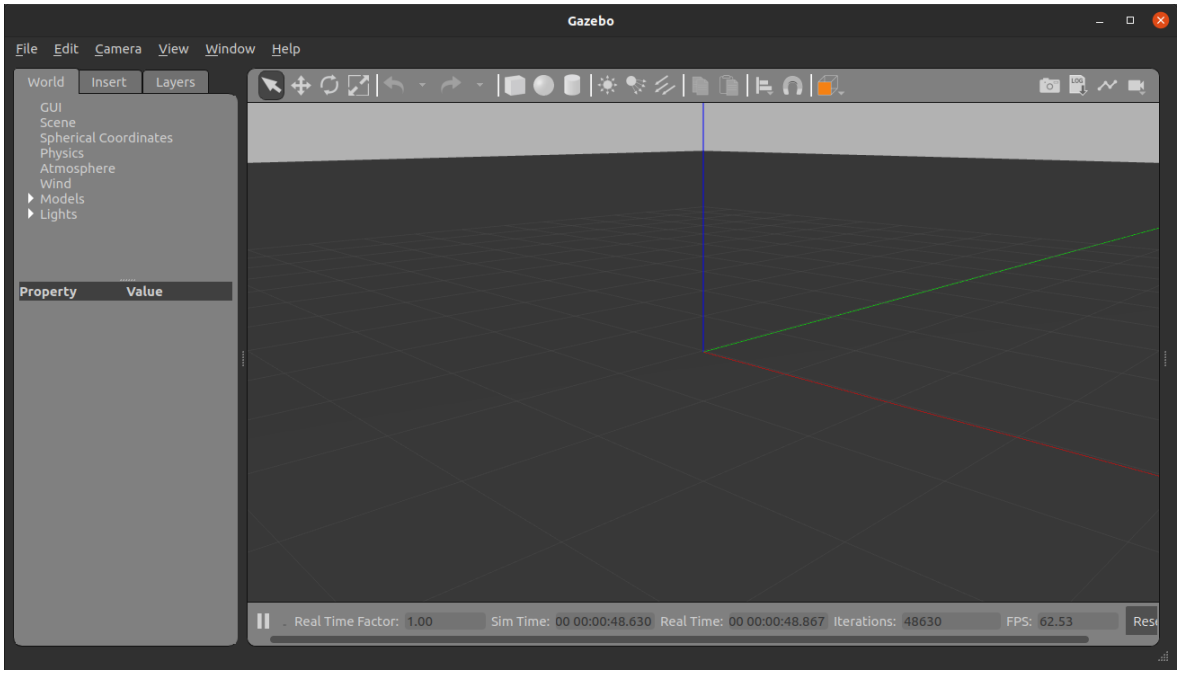


Figure 4.62: Empty world in Gazebo

The ROS Plugin for Gazebo ensures integration between the two platforms, enabling direct communication with ROS. This allows both simulated and real robots to be controlled using the same software interface, making Gazebo an ideal platform for testing, developing, and validating robotic systems in a virtual environment before deployment on physical hardware.

This plugin facilitates bi-directional communication through ROS topics, services, and actions, allowing sensor data from Gazebo—such as LiDAR, cameras, and IMUs—to be published as ROS messages while also enabling ROS-based velocity and trajectory commands to control simulated robots. Additionally, the plugin supports `ros_control`, making it possible to implement position, velocity, and effort controllers, which are essential for tuning PID loops before testing them on real actuators.

```
    <launch>
  <arg name="model" default="$(env TURTLEBOT3_MODEL)"
   ↪  doc="model type [burger, waffle, waffle_pi]"/>
  <arg name="x_pos" default="0.0"/>
  <arg name="y_pos" default="0.0"/>
  <arg name="z_pos" default="0.0"/>

  <include file="$(find gazebo_ros)/launch/empty_world.launch">
    <arg name="world_name"
     ↪  value="$(find turtlebot3_gazebo)/worlds/empty.world"/>
    <arg name="paused" value="false"/>
    <arg name="use_sim_time" value="true"/>
    <arg name="gui" value="true"/>
    <arg name="headless" value="false"/>
    <arg name="debug" value="false"/>
  </include>

  <param name="robot_description" command=
  "$(find xacro)/xacro --inorder
$(find turtlebot3_description)/
urdf/turtlebot3_$(arg model).urdf.xacro" />

  <node pkg="gazebo_ros" type="spawn_model" name="spawn_urdf"
   ↪  args="-urdf -model turtlebot3_$(arg model) -x $(arg x_pos) -y
  $(arg y_pos) -z $(arg z_pos) -param robot_description" />
</launch>
```

The provided example demonstrates how the **ROS Plugin for Gazebo** enables the spawning and control of a robot model within a simulated environment, enabling **smooth and efficient integration** with the **Robot Operating System (ROS)**. The launch file initializes an empty **Gazebo** world and loads a robot model described in a **URDF (Unified Robot Description Format)** file using the `spawn_model` node from the `gazebo_ros` package. Additionally,

the `robot_state_publisher` node is included to publish the robot's joint states, ensuring that its transformations can be visualized and utilized in **ROS-based frameworks** such as **MoveIt** or **RViz**. This integration allows developers to test **robot behaviors, sensor data integration, and control algorithms** in a virtual environment before deploying them on physical hardware.

It facilitates bi-directional communication through **ROS topics, services, and actions**, enabling sensor data from Gazebo—such as **LiDAR, cameras, and IMUs**—to be published as **ROS messages** while also allowing **ROS-based velocity and trajectory commands** to control simulated robots. Additionally, the plugin supports **ros_control**, enabling the implementation of **position, velocity, and effort controllers**, which are essential for tuning **PID loops** before applying them to real actuators.

This specific example shows a **ROS launch file** that spawns a **TurtleBot3** model shown fig. 4.63 in an empty **Gazebo** simulation environment. This file provides flexibility by allowing users to specify the **TurtleBot3 model type** (`burger`, `waffle`, or `waffle_pi`) and configure the **robot's initial position**. It also sets critical simulation parameters, such as **enabling GUI rendering, synchronizing ROS time with Gazebo simulation time, and dynamically loading the robot's description** based on the selected model type. The launch file ensures a well-structured simulation environment where **robotic software, motion planning, and perception algorithms** can be tested under realistic conditions.

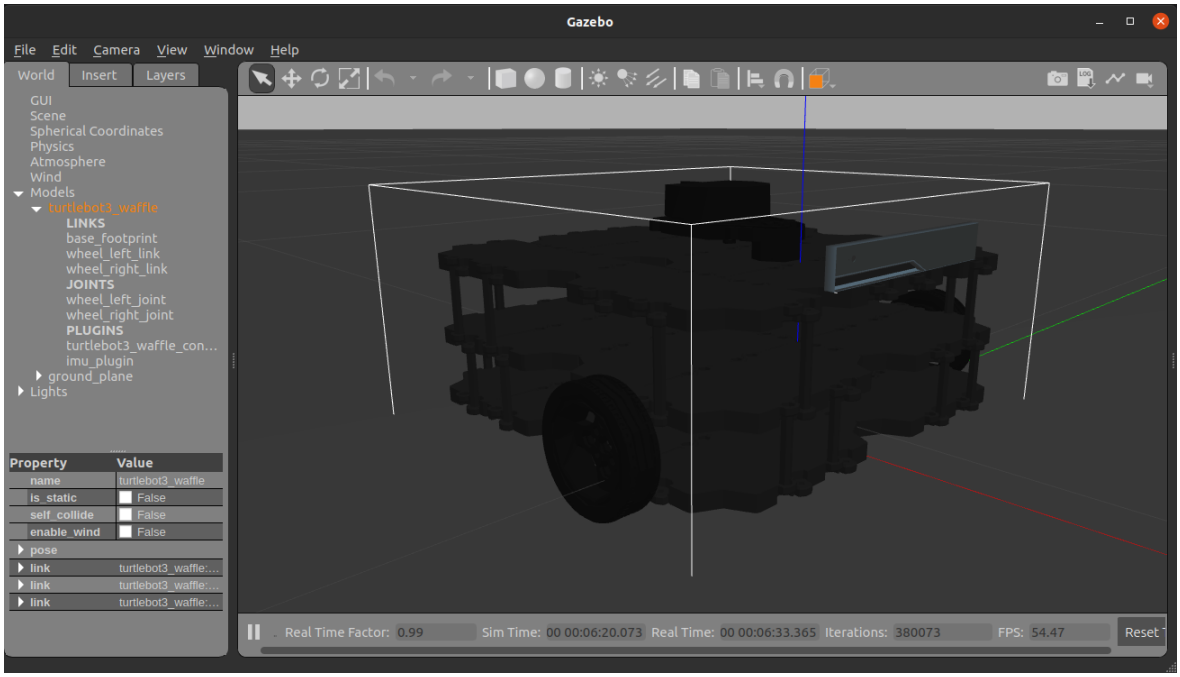


Figure 4.63: TurtleBot3 Waffle spawned in empty world

The Gazebo Graphical User Interface (GUI) provides an interactive environment for users to visualize and manipulate their simulated worlds in real-time. One of the key features

of the GUI is the set of side tabs, which organize various tools and functionalities. Among these, the left side pannel that appears fig. 4.64 World, Insert, and Layers tabs are particularly important for managing the simulation environment and objects within it.

The **World Tab** in Gazebo's GUI allows users to manage and configure the properties of the simulation world, providing several options for modifying the environment settings. Users can adjust the **gravity settings** to control the strength of gravity in the simulation, select the **physics engine** (such as **ODE**, **Bullet**, or **DART**) to determine the level of simulation fidelity and performance, and customize **time and weather conditions**, including factors like sunlight, fog, and rain. Additionally, the World tab provides detailed information about the models within the simulation, including their **joints** and **links**. Users can visualize and modify the connections between different parts of a robot or object, defining how they move and interact with each other. The **links** represent rigid bodies, while **joints** define the relative motion between those bodies, such as revolute, prismatic, or fixed joints. This tab plays a crucial role in fine-tuning the simulation environment and robot behavior, ensuring that the simulation behaves as expected for the application at hand. It is an essential tool for accurately replicating real-world conditions and testing robotic systems in varied scenarios.

The **Insert Tab** allows users to add various objects and components to the simulation environment. Users can insert robot models, lights, sensors, and even other world elements, which helps populate the simulation for testing and development. Additionally, the tab makes it easy to add custom plugins or adjust the robot's attributes in the virtual world.

The **Layers Tab** provides control over the visibility of different elements within the simulation. Users can toggle the visibility of models, sensors, and other objects in the scene to focus on specific parts of the simulation. This helps streamline the workspace, especially when dealing with complex environments and large-scale simulations.

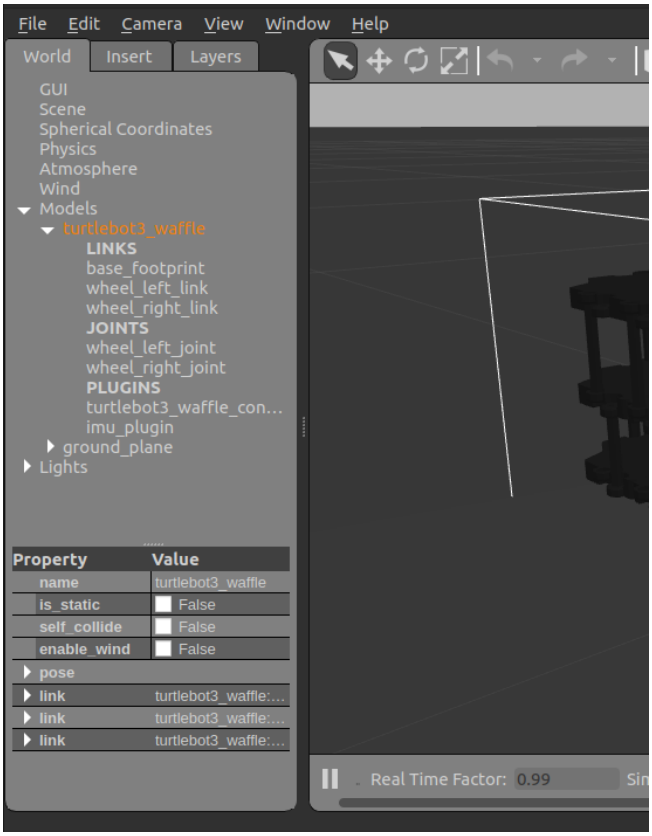


Figure 4.64: Gazebo Graphical User Interface left side pannel

The lower part of the Gazebo GUI displayed in fig. 4.65 provides critical real-time simulation information and performance metrics. One of the most important features is the **Real-Time Factor (RTF)**, which indicates the ratio between real-time and simulated time. This factor helps users determine how efficiently the simulation is running, with values close to 1.0 indicating that the simulation is running in real-time. If the RTF is greater than 1.0, it suggests that the simulation is running faster than real time, while a value less than 1.0 indicates that it is running slower.

In addition to RTF, it also displays **Sim Time**, which shows the simulation's elapsed time. This is useful for tracking the progression of events in the simulation and synchronizing it with other systems. The **Real Iterations** and **Sim Iterations** counters provide insight into the number of iterations performed by the simulation per second for real-time and simulated time, respectively. Monitoring these values helps users assess the efficiency of the simulation and diagnose performance issues if the simulation is not proceeding as expected.

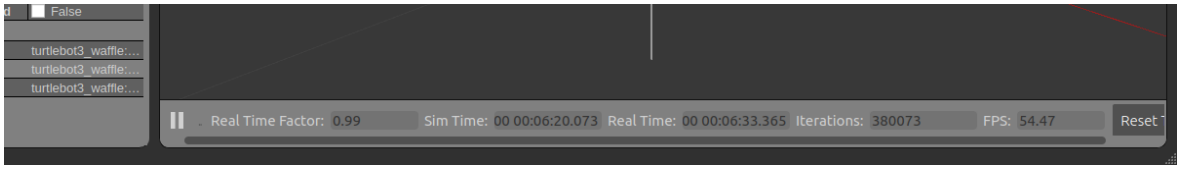


Figure 4.65: Gazebo Graphical User Interface lower part

The top part of the Gazebo GUI (fig. 4.66) provides several essential controls and information related to the simulation's overall operation. At the top-left corner, users will find the **File** menu, which includes options to open, save, and manage Gazebo worlds. It also allows users to load and save configurations, and set preferences for simulation settings.

In addition, the top part of the GUI provides options for manipulating the lighting within the simulation. Users can select from **Point**, **Spot**, and **Directional** lights to illuminate different parts of the world. Point lights emit light in all directions from a single point, Spot lights create a focused beam of light, and Directional lights simulate sunlight, casting parallel rays in a specific direction. This allows for realistic and customizable lighting in the simulation environment.

The **Selection Light** tool enables users to adjust the lighting between two or more objects in the simulation, offering more control over how objects are illuminated and how shadows are cast in the environment.

Moreover, the GUI allows users to switch between different **perspective views**, such as top-down, side, or camera views, to inspect and interact with the simulation from different angles.

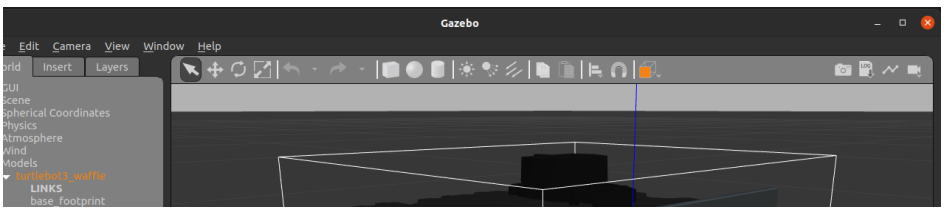


Figure 4.66: Gazebo Graphical User Interface top part

Right-clicking on an object in the Gazebo simulation environment brings up a context-sensitive menu that allows users to perform a variety of actions to interact with and manipulate the object. The options available in this menu include:

1. **Move To**: This option allows users to move a selected object to a specified location in the simulation world. After selecting this option, users can click on a point in the world to which the object will be moved, making it easier to position objects accurately within the environment.

2. **Follow**: The Follow option enables users to make the camera follow a particular object in the simulation. When this option is activated, the camera will automatically track the

movement of the selected object, allowing users to observe its behavior from a fixed perspective, which can be useful when testing robot movements or simulating dynamic scenarios.

3. **Edit**: The Edit option opens a set of interactive tools that allow users to modify the properties of the selected object, such as its position, orientation, size, and material properties.

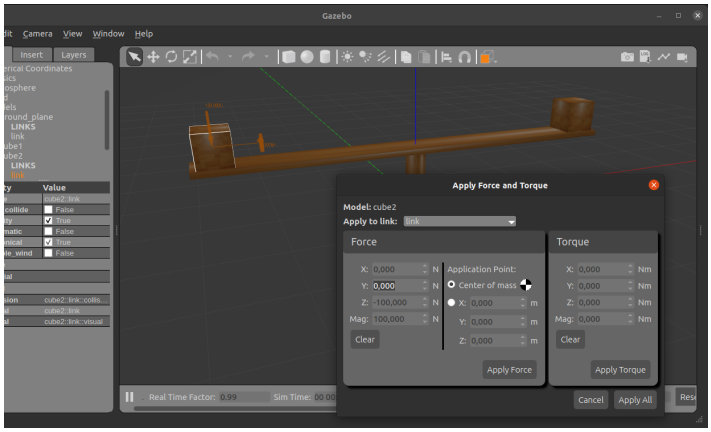


Figure 4.67: Example of force applied on one side of a seesaw in gazebo

4. **Apply Force/Torque**: This option gives users the ability to apply a force or torque to the selected object, which is especially useful for testing how the object reacts under various physical conditions.fig. 4.67 shows how users can specify the direction, magnitude, and duration of the applied force or torque, allowing for controlled experiments on the object's behavior within the simulated environment.

4.60.2 RViz

RViz (ROS Visualization) is an open-source 3D visualization tool that provides real-time graphical representations of robotic systems.

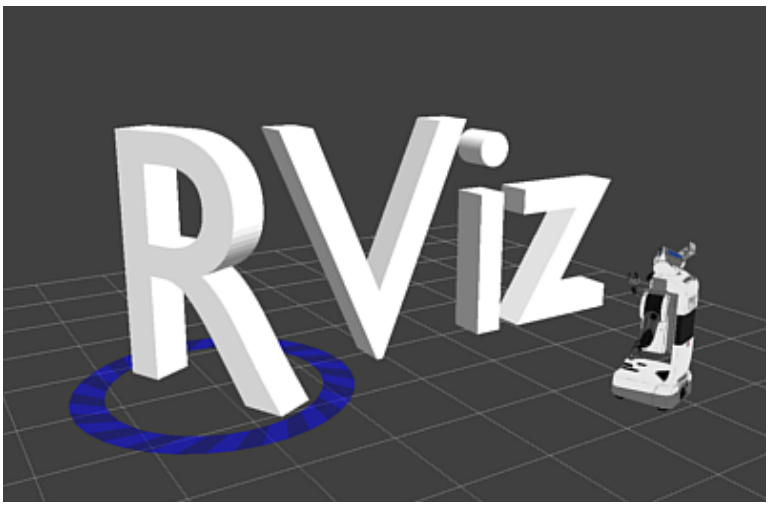


Figure 4.68: Rviz (Ros Visualization)

It serves two primary purposes: (1) visualizing sensor data, such as LiDAR scans, point clouds from 3D sensors (e.g., RealSense, Kinect), and camera images, in an intuitive 3D environment; and (2) enabling interactive control of robotic systems by sending commands like navigation goals or waypoints. In this project, RViz was used extensively to monitor sensor outputs, validate navigation algorithms, and debug the robot's behavior during simulation. Its seamless integration with ROS topics and plugins made it an indispensable tool for visualizing complex data streams, such as laser range finder (LRF) distances and Point Cloud Data (PCD), without requiring additional programming.

4.61 IMPLEMENTATION OF THE SIMULATION ENVIRONMENT

The implementation of the simulation environment is carefully designed to ensure that the results obtained in simulation closely reflect real-world performance. Most simulation parameters, including the robot's dimensions, mass properties, sensor specifications, and environmental conditions, are selected to match the specifications outlined in the competition framework. This ensures that the robot developed based on simulation results can seamlessly transition from a virtual setting to real-world deployment with minimal modifications.

A key aspect of this simulation is the accurate modeling of robot dynamics, actuator characteristics, and sensor behavior. The physics engine parameters, such as friction coefficients, and sensor noise models, are tuned to replicate real-world conditions as precisely as possible. Additionally, the design of the virtual environment, including terrain features, obstacles, and lighting conditions, is configured to match the competition setup. This allows for realistic testing and validation of navigation and control algorithms.

By incorporating these considerations, the simulation provides a reliable testing ground for developing and refining motion planning, perception, and control strategies. This approach reduces the gap between simulated and real-world performance, ensuring that insights gained from the virtual environment translate effectively to the physical robot. However, like any simulation-based approach, there are inherent advantages and disadvantages when using simulators to test robot behaviors, as discussed in [28].

Despite these limitations, careful selection of simulation parameters—such as physics engine settings, sensor noise models, and environmental conditions—enhances the accuracy of the virtual testing environment. The following subsections detail the implementation of the robot model, world design, and control and sensor integration, outlining how each component contributes to achieving a high-fidelity simulation.

4.61.1 Robot Model (URDF/SDF)

4.61.2 World Design

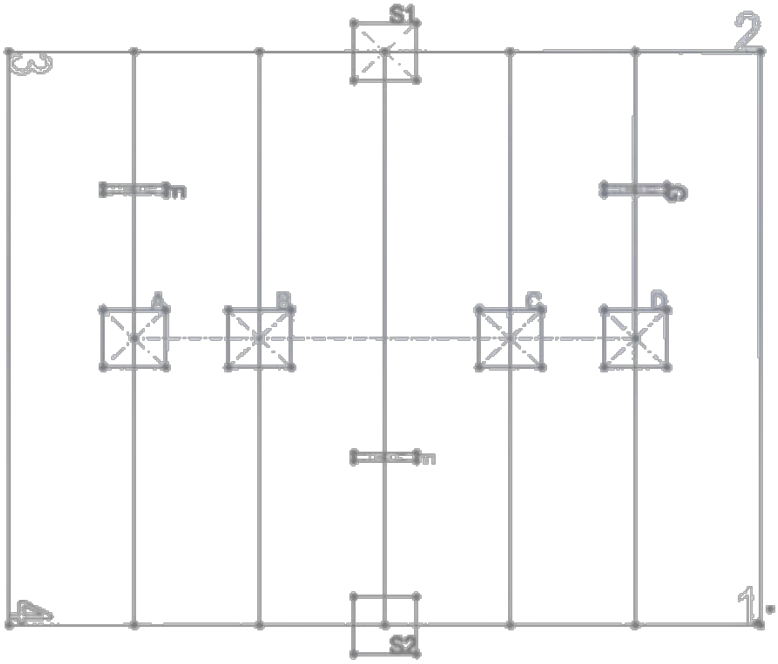


Figure 4.69: Teknofest competition real map layout

The simulation environment was designed to replicate the competition layout in fig. 4.69 as closely as possible. The terrain was constructed using custom models to accurately mimic the competition area, incorporating key features such as a **white wooden floor**, **black lines for path following**, **platforms for load dynamics**, **obstacles**, and **friction variations** to simulate real-world conditions.

In Gazebo, this entire environment is saved as a world file, which includes all the models, textures, and configurations necessary to recreate the simulation. The world file is written in the Simulation Description Format (SDF), an XML-based format used to describe the properties and behavior of objects and environments in Gazebo.

SDF allows for easy definition of physical properties, geometries, lighting, and sensor configurations, making it a versatile and standard way to represent simulation environments. The SDF format ensures that the simulation setup is reproducible, shareable, and can be modified easily for different testing scenarios. Similar to the Unified Robot Description Format (URDF), which is used for defining robot models in ROS, SDF provides a structured way to describe objects and environments. While URDF focuses primarily on robot kinematics and geometry, SDF is more comprehensive and extends its capabilities to encompass the full environment, including physics properties, sensor configurations, and world dynamics.

The world file was made through the design of individual SDF files for each model within the environment. These individual models were first defined with each having its own dedicated SDF file. Once the models were completed, they were then integrated into a single world file, named `competition_area.world` (in SDF format). This world file serves as the central configuration, bringing together all the models, their properties, and the environment settings.

4.61.2.1 Environment Layout

Designed to replicate the competition area closely the world contains custom models were created to represent key elements of the space, ensuring that the robot's interaction with its surroundings is as realistic as possible. Key components of the environment layout include the following:

- **Flooring and Pathways:** A **white wooden floor** was chosen to resemble the actual competition floor, providing a surface with consistent friction properties for the robot to interact with. The **black lines for path following** were added on the white floor according to the competition specifications, acting as markers for the robot's autonomous navigation algorithms to follow.

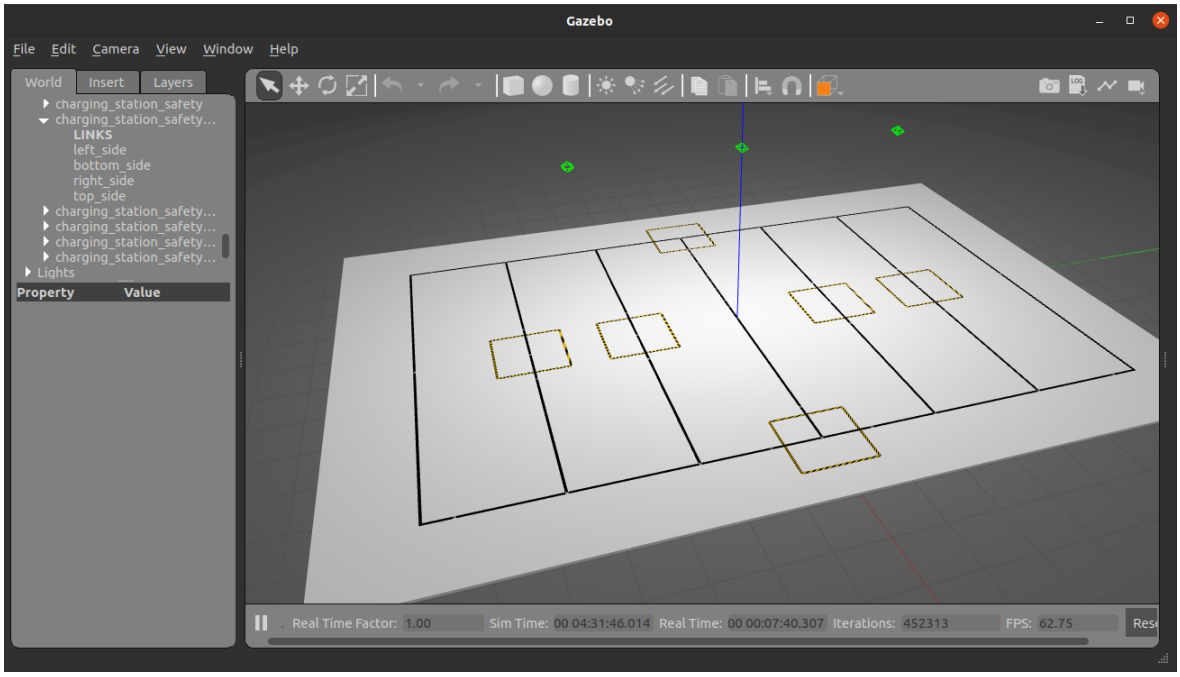


Figure 4.70: White wooden floor with black lines in gazebo

The black lines for path following were also incorporated into the simulation as individual objects within the Gazebo environment. Each line was treated as a separate

model to allow easy modifications, such as adjusting their position, length, or orientation, without affecting the rest of the simulation environment. This modular approach makes it easier to tweak the lines for different test scenarios, ensuring flexibility and quick adjustments during development and testing.

```
...
<wall_time>1738074256 296636706</wall_time>
<iterations>117145</iterations>
<model name='black_line'>
  <pose>0 0 0.06 0 -0 0</pose>
  <scale>1 1 1</scale>
  <link name='line_link'>
    <pose>0 0 0.06 0 -0 0</pose>
    <velocity>0 0 0 0 -0 0</velocity>
    <acceleration>0 0 0 0 -0 0</acceleration>
    <wrench>0 0 0 0 -0 0</wrench>
  </link>
</model>
<model name='black_line_clone'>
  <pose>0 2.33333 0.06 0 -0 0</pose>
  <scale>1 1 1</scale>
  <link name='line_link'>
    <pose>0 2.33333 0.06 0 -0 0</pose>
    <velocity>0 0 0 0 -0 0</velocity>
    <acceleration>0 0 0 0 -0 0</acceleration>
    <wrench>0 0 0 0 -0 0</wrench>
  </link>
</model>
<model name='black_line_clone_0'>
  <pose>0 4.666 0.06 0 -0 0</pose>
  <scale>1 1 1</scale>
  ...
```

Additionally, QR code tags were placed at key locations, such as loading/unloading points, stations, and before turns, to provide the robot with precise location information.

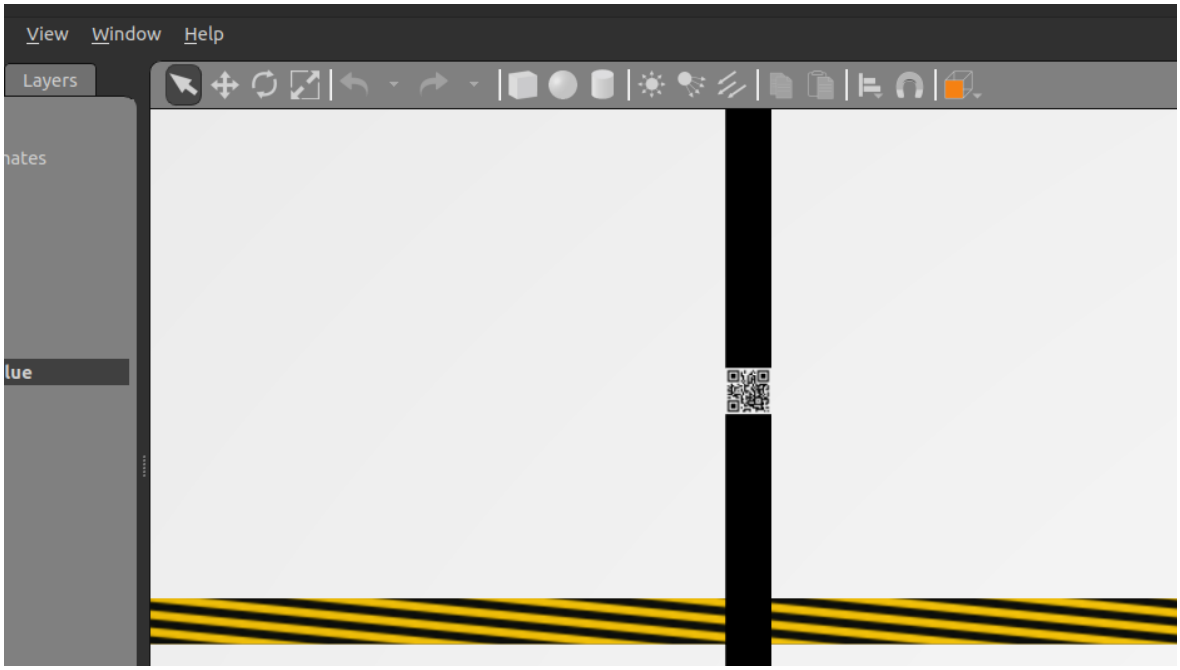


Figure 4.71: Example of Qr Code tag before a loading point

the `<friction>` tag parameters of the white floor, displayed in fig. 4.70, were specifically chosen to replicate the conditions of wood flooring. The static friction coefficient was set to 0.4, representing the resistance to the start of sliding motion. The dynamic friction coefficient was set to 0.35, modeling the friction while the robot is already sliding. These values were carefully selected to ensure that the robot's interactions with the floor behave as expected in real-world conditions.

The `<static>` tag ensures that the floor model is fixed and does not move during the simulation. The `<pose>` tag is used to position the floor in the environment, placing it just slightly above the ground to avoid collision with the ground plane. The `<collision>` tag defines the physical properties for detecting interactions, including the geometry of the floor as a box shape. Additionally, the `<visual>` tag defines how the floor appears in the simulation, with the material set to a white color to represent the wooden floor's appearance.

```
<model name='wooden_floor'>
<static>1</static>
<pose>0 0 0.01 0 -0 0</pose>
<link name='floor_link'>
  <collision name='floor_collision'>
    <geometry>
      <box>
        <size>12 17 0.1</size>
      </box>
    </geometry>
    <max_contacts>10</max_contacts>
    <surface>
      <contact>
        <ode/>
      </contact>
      <bounce/>
      <friction>
        <ode/>
        <torsional>
          <ode/>
        </torsional>
        <static_friction>0.4</static_friction> <!-- Adjusted for
        ↪ wooden floor -->
        <dynamic_friction>0.35</dynamic_friction> <!-- Adjusted
        ↪ for wooden floor -->
      </friction>
    </surface>
  </collision>
  <visual name='floor_visual'>
    <geometry>
      <box>
        <size>12 17 0.1</size>
      </box>
    </geometry>
    <material>
      <ambient>1 1 1 1</ambient>
      <diffuse>1 1 1 1</diffuse>
    </material>
  </visual>
  <self_collide>0</self_collide>
```

```
      <enable_wind>0</enable_wind>
      <kinematic>0</kinematic>
    </link>
  </model>

```

- **Obstacles and Load Platforms:** The environment includes various **obstacles** such as walls and dynamic objects, designed to challenge the robot's obstacle avoidance and path planning abilities. **Platforms for load dynamics** were added to simulate loading and unloading points, where the robot needs to deliver or pick up objects, mimicking the tasks required during the competition.

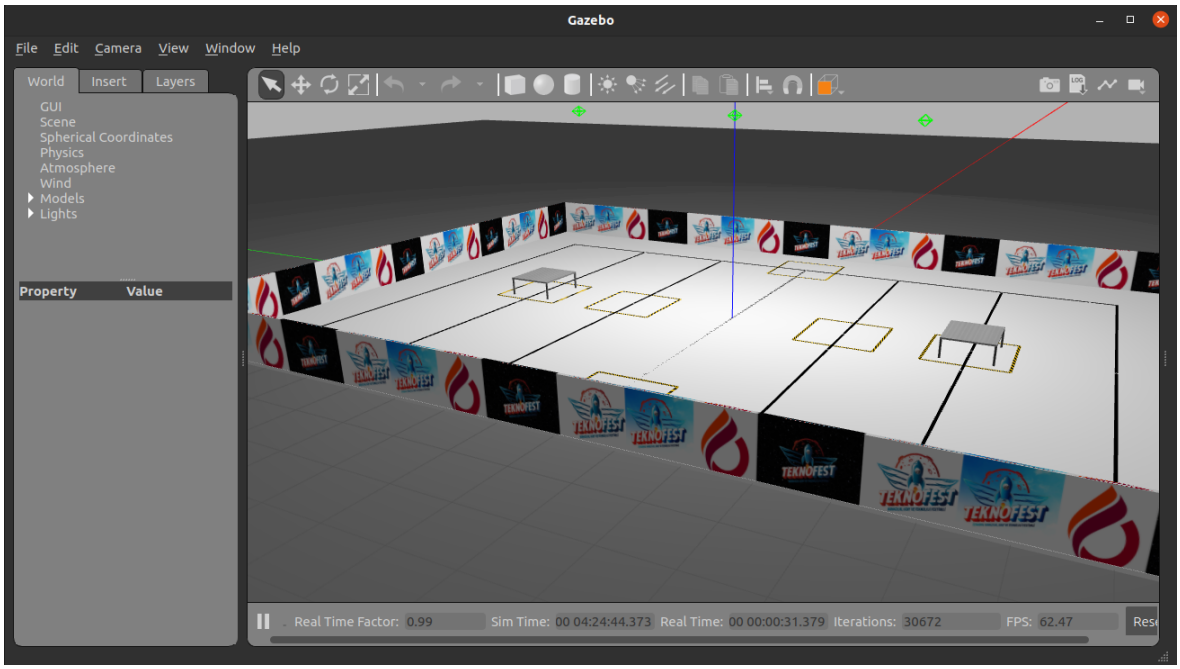


Figure 4.72: Competition aera bounded by ad hoardings

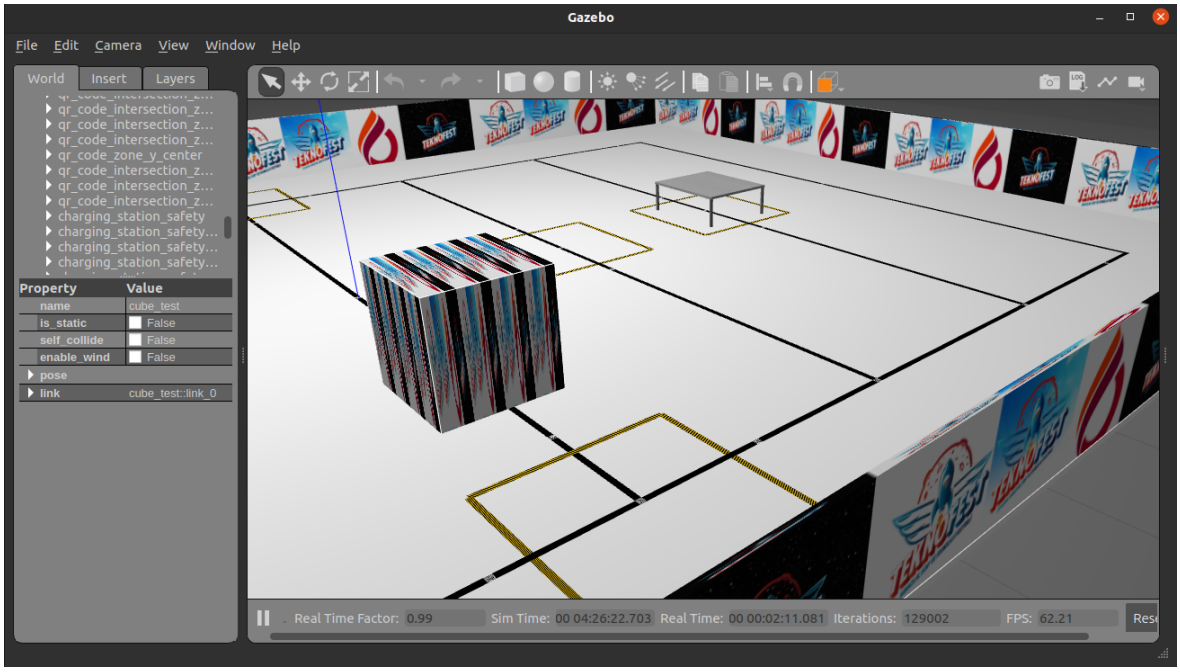


Figure 4.73: Competition area line interrupted by permanent obstacle

The platform model, as shown in the code snippet, is designed with a central table surface and four supporting legs. The structure is composed of multiple links, where each leg is defined separately, and they are all connected to the table surface through fixed joints.

The `<model>` tag defines the platform, which includes the physical properties and geometric shapes of the table and legs.
Each link, such as `table_surface` and `front_left_leg`, `front_right_leg`, etc., has its own inertial properties (`<inertial>`) and a collision geometry defined under the `<collision>` tag.

For instance, the `<collision>` tag for the table surface has a defined friction property, with a coefficient of 1 for both static and dynamic friction, simulating a high-friction surface. This friction coefficient can be adjusted to simulate the specific characteristics of a material, such as wood or metal.

Each leg is represented as a cylinder, with its own collision properties and friction settings, ensuring realistic interaction with the robot during the simulation. The friction properties of each leg are defined in the `<surface>` `<friction>` section using `ode` settings. These settings also include the `<bounce>` and `<contact>` properties, which help simulate realistic physical interactions between the objects in the environment. Each of these legs also has a specific pose and position in the simulation.

The joints, such as `front_left_joint`, connect each leg to the table surface with a

`fixed` type, meaning that the legs do not move relative to the table. The pose of each joint defines the exact position and orientation of the legs in the simulation environment.

The overall pose of the platform, including its position in the world, is defined at the end of the model, specifying the coordinates and orientation for the platform's placement in the simulation.

Additionally, the platform's visual properties are set using the `<visual>` tag, with a custom material representing the surface texture, such as stainless steel, applied to the table's surface. To ensure accurate physical interactions, the `<inertial>` tag defines the mass and moments of inertia of the platform and its legs, ensuring a realistic response to forces and torques applied during the simulation. The `<collision>` tag specifies the geometric shape used for physics calculations, which may be simplified compared to the visual model to improve computational efficiency while maintaining accurate contact and collision responses. The platform's legs also incorporate both `<collision>` and `<inertial>` properties, allowing them to contribute to the overall stability of the structure while ensuring that the physics engine correctly simulates interactions such as impacts, weight distribution, and external forces acting on the table.

```
<model name='platform'>
  <link name='table_surface'>
    <inertial>
      <mass>13.98</mass>
      <inertia>
        <ixx>0.1</ixx>
        <ixy>0</ixy>
        <ixz>0</ixz>
        <iyy>0.1</iyy>
        <iyz>0</iyz>
        <izz>0.1</izz>
      </inertia>
      <pose>0 0 0 0 -0 0</pose>
    </inertial>
    <collision name='surface_collision'>
      <pose>0 0 0.367 0 -0 0</pose>
      <geometry>
        <box>
          <size>1.1 0.95 0.03</size>
        </box>
```

```
21            </geometry>
22            <surface>
23              <friction>
24                <ode>
25                  <mu>1</mu>
26                  <mu2>1</mu2>
27                </ode>
28                <torsional>
29                  <ode/>
30                </torsional>
31              </friction>
32              <contact>
33                <ode/>
34              </contact>
35              <bounce/>
36            </surface>
37            <max_contacts>10</max_contacts>
38          </collision>
39          ...
```

```
      ...
      <visual name='surface_visual'>
        <pose>0 0 0.367 0 -0 0</pose>
        <geometry>
          <box>
            <size>1.1 0.95 0.03</size>
          </box>
        </geometry>
        <material>
          <script>
            <uri>model://platform/materials/scripts</uri>
            <uri>model://platform/materials/textures</uri>
            <name>stainless_steel_texture</name>
          </script>
        </material>
      </visual>
      ...

```

```
    ...
    <link name='front_left_leg'>
      <inertial>
        <mass>2.796</mass>
        <inertia>
          <ixx>0.01</ixx>
          <ixy>0</ixy>
          <ixz>0</ixz>
          <iyy>0.01</iyy>
          <iyz>0</iyz>
          <izz>0.01</izz>
        </inertia>
        <pose>0 0 0 0 -0 0</pose>
      </inertial>
      <collision name='collision'>
        <pose>0.53 0.455 0.1835 0 -0 0</pose>
        <geometry>
          <cylinder>
            <radius>0.02</radius>
```

```
            <length>0.367</length>
          </cylinder>
        </geometry>
        <surface>
          <friction>
            <ode>
              <mu>1</mu>
              <mu2>1</mu2>
            </ode>
            <torsional>
              <ode/>
            </torsional>
          </friction>
          <contact>
            <ode>
              <kp>100000</kp>
              <kd>1</kd>
            </ode>
          </contact>
          <bounce/>
        </surface>
        <max_contacts>10</max_contacts>
      </collision>
      <visual name='visual'>
        <pose>0.53 0.455 0.1835 0 -0 0</pose>
        <geometry>
          <cylinder>
            <radius>0.02</radius>
            <length>0.367</length>
          </cylinder>
        </geometry>
        <material>
          <script>
            <uri>file://media/materials/scripts/gazebo.material</
             ↪  uri>
            <name>Gazebo/Grey</name>
          </script>
        </material>
      </visual>
      <self_collide>0</self_collide>
```

```
59          <enable_wind>0</enable_wind>
60          <kinematic>0</kinematic>
61        </link>
62        <link name='front_right_leg'>
63          <inertial>
64            <mass>2.796</mass>
65            <inertia>
66              <ixx>0.01</ixx>
67              <ixy>0</ixy>
68              <ixz>0</ixz>
69          ...
```

Ad hoardings and obstacles were incorporated into the environment using a simple yet effective approach. A cube shape was used to create the basic geometry of these objects, with their dimensions adjusted to meet the specific requirements of the simulation. Textures were applied to the cubes to give them the appearance of real-world hoardings and obstacles, ensuring that they serve as realistic visual and physical barriers within the simulation.

These objects were assigned physical properties, such as mass and friction, and collisions were defined to ensure proper interaction with the robot. The hoardings and permanent obstacles were defined as static objects to prevent them from moving during the simulation, ensuring they remain fixed in place as intended.

The following lines provide an example of the visual and collision properties for the hoardings. These lines demonstrate how the hoardings models were assigned the name `cube_test` during the individual SDF design phase of the world. The code defines the geometry, textures, and physical properties for the hoardings.

```
...
model name='cube_test_clone_clone'>
  <link name='link_0'>
    <inertial>
      <mass>1</mass>
      <inertia>
        <ixx>0.166667</ixx>
        <ixy>0</ixy>
        <ixz>0</ixz>
        <iyy>0.166667</iyy>
        <iyz>0</iyz>
        <izz>0.166667</izz>
      </inertia>
      <pose>0 0 0 0 -0 0</pose>
    </inertial>
    <pose>-0 -0 0 0 -0 0</pose>
    <visual name='visual'>
      <pose>0 0 0 0 -0 0</pose>
      <geometry>
        <box>
          <size>0.05 16.9 1</size>
        </box>
      </geometry>
      <material>
```

```
            <lighting>1</lighting>
            <script>
              <uri>model://cube_test/materials/scripts</uri>
              <uri>model://cube_test/materials/textures</uri>
              <name>teknofest_logo</name>
            </script>
            <shader type='pixel'/>
          </material>
          <transparency>0</transparency>
          <cast_shadows>1</cast_shadows>
        </visual>
        <collision name='collision'>
          <laser_retro>0</laser_retro>
          <max_contacts>10</max_contacts>
          <pose>0 0 0 0 -0 0</pose>
          <geometry>
            <box>
              <size>0.05 16.9 1</size>
            </box>
          </geometry>
          <surface>
            <friction>
              <ode>
                <mu>1</mu>
                <mu2>1</mu2>
                <fdir1>0 0 0</fdir1>
                <slip1>0</slip1>
                <slip2>0</slip2>
              </ode>
              <torsional>
                <coefficient>1</coefficient>
                <patch_radius>0</patch_radius>
                <surface_radius>0</surface_radius>
                <use_patch_radius>1</use_patch_radius>
                <ode>
                  <slip>0</slip>
                </ode>
              </torsional>
            </friction>
            <bounce>
```

```
            <restitution_coefficient>0</restitution_coefficient>
            <threshold>1e+06</threshold>
          </bounce>
          <contact>
            <collide_without_contact>0</collide_without_contact>
            <collide_without_contact_bitmask>1</collide_without_c
             ↪  ontact_bitmask>
            <collide_bitmask>1</collide_bitmask>
            <ode>
              <soft_cfm>0</soft_cfm>
              <soft_erp>0.2</soft_erp>
              <kp>1e+13</kp>
              <kd>1</kd>
              <max_vel>0.01</max_vel>
              <min_depth>0</min_depth>
            </ode>
            <bullet>
              <split_impulse>1</split_impulse>
              <split_impulse_penetration_threshold>-0.01</split_i
               ↪  mpulse_penetration_threshold>
              <soft_cfm>0</soft_cfm>
              <soft_erp>0.2</soft_erp>
              <kp>1e+13</kp>
              <kd>1</kd>
            </bullet>
          </contact>
        </surface>
      </collision>
      <self_collide>0</self_collide>
      <enable_wind>0</enable_wind>
      <kinematic>0</kinematic>
    </link>
    <static>1</static>
    <allow_auto_disable>1</allow_auto_disable>
    <pose>-6.06431 0.045196 0.46 0 -0 0</pose>
    <enable_wind>0</enable_wind>
  </model>
  ...
```

The design of the QR codes followed a similar approach to most other models in

the world. Each QR code was represented by a textured cube, with textures made to resemble the unique images that contain the right location information.

```
<?xml version='1.0'?>
<sdf version='1.7'>
  <model name='qr_code'>
    <link name='link_0'>
      <pose>0 0 0 0 0 0</pose>
      <visual name='visual'>
        <pose>0 0 0 0 0 0</pose>
        <geometry>
          <box>
            <size>0.05 0.05 0.001</size>  <!-- Increase size
             ↪  of the box -->
          </box>
        </geometry>
        <material>
          <lighting>1</lighting>
          <script>
            <uri>model://qr_code/materials/scripts</uri>
            <uri>model://qr_code/materials/textures</uri>
            <name>qr_code_content</name>
          </script>
          <shader type='pixel'/>
        </material>
        <transparency>0</transparency>
        <cast_shadows>1</cast_shadows>
      </visual>
    </link>
    <static>1</static>
    <allow_auto_disable>1</allow_auto_disable>
  </model>
</sdf>

```

The above SDF code represents the individual model of the QR code. It contains only visual information and does not define any physical properties, as the QR code is used for location identification within the simulation. The model is defined as static to prevent movement and includes a texture that simulates the unique QR code image.

To simplify the referencing of points on the map in fig. 4.69, the area was divided into several well-defined zones. This subdivision facilitates the robot's movement management by allowing specific tasks to be assigned to each zone. All tags were then

assigned unique values based on their relative locations to critical points such as loading/unloading stations, intersections, and key passage points. These QR codes serve as essential reference markers, enabling the robot's localization system to determine its exact position and adjust its trajectory accordingly.

- **Station 1:** Located between corners 1 and 4, this zone represents station 1.
- **Station 2:** Located between corners 2 and 3, this zone corresponds to station 2.
- **Zone A:** Contains the loading/unloading point A.
- **Zone B:** Contains the loading/unloading point B.
- **Zone C:** Contains the loading/unloading point C.
- **Zone D:** Contains the loading/unloading point D.

The QR code's content is specified using a `material` element in the SDF model. The `qr_code_contents.material` file defines the texture that represents the unique image of the QR code. The `material` file is referenced within the visual element of the QR code model using a `<script>` tag, which links to the texture folder containing the QR code images.

By separating the texture definition into the `qr_code_contents.material` file, it allows for easy updates and maintenance of the QR codes used in the simulation without needing to modify the main model files.

```
    ...
    {
      texture_unit
      {
        texture intersection_zone_c_station_1.png
      }
    }
  }
}

material intersection_zone_c_station_2
{
  technique
  {
    pass
    {
      texture_unit
```

```
        {
          texture intersection_zone_c_station_2.png
        }
      }
    }
  }

  material intersection_zone_d_station_1
  {
    technique
    {
      pass
      {
        texture_unit
        {
          texture intersection_zone_d_station_1.png
        }
      }
    }
  }

  material intersection_zone_d_station_2
  {
    technique
    {
      pass
      {
        texture_unit
        {
          texture intersection_zone_d_station_2.png
        }
      }
    }
  }

  material intersection_zone_x_station_1
  {
    technique
    {
      pass
```

```
58        {
59          texture_unit
60          {
61            texture intersection_zone_x_station_1.png
62          }
63        }
64      }
65    }
66
67    material intersection_zone_x_station_2
68    {
69      technique
70      {
71        pass
72        {
73          texture_unit
74          {
75            texture intersection_zone_x_station_2.png
76          }
77        }
78      }
79    }
80
81    material intersection_zone_y_station_1
82    {
83      technique
84      {
85        pass
86        {
87          texture_unit
88          {
89            texture intersection_zone_y_station_1.png
90          }
91        }
92      }
93    }
94
95    material intersection_zone_y_station_2
96    {
97      technique
```

```
98      {
99        pass
100       {
101         texture_unit
102         {
103           texture intersection_zone_y_station_2.png
104         }
105       }
106     }
107   }
108   ...
```

Figure 4.74: Qr code tag placed at the intersection of line of the zone C and the station 2

- **Random Clutter Generation:** Procedural generation methods were used to add **random clutter**, simulating items or obstacles that may appear unpredictably, requiring the robot to adapt to ever-changing environments.
- **Real-World Simulation Features:** External environmental factors such as wind were not simulated, as the competition setting assumes an indoor environment. Basic ambient and directional lighting were configured to ensure consistent visibility for sensor-based perception tasks.

  Poor lighting similar to conditions in fig. 4.75 can introduce challenges such as motion blur, sensor noise, and shadow distortions, making it difficult for cameras to differentiate objects from the background. Additionally, extreme lighting conditions, such as glare or overexposure, may lead to incorrect sensor readings, affecting navigation and localization accuracy.

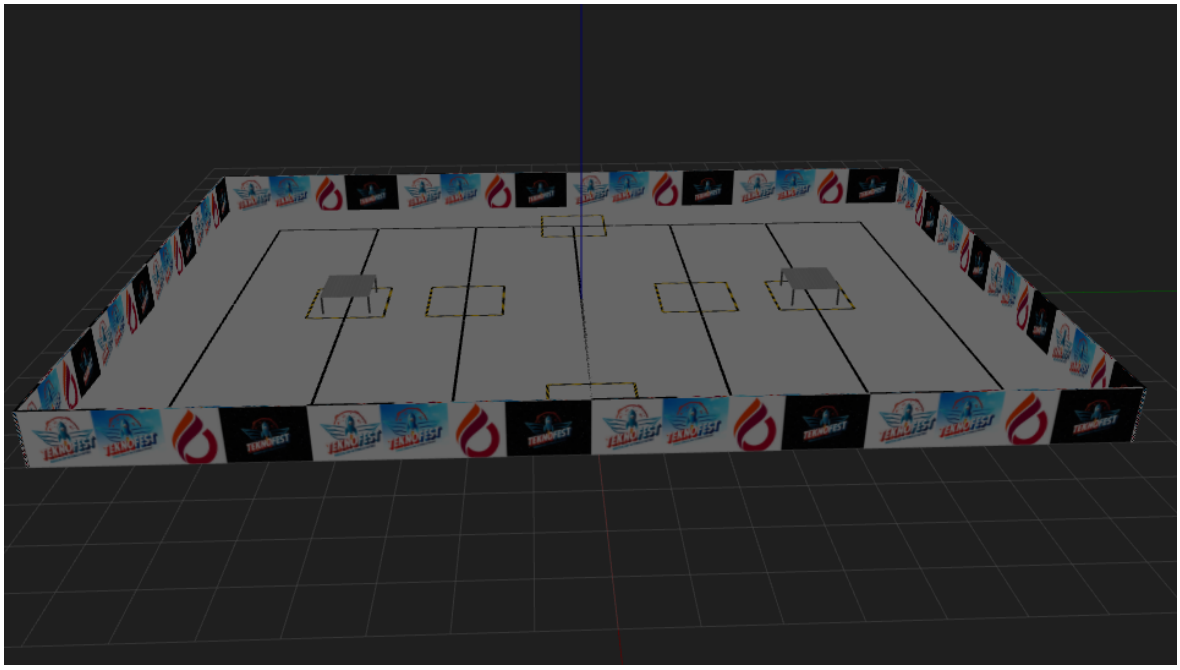


Figure 4.75: Effect of lighting conditions in simulation environment

On the other hand, good lighting shown in fig. 4.76 improves the performance of vision-based tasks such as object detection and QR code recognition. A well-lit environment with uniform brightness and minimal shadows ensures that cameras and sensors receive clear and consistent data, reducing the chances of misinterpretation due to varying illumination levels.

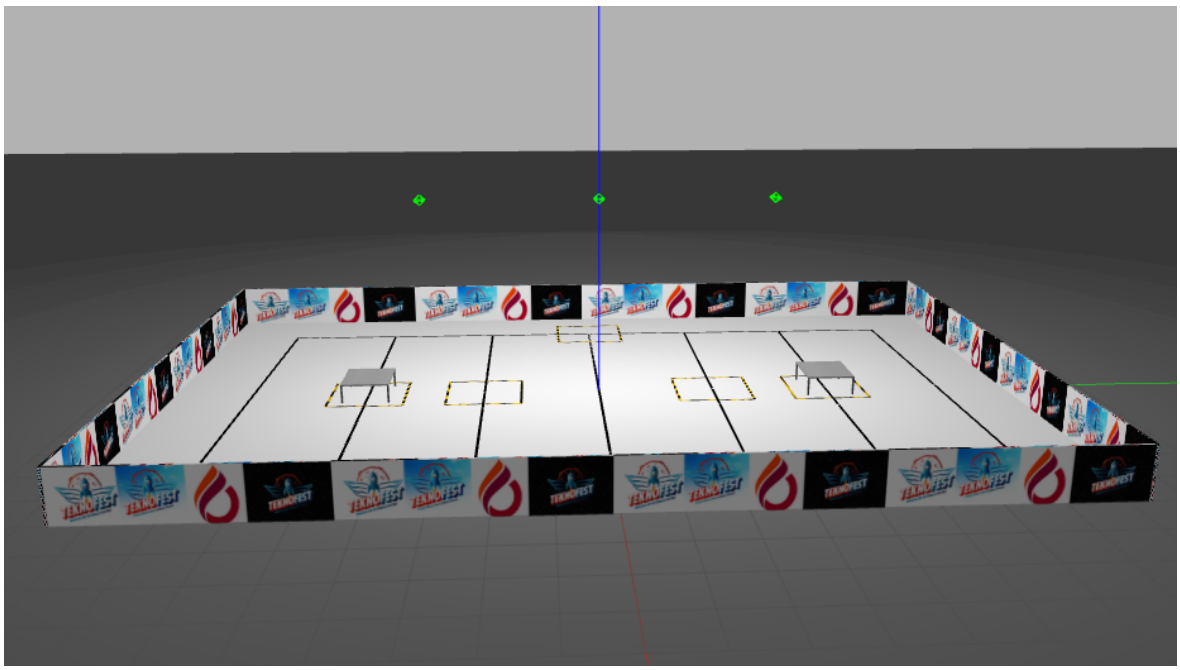


Figure 4.76: Effect of lighting conditions in simulation environment

4.61.2.2 Physics Configuration

I should maybe say more about this

4.61.2.3 Realism Enhancements

Is it necessary ?

4.61.3 Control and sensor Integration

You should be able to do something about this

4.62 VALIDATION OF THE SIMULATION

4.63 CHALLENGES AND SOLUTIONS

4.64 URDF

4.65 UNDERSTANDING ROBOT MODELING USING URDF

The Unified Robot Description Format (URDF) is an XML file format used to describe the physical properties of a robot in robotics applications, in particular within the Robot Operating System (ROS) ecosystem. It specifies the robot structure (links, joints, sensors and actuators etc.)

URDF can represent the kinematic and dynamic description of the robot, the visual representation of the robot, and the collision model of the robot. The following tags are the commonly used URDF tags to compose a URDF robot model:

4.65.1 link:

The link tag represents the single link of a robot. Using this tag, we can model a robot link and its properties. The modeling includes the size, the shape, and the color; it can even import a 3D mesh to represent the robot link. We can also provide the dynamic properties of the link, such as the inertial matrix and the collision properties. The syntax is as follows:

```
<link name="<name of the link>">
    <inertial>...........</inertial>
    <visual> ............</visual>
    <collision>..........</collision>
</link>
```

The following is a representation of a single link. The Visual section represents the real link of the robot, and the area surrounding the real link is the Collision section. The Collision section encapsulates the real link to detect a collision before hitting the real link:

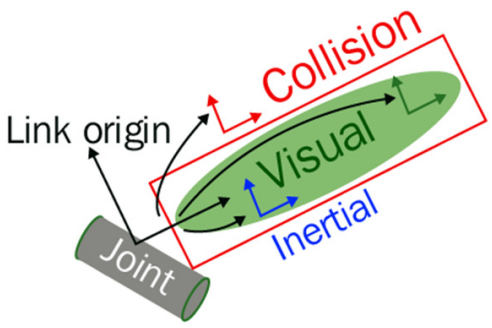


Figure 4.77: A visualization of the URDF link [1]

4.65.2 joint:

The joint tag represents a robot joint. We can specify the kinematics and dynamics of the joint and set the limits of the joint movement and its velocity. The joint tag supports the different types of joints, such as revolute, continuous, prismatic, fixed, floating, and planar. The syntax is as follows:

```
<joint name="<name of the joint>">
<parent link="link1"/>
<child link="link2"/>
<calibration .... />
<dynamics damping = ..../>
<limit effort = ..../>
</joint>
```

A URDF joint is formed between two links; the first is called the Parent link, and the second is called the Child link. Note that a single joint can have a single parent and multiple children at the same time. The following is an illustration of a joint and its links:

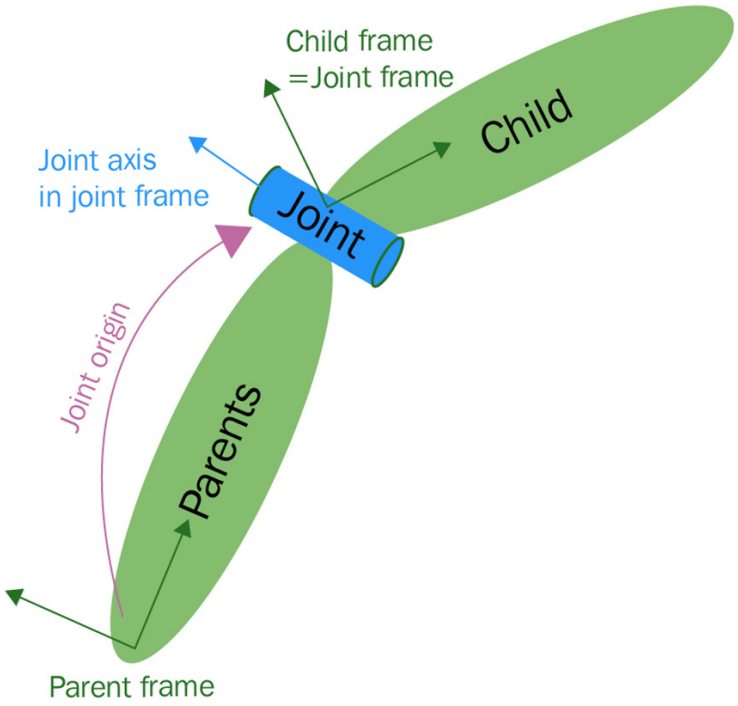


Figure 4.78: A visualization of the URDF joint [1]

4.65.3 robot:

This tag encapsulates the entire robot model that can be represented using URDF. Inside the robot tag, we can define the name of the robot, the links, and the joints of the robot. The syntax is as follows:

```
<robot name="<name of the robot>">
<link> ..... </link>
<joint> ..... </joint>
<joint> ........</joint>
</robot>
```

A robot model consists of connected links and joints. Here is a visualization of the robot model:

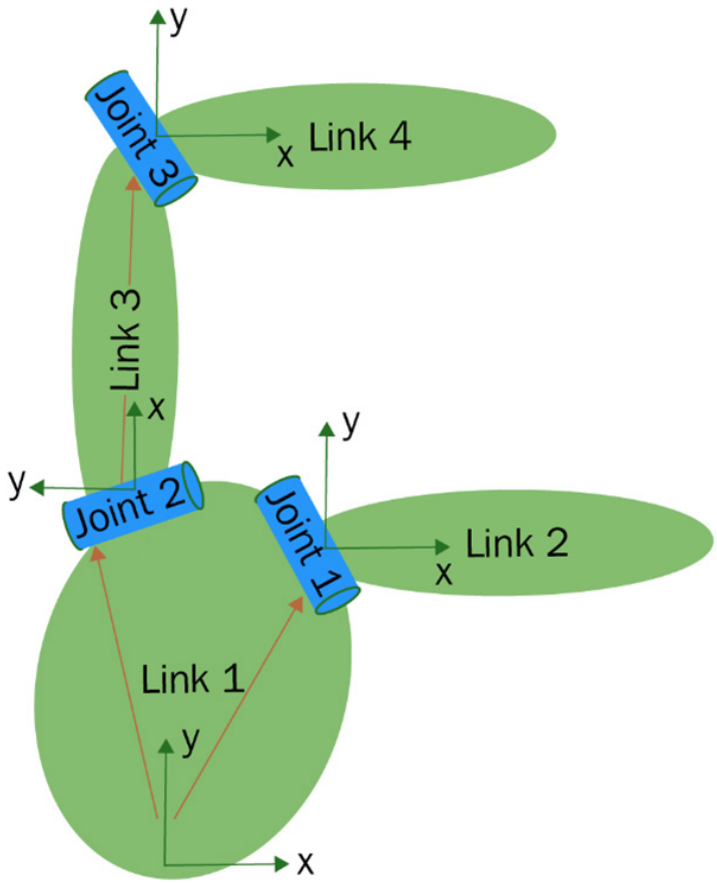


Figure 4.79: A visualization of a robot model with joints and links [1]

4.65.4 gazebo:

This tag is used when we include the simulation parameters of the Gazebo simulator inside the URDF. We can use this tag to include gazebo plugins, gazebo material properties, and more. The following shows an example that uses gazebo tags:

```
<gazebo reference="link_1">
<material>Gazebo/Black</material>
</gazebo>
```

You can find more about URDF tags at wiki.ros [29]. We are now ready to use the elements listed earlier to create a new robot from scratch. In the next section, we are going to create a new ROS package containing a description of the different robots.

4.65.5 Adding physical and collision properties to a URDF model

Before simulating a robot in a robot simulator, such as Gazebo or CoppeliaSim, we need to define the robot link's physical properties, such as geometry, color, mass, and inertia, as well as the collision properties of the link. Good robot simulations can be obtained only if the robot dynamic parameters (for instance, its mass, inertia, and more) are correctly specified in the urdf file. In the following code, we include these parameters as part of the base_link:

```
<link name="base_link">
...
<collision>
  <geometry>
     <box size="0.9 0.85 0.5"/>
  </geometry>
    <origin xyz="0.0 0.0 0.025" rpy="0.0 0.0 0.0"/>
</collision>
<inertial>
<origin xyz="0 0 0" rpy="0 0 0"/>
<mass value="35"/>
<inertia ixx="3.2" ixy="0.0" ixz="0.0" iyy="4" iyz="0.0" izz="$3.9"/>
</inertial>  </link>
```

4.65.6 Transmission:

transmission tag is used to model the relationship between a robot's joints and actuators (such as motors, servos, or other mechanical devices that provide motion). It defines how power or motion is transferred from an actuator to a joint in the robot's structure. The ¡transmission¿ tag usually works with ¡joint¿ and ¡actuator¿ tags to specify how an actuator controls the motion of the robot's joints:

```
<robot name="example_robot">

<!-- Define the joint -->
<joint name="joint_1" type="revolute">
  <parent link="base_link"/>
  <child link="link_1"/>
  <axis xyz="0 0 1"/>
  <limit effort="10.0" velocity="1.0" lower="-1.57" upper="1.57"/>
</joint>

<!-- Define the transmission -->
<transmission name="trans_1">
  <type>transmission_interface/SimpleTransmission</type>
  <joint name="joint_1"/>
  <actuator name="motor_1">
    <mechanicalReduction>100.0</mechanicalReduction>  <!-- Gear ratio
    ↪  -->
  </actuator>
</transmission>

<!-- Define the actuator (motor) -->
<gazebo>
  <plugin name="motor_1_plugin" filename="libgazebo_motor_plugin.so">
    <motor_type>electric</motor_type>
    <max_power>100.0</max_power>
  </plugin>
</gazebo>

</robot>

```

<joint>: The joint joint_1 connects the base_link to link_1 and allows rotational movement. It has limits on effort and velocity. <transmission>: The transmission trans_1 links joint_1 to the actuator (motor motor_1). It uses the SimpleTransmission type. <mechanicalReduction>: The actuator has a gear reduction of 100:1, meaning for every 100 rotations of the motor, the joint will rotate once. <actuator>: This specifies the motor (motor_1) that will control joint_1. <gazebo>: This block includes a Gazebo plugin (libgazebo_motor_plugin.so) to simulate the motor's behavior in a Gazebo simulation environment, with specific motor properties like motor_type and max_power.

in summery:

Dependencies for URDF Simulation in Gazebo

Step	Component	Effect if Missing
1	Links (`<link>`)	The robot has no physical structure, making it impossible to define shapes, visualize, or interact with physics.
2	Joints (`<joint>`)	The robot will be completely rigid. No movement or articulation between parts is possible.
3	Inertia (`<inertial>`)	Gazebo will generate warnings or unstable behavior because the physics engine relies on mass and inertia properties to simulate motion correctly.
4	Collision (`<collision>`)	The robot will pass through objects and not interact with the environment physically. It may also affect contact-based sensors.
5	Gazebo Plugin (`<plugin>`)	The robot cannot interact with Gazebo's physics, controllers, or sensors. Features like camera feeds, joint control, and custom physics will not work.
6	Gazebo Simulation	The robot cannot be tested in a realistic environment with physics, gravity, and other external forces. It remains a static model without dynamic behavior.
7	Transmission (`<transmission>`)	Motors will not work. Even if controllers are added, they will not be able to apply forces to move the joints.

Table 4.21: Essential Dependencies for Simulating a URDF in Gazebo

4.66 CREATING URDF MODEL

After learning about URDF and its important tags, we can start some basic modeling using URDF. The robot's URDF model comprises eight rigid links and seven joints, designed to balance geometric simplicity with functional accuracy. The central chassis (base_link), modeled as a rectangular prism, forms the structural foundation. Symmetrically attached to

this base are two cylindrical wheels (left_wheel, right_wheel), each connected via continuous rotation joints to enable differential steering. A vertical lifting mechanism, represented as a cylinder (lifting_mechanism), extends upward from the chassis through a prismatic joint, providing linear motion for height adjustment. Rigidly mounted atop this actuator is a box-shaped platform (platform), secured by a fixed joint to ensure stability. Three sensor units—two cameras (camera1, camera2) and a LiDAR (lidar)—are modeled as compact boxes and affixed to the platform through additional fixed joints, ensuring precise perceptual alignment. By prioritizing minimalistic shapes (cylinders for rotational elements, boxes for planar surfaces) and logical joint configurations (two continuous, one prismatic, and four fixed), the design achieves computational efficiency while retaining fidelity to the robot's core mechanical and sensing capabilities.

4.66.1 Understanding robot modeling using xacro

The flexibility of URDF reduces when we work with complex robot models. Some of the main features that URDF is missing include simplicity, reusability, modularity, and programmability. If someone wants to reuse a URDF block 10 times in their robot description, they can copy and paste the block 10 times. If there is an option to use this code block and make multiple copies with different settings, it will be very useful while creating the robot description. The URDF is a single file and we can't include other URDF files inside it. This reduces the modular nature of the code. All code should be in a single file, which reduces the code's simplicity. Also, if there is some programmability, such as adding variables, constants, mathematical expressions, and conditional statements in the description language, it will be more userfriendly. Robot modeling using xacro meets all of these conditions. Some of the main features of xacro are as follows:

- **Simplify URDF:** xacro is a cleaned-up version of URDF. It creates macros inside the robot description and reuses the macros. This can reduce the code length. Also, it can include macros from other files and make the code simpler, more readable, and more modular.
- **Programmability:** The xacro language supports a simple programming statement in its description. There are variables, constants, mathematical expressions, conditional statements, and more that make the description more intelligent and efficient.

Instead of .urdf, we need to use the .xacro extension for xacro files. Here is an explanation of the xacro code:

```
<?xml version="1.0"?>
<robot xmlns:xacro="http://www.ros.org/wiki/xacro" name="my_robot">
```

These lines specify a namespace that is needed in all xacro files to parse the xacro file. After specifying the namespace, we need to add the name of the xacro file. In the next section.

4.66.2 Using properties

Using xacro, we can declare constants or properties that are the named values inside the xacro file, which can be used anywhere in the code. The main purpose of these constant definitions is that instead of giving hardcoded values on links and joints, we can keep constants, and it will be easier to change these values rather than finding the hardcoded values and then replacing them. An example of using properties is given here. We declare the length and radius of the base link and the pan link. So, it will be easy to change the dimension here rather than changing the values in each one:

```
<!-- body value -->
<xacro:property name="base_length" value="0.9" />
<xacro:property name="base_width" value="0.85" />
<xacro:property name="base_hight" value="0.5" />

<!-- Wheel values -->
<xacro:property name="wheel_r" value="0.15" />
<xacro:property name="wheel_length" value="0.05" />

<!-- Lidar values  -->
<xacro:property name="lidar_r" value="0.1" />
<xacro:property name="lidar_l" value="0.05" />
```

We can use the value of the variable by replacing the hardcoded value with the following definition:

```
<link name="base_link">
  <visual>
    <geometry>
      <box size="${base_length} ${base_width} ${base_hight}"/>
    </geometry>
      <origin xyz="0.0 0.0 ${base_hight/2.0}" rpy="0.0 0.0 0.0"/>
```

```
        <material name="green"/>
    </visual>
```

Here, the value 0.9, is replaced with ”base_length”, and ”0.85” is replaced with ”base_width”.

4.66.3 Using the math expression

We can build mathematical expressions inside $ using basic operations such as +, -, *, /, unary minus, and parentheses. Exponentiation and modulus are not supported yet. The following is a simple math expression used inside the code:

```
  <link name="platform_link">
  <visual>
    <geometry>
      <box
       ↪  size="${base_length/1.5} ${base_width/1.5} ${base_hight/8}"/>
    </geometry>
      <origin xyz="0.0 0.0 0" rpy="0.0 0.0 0.0"/>
      <material name="green"/>
  </visual>
```

4.66.4 Using macros

One of the main features of xacro is that it supports macros. We can use xacro to reduce the length of complex definitions. Here is a xacro definition we used in our code to specify inertial values:

```
  <xacro:macro name="box_inertia" params="m l w h xyz rpy">
  <inertial>
     <origin xyz="${xyz}" rpy="${rpy}"/>
     <mass value="${m}"/>
     <inertia ixx="${ (m/12)*(h*h + l*l) }" ixy="0.0" ixz="0.0"
      ↪  iyy="${(m/12)*(w*w + l*l)}" iyz="0.0"
      ↪  izz="${(m/12) * (w*w + h*h)}"/>
  </inertial>
 </xacro:macro>
```

Here, the macro is named box_inertia, and its parameters are {m ,l ,w ,h ,xyz ,rpy}. we can pass these parameters as a vaues or as a xacro property:

```
<xacro:box_inertia m="5.0" l="${2*base_length}" w="${2*base_width}"
 ↪  h="${2*base_hight}" xyz="0.0 0.0 ${base_hight/2.0}"
 ↪  rpy="0.0 0.0 0.0"/>
```

4.66.5 Including other xacro files

We can extend the capabilities of the robot xacro by including the xacro definition of sensors using the xacro:include tag. The following code snippet shows how to include a sensor definition in the robot xacro:

```
<xacro:include filename="$(find ros_robot_pkg)/urdf/definition.xacro"/>
```

Here, we include a xacro file to call the definitions and the constants.

4.67 VISUALIZING THE 3D ROBOT MODEL IN RVIZ

After designing the URDF, we can view it on RViz. We can create a launch file and put the following code into the launch folder:

```
<launch>
<param name="robot_description" command=
 ↪  "$(find xacro)/xacro $(find the_pkg_name)/.../my_robot.urdf.xacro"
 ↪  />
<node name="robot_state_publisher" pkg="robot_state_publisher"
 ↪  type="robot_state_publisher" />
<node name="rviz" pkg="rviz" type="rviz"
 ↪  args="-d $(find the_pkg_name)/rviz/config.rviz" />
<node name="joint_state_publisher" pkg="joint_state_publisher"
type="joint_state_publisher"/>
<node name="joint_state_publisher_gui" pkg="joint_state_publisher_gui"
 ↪  type="joint_state_publisher_gui"/>
<!--  Controller Manager  -->
  <node name="controller_spawner" pkg="controller_manager"
   ↪  type="spawner" respawn="false" output="screen"
        args="diff_drive_controller" />
</launch>
```

The <launch> tag is the root tag that defines the entire launch file. All the nodes and parameters that need to be launched are specified within this tag.

The <param> tag sets the robot_description parameter, which specifies the URDF or XACRO file that contains the robot's description. In this case, the command attribute runs the xacro tool to process the my_robot.urdf.xacro file located in the package specified by the_pkg_name.

The <node> tag launches the robot_state_publisher node. This node reads the robot's description and publishes the state of the robot (e.g., joint positions, transformations) to ROS topics. It uses the robot_description parameter that was set earlier.

The next <node> tag launches RViz, the visualization tool used to display the robot in a 3D environment. The args attribute specifies a pre-configured RViz setup file (config.rviz) located in the package the_pkg_name. This setup is used for visualizing the robot model and its movements.

The subsequent <node> tags launch two joint state publisher nodes.
The joint_state_publisher node publishes the joint states (such as the positions of robot joints) to ROS topics. The joint_state_publisher_gui node includes a graphical user interface (GUI) that allows users to interactively control the joint states of the robot.

Finally, the <node> tag for the controller_spawner node is responsible for spawning and managing robot controllers. The node is part of the controller_manager package, and the spawner executable is used to spawn a controller, in this case, diff_drive_controller. The respawn attribute is set to false, so the node will not automatically respawn if it crashes. The output attribute ensures that the output from the node is printed to the screen.

We can launch the model using the following command:

```
1        roslaunch the_pkg_name launch_file_name.launch
```

If everything works correctly, we will get a pan-and-tilt mechanism in RViz, as shown here:

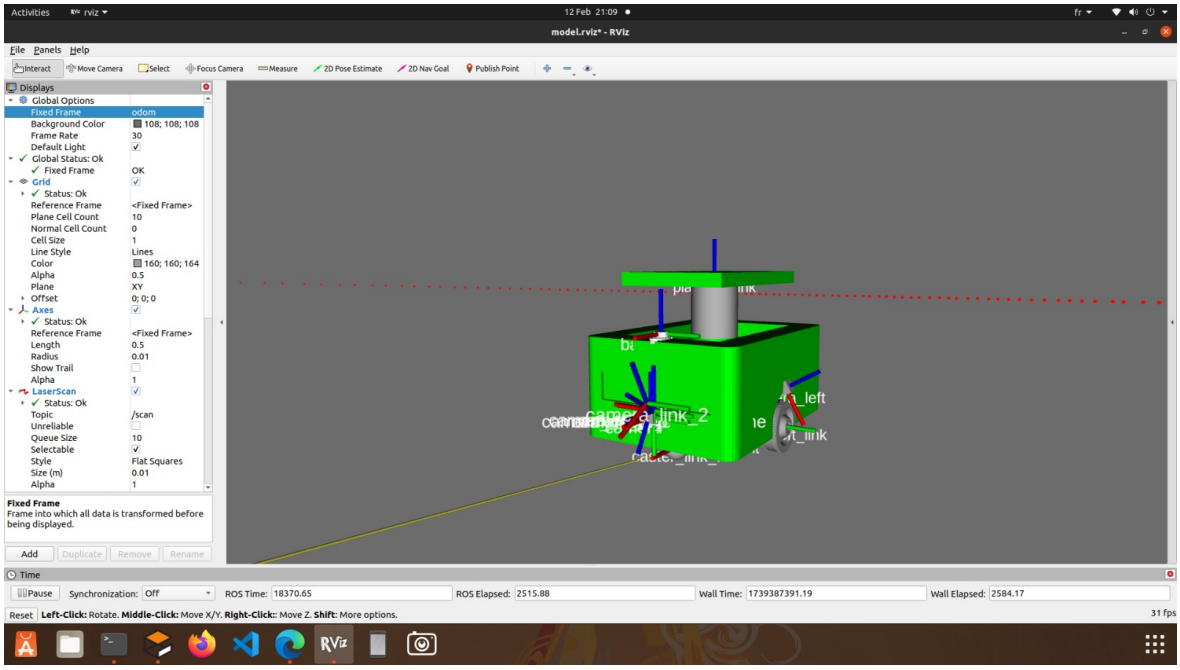


Figure 4.80: A visualization of a robot model with Rviz

4.67.1 Interacting with joints in Rviz

In the previous version of ROS, the GUI of `joint_state_publisher` was enabled thanks to a ROS parameter called `use_gui`. To start the GUI in the launch file, this parameter had to be set to true before starting the `joint_state_publisher` node. In the current version of ROS, launch files should be updated to launch `joint_state_ publisher_gui` instead of using `joint_state_publisher` with the `use_gui` parameter.

We can see that an extra GUI came along with RViz; it contains sliders to control the Whell joints and the lifting platform joint. This GUI is called the Joint State Publisher Gui node and belongs to the `joint_state_publisher_gui` package:

```
1 <node name="joint_state_publisher_gui" pkg="joint_state_
2 publisher_gui" type="joint_state_publisher_gui" />
```

We can include this node in the launch file using the following statement. The limits of pan-and-tilt should be mentioned inside the joint tag:

```
<joint name="platform_lift_joint" type="prismatic">
    <origin xyz="0.0 0.0 ${base_hight / 2}" rpy="0.0 0.0 0.0"/>
    <parent link="base_link"/>
    <child link="platform_lift_link"/>
    <axis xyz="0 0 1"/> <!-- Movement along the Z-axis -->
    <!-- Motion range and limits -->
     <limit lower="0.0" upper="${base_hight/2}" effort="50"
      ↪  velocity="1.0"/>
</joint>
```

The ¡limit¿ tag defines the limits of effort, velocity, and angle. In this scenario, effort is the maximum force supported by this joint, expressed in Newton; lower and upper indicate the lower and upper limits of the joint, in radians for the revolute joint and in meters for the prismatic joints. velocity is the maximum joint velocity expressed in m/s. The following screenshot shows the user interface that is used to interact with the robot joints: In this user

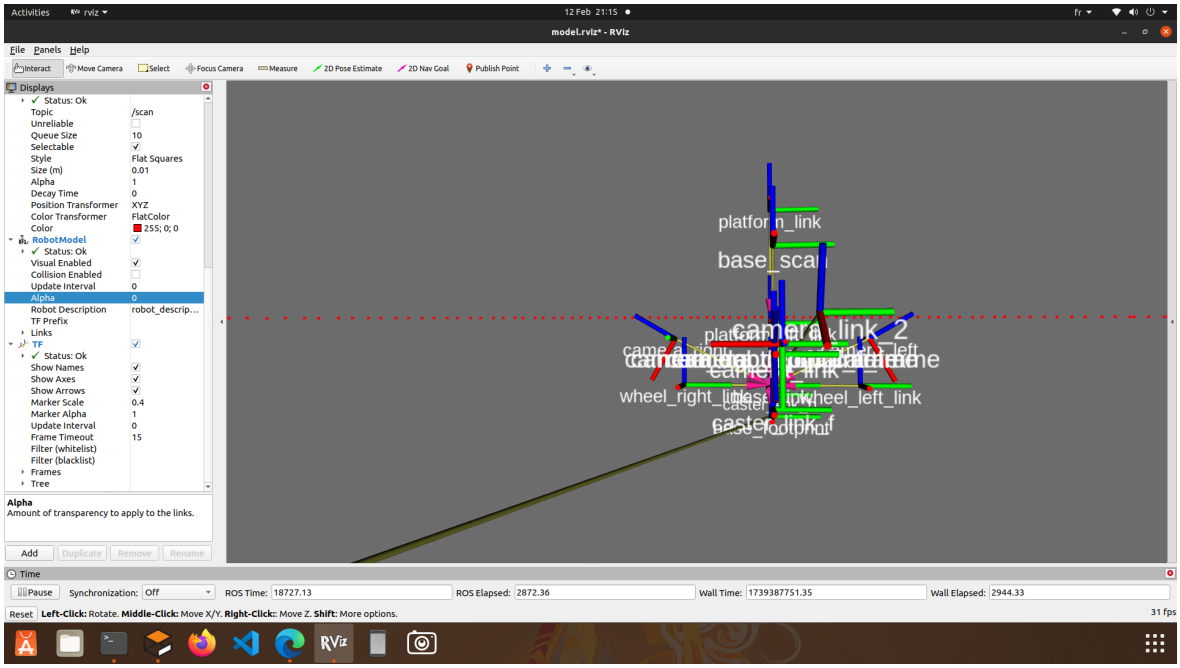


Figure 4.81: The joint level of the platform lifting mechanism

interface, we can use the sliders to set the desired joint values. The basic elements of a urdf file have been discussed. In the next section, we will add additional physical elements to our robot model.

4.68 NAVIGATION

Autonomous navigation is a rapidly growing field and has become a pivotal area of research and application in robotics, with numerous applications in industries such as transportation, manufacturing, and warehousing. One of the fundamental tasks for autonomous robots is the ability to navigate their environment independently with minimal human intervention, that is a crucial factor or a key milestone for the development of intelligent systems capable of interacting with the real world. Among the various techniques used for autonomous navigation, line following remains one of the most essential and widely researched methods, especially for mobile robots, where the robot must track a specific line on the ground. While it may appear straightforward, line following involves a variety of challenges, including sensor calibration, precise control of the robot's motors, and handling of unpredictable environmental factors.For this project the primary objective was eventually designing and developing a simulated robot capable of accomplishing a specific task while following a line and avoiding obstacles and maintain accurate control over its movements within a simulated environment using the **Robot Operating System (ROS)**, which is widely used in both research and industry due to its flexibility, modularity, and wide range of libraries and tools. ROS provides a powerful framework for developing and simulating robotic applications.

METHODS USED TO DESIGN:

It is necessary outline the methodology used to design the robot, its navigation system, and the simulation environment. The method should cover both the hardware (even though it's simulated) and software design, as well as the control algorithms used to ensure the robot follows the line autonomously.

The design of the autonomous line-following robot involved a series of methodical steps to ensure the successful integration of hardware (simulated), software (ROS-based), and control algorithms to enable autonomous navigation. The following sections describe the approach taken to design and implement the robot and its navigation system in the simulation environment.

4.69 FOR LINE DETECTION AND FOLLOWING:

4.69.1 Camera-based Vision Method:

Using **cameras** for line-following is an advanced approach in robotics, where the robot uses visual information to detect and track a line or path. This technique, often referred to as

vision-based line following, involves utilizing computer vision algorithms to process images captured by the robot's camera and determine the robot's position relative to the line. To use a camera for line-following, the camera is needed to be mounted on the robot, typically facing downward or slightly tilted to capture the surface on which the line is drawn which is the case with the robot used for this project.

This process was accomplished through many steps via simulation such :

SETTING UP THE SIMULATION ENVIRONMENT

The simulation platform was set as with the following components:

- **Robot Model**: The robot in the simulation should have a camera mounted on it. The robot model could be a differential-drive robot, a mobile platform with wheels, or a more complex robot with additional sensors. **The robot model used is a differential-drive mobile robot.**
- **Camera Sensor**: Simulated cameras in the environment will capture images of the ground, where the line is located. The camera was set up to view downward, directly in front of the robot.
- **Line (Path)**: lines on the ground can be created in the simulation. The line can be straight, curved, or even follow a more complex path. For this project black lines were drawn within the world created in Gazebo.
- **Simulator**: The simulation platform used is:

  Gazebo: Commonly used with **ROS** (Robot Operating System) for robot control and visualization.

IMAGE PROCESSING FOR LINE DETECTION

After setting up the simulated robot and camera, the robot will need to process the images captured by the camera to detect the line. The core part of this system involves **image processing** and **vision algorithms**.

- **Steps for Image Processing:**
- **Capture Image from the Camera**:

  In the simulation, it is necessary to get access to the camera feed in real-time. With **ROS**, there can be subscriber to the camera's image topic such **/camera/rgb/image_raw**

- **Convert the Image to Grayscale**:

  grayscale conversion can be used to reduce the complexity of the image. Since the line will typically have a contrasting colour (black or white), working with a grayscale image makes it easier to detect the line.

- **Thresholding** will convert the grayscale image into a binary image where the line is white (or black) and the background is the opposite colour. You can use a simple threshold or adaptive thresholding for better results in varying lighting conditions.

- **Detect the Line**:

  Once the image is binary, **edge detection**, **contour detection**, or **Hough Transform** can be used cto detect the line. For instance, you can use **Hough Line Transform** to detect straight lines. For the project they were combined and used together for line detection.

- **Determine the Robot's Position Relative to the Line**:

  The centroid of a detected line is calculated t hoo measure or estimate w far the robot is from the centre of the line in the camera frame.

4.69.2 1.2 Control Algorithm for Line Following

Once the line is detected, the robot needs to be controlled to follow it. The basic principle is to adjust the robot's steering based on its position relative to the line. PID Controller algorithm can be used to keep the robot following line in a steady way.

The **PID (Proportional-Integral-Derivative)** controller is commonly used in line-following robots.

- **Proportional**: The steering correction is proportional to how far the robot is from the line's centre.

- **Integral**: This helps eliminate accumulated errors over time.

- **Derivative**: This predicts and reacts to the rate of change in the error (speed of deviation).

4.69.3 1.3 Integrating the Line Following with the Simulator

Finally, the image processing and control algorithms needed to be integrated into the simulation environment. With ROS this integration is usually made through Gazebo. When **ROS** is used the robot cab ne set up with a simulated camera and subscribe to the camera feed. ROS provides libraries like CV BRIDGE to convert the ROS image messages into

4.70 FOR BUILDING MAP

4.70.1 LIDAR

The map was built using SLAM (Simultaneous Localization and Mapping) in a simulation thanks to the lidar sensor. Using LIDAR (Light Detection and Ranging) with SLAM (Simultaneous Localization and Mapping) is a common and effective approach for building a map of an environment while simultaneously localizing the robot within that environment. In ROS, LIDAR is often used as the primary sensor for SLAM, especially for 2D SLAM algorithms like GMapping and Hector SLAM. The algorithm used for SLAM was GMapping in this project.The lidar can be used to avoid obstacles as well.

4.70.2 QR Code Scanning

QR Code Detection with OpenCV was used, the OpenCV's QRCodeDetector detects and decode QR codes in the robot's camera feed. The QR code are used to help the robot to navigate autonomously, the QR code information to know its current position and calculate the closest path to the destination.

After building the map , it will be saved for autonomous navigation purpose.

4.71 REALISTIC CONSTRAINTS

4.72 COMPUTATIONAL-POWER-AND-RESOURCES

4.72.1 cpu-and-gpu-limitations

- CPU Limitations: Simulations, especially those involving complex algorithms like SLAM or sensor fusion, can be CPU-intensive. The computational demand increases with the complexity of the robot's tasks, such as real-time mapping, localization, or decision-making. A limited CPU performance could cause delays, lag, or even make real-time processing difficult.

- GPU Constraints: If you're using computer vision algorithms (e.g., QR code recognition, camera-based line-following), a GPU can greatly accelerate image processing. However, not all simulations leverage GPU power, and if the GPU is not sufficient or not utilized properly, the simulation could run slower or experience bottlenecks.

4.72.2 memory-ram-constraints

- High Memory Usage: Simulations that involve large environments, dense sensor data

(such as LIDAR point clouds), or high-resolution images can require a significant amount of RAM. If the memory usage exceeds the available capacity, it can lead to slow performance, crashes, or even the inability to run the simulation at all.

- Data Storage for Sensor Data: Storing large amounts of sensor data (e.g., from LIDAR, cameras, IMUs) generated during a simulation can strain the system's storage, especially if you need to log or save sensor outputs for later analysis. In a large-scale simulation, this could be a limiting factor.

4.72.3 real-time-performance

- Real-Time Simulation Constraints: Achieving real-time performance in simulations can be difficult, especially when dealing with complex tasks such as real-time SLAM or path planning. The simulation might not run at the required frame rate (e.g., 30Hz or higher), leading to delays in robot control and decision-making.

- Simulation Time vs Real Time: If the simulation is not running at real-time speed (1:1 with physical time), it can make it harder to validate time-sensitive behaviors. For example, a robot using SLAM may not update its map fast enough in a simulation that runs too slowly, affecting navigation and decision-making in real-world applications.

4.73 COMPLEXITY-OF-THE-SIMULATED-ENVIRONMENT

4.73.1 size-and-detail-of-the-simulation

- Environmental Complexity: Large and complex simulated environments with many dynamic obstacles, detailed textures, and various types of surfaces can be computationally expensive. More detailed environments require more processing power to render, simulate physics, and handle sensor data.

- Realistic Physics: Physics engines in simulations (e.g., Gazebo, V-REP) simulate the interactions between the robot and the environment, including forces like friction, gravity, and object collisions. While necessary for realistic testing, these physics simulations can be computationally demanding, especially in dynamic environments with many objects.

4.73.2 dynamic-objects-and-movements

- Real-Time Object Simulation: When simulating environments with moving objects (e.g., pedestrians or vehicles), the computation required to simulate their motion and

interactions with the robot can add significant overhead. This becomes particularly challenging if multiple objects are moving in complex patterns at the same time.

4.74 SIMULATING-SENSOR-DATA

4.74.1 a.-sensor-data-processing-load

- LIDAR and Point Cloud Data: LIDAR sensors generate large amounts of data, especially in 3D environments. Processing the point cloud data in real time requires significant computing resources, particularly when applying algorithms like SLAM to build and update maps. The more data points and the larger the map, the more processing power is required.

- Camera Data for Visual Processing: Cameras generate high-resolution images that need to be processed for tasks like QR code detection or line-following. Processing these images (especially with advanced computer vision techniques such as feature detection or deep learning) can be computationally expensive. Depending on the image resolution and the complexity of the detection algorithms, this could put a strain on the available computing resources.

4.74.2 real-time-sensor-fusion

- Combining Data from Multiple Sensors: If you are fusing data from multiple sensors (e.g., combining LIDAR, IMU, camera data for SLAM), the computational load increases significantly. Sensor fusion algorithms, such as Kalman Filters or particle filters, need to process data from all sensors in real time, which may not be feasible with limited computational resources.

4.75 ALGORITHMIC-CONSTRAINTS

4.75.1 a.-computational-cost-of-slam

- SLAM Algorithm Complexity: Algorithms used for SLAM (like Extended Kalman Filters, GraphSLAM, or particle filters) are computationally expensive, especially when the robot has to map a large area in real-time. As the environment grows, the number of calculations needed to maintain and update the map increases, potentially leading to slower performance or the need for more powerful hardware.

- Map Size and Resolution: The higher the resolution and accuracy of the map, the more computational resources are required to store and update it. Large maps with high-

detail features demand significant memory and processing power to handle updates, store the data, and process localization.

4.75.2 b.-path-planning-and-decision-making

- Complex Path Planning Algorithms: Path planning algorithms, such as A*, RRT, or D* algorithms, may require substantial computational resources depending on the complexity of the environment. If your robot is navigating a large or cluttered environment, calculating collision-free paths in real-time becomes a challenge, especially if there are many dynamic obstacles to avoid.

- Decision-Making Algorithms: When the robot makes decisions based on sensor input, running machine learning algorithms or decision trees to determine the next action (e.g., go towards a QR code or follow a line) can also be computationally expensive. Depending on the complexity of the logic, this could limit the speed and responsiveness of the simulation.

4.76 SIMULATION-SOFTWARE-LIMITATIONS

4.76.1 simulation-engine-efficiency

- Performance of the Simulation Engine: Different simulation platforms (Gazebo, V-REP, Webots, etc.) have varying levels of efficiency. Some simulators might be highly optimized for certain types of robots or algorithms, while others may be slower or require more resources to simulate complex systems. Choosing the right simulation platform for your application is critical for balancing performance and accuracy.

- Plugin Overhead: Many simulators rely on plugins for additional functionality (e.g., camera sensors, LIDAR). The more plugins you add or the more complex the plugin behavior, the more computational overhead is introduced. This can affect simulation performance, especially in large-scale environments or real-time applications.

4.76.2 parallelization-and-multithreading

- Limited Parallel Processinh: Not all simulation environments or algorithms are well-optimized for parallel processing, which means that tasks may not fully utilize multi-core CPUs or GPUs. For example, in simulations involving real-time SLAM, the ability to parallelize sensor data processing or SLAM computation can significantly reduce the computational load, but not all algorithms or environments support this effectively.

- Threading Issues: Running multiple processes (e.g., sensor readings, actuator control, SLAM) in parallel in a simulation may introduce issues such as deadlock or race conditions if not properly managed. This can lead to slower simulation times or unresponsive behavior in your robot model.

4.77 SIMULATING-REAL-TIME-CONSTRAINTS

4.77.1 real-time-control-vs.-simulation-speed

- Synchronization Issues: Achieving true real-time performance is difficult in a simulation. Many simulations allow you to adjust the time scale (e.g., running the simulation faster than real time for testing), but this introduces the issue that the control algorithms might not have the same timing constraints they would in a real robot. Ensuring that the simulation runs with a fixed time step, synchronized with the robot's control loops, is essential but can be computationally demanding.

- Hardware-in-the-loop (HIL) Simulation: When integrating real hardware with a simulator (e.g., for testing SLAM on real sensors), the latency and real-time computation required can cause performance bottlenecks. This is especially true if communication between the simulation and physical robot hardware is slow or not synchronized properly.

The design of our industrial robot involved a structured approach that included problem formulation, engineering problem-solving, and the application of appropriate analysis and modelling methods. our primary role in the project focused on the programming tasks, ensuring the implementation of the robot's control system, QR code recognition, navigation algorithms, and communication between ROS and the web interface.

4.78 PROBLEM FORMULATION

The key engineering challenges we addressed through programming were:

1. Navigation System with junction detection**:** Implementing a control algorithm to follow a black line and detect a junction.
2. Load and Unload Identification**:** Developing a QR code recognition system.
3. Communication Between ROS and Web Interface**:** Ensuring seamless data transfer between the robot's ROS-based system and a web-based user interface.

4.79 ENGINEERING PROBLEM-SOLVING

4.79.1 Navigation System (Line Following and junction detection Algorithm)

The robot needed to detect and follow a black line accurately. To achieve this, I explored two potential solutions:

- Computer Vision Approach**:** Using OpenCV to process camera input and detect the black line.
- Sensor-Based Approach**:** Using simulated infrared sensors in ROS.

We opted for the computer vision approach due to its flexibility in real-world applications. I implemented an algorithm using OpenCV in Python, which:

- Captured images from the robot's camera.
- Applied image processing techniques (grayscale conversion, thresholding, edge detection).
- Used contour detection to track the black line and adjust the robot's movement accordingly.

4.79.2 Load and Unload Point Detection (QR Code Scanning)

To recognize loading and unloading points, I implemented a QR code detection system using QReader library for detecting and decoding QR codes.

The system was designed to extract location data from QR codes and send it to the navigation system to adjust the robot's path.

4.79.3 Communication Between ROS and Web Interface

Since ROS does not natively communicate with web technologies, I implemented a real-time communication system using a WebSockets (Socket.IO) to enable bidirectional data transfer and ROSBridge to translate ROS messages into JSON format for the web interface.

This setup allowed users to monitor the robot's status and send commands through a web-based interface built with React.js.

4.79.4 Application of Theoretical and Applied Knowledge

The work applied key theoretical and practical knowledge across multiple domains. Computer vision and image processing techniques were utilized for line detection and QR code recognition, ensuring accurate navigation and object identification. Robotics and control algorithms were implemented to facilitate smooth and efficient movement. Networking and web communication played a crucial role in establishing real-time data transfer between ROS and the web interface, enabling seamless interaction. Additionally, software engineering best practices were followed to structure ROS nodes effectively, optimize system performance, and debug potential issues, ensuring a well-organized and robust implementation.

Through this structured approach, I successfully developed the necessary programming solutions for the industrial robot, ensuring accurate navigation, QR code recognition, and seamless communication between the robot and the web interface.

4.80 USER INTERFACE

The UI is structured into modular React components, each dedicated to displaying specific robot-related information. These components dynamically consume state from the Zustand core, ensuring real-time synchronization between the ROS updates and UI rendering. This modular approach enhances maintainability and flexibility, allowing for seamless updates to the user interface as data changes, while also ensuring the UI remains responsive and in sync with the backend processes.

The system enables real-time robot movement control with built-in process validation, ensuring smooth operation during task execution. It supports live camera and QR code feed display, providing real-time visual feedback. Dynamic map updates are implemented based on the robot's movement and scanned locations, offering continuous situational awareness. Task execution and monitoring are integrated, including cargo loading and unloading, with clear updates on progress. Interactive gear control is featured, with process-state validation to prevent gear changes during active tasks, ensuring safe and efficient operation throughout the system.

4.80.1 Design Hierarchy

The application follows a structured GUI hierarchy where the App component serves as the central entry point, interacting with a Core Store for managing state. Within the App, the MainLayout organizes key sections, including a NavBar, a Task section, and a Remote module. The Remote module further breaks down into essential components such as Camera, Map, RemoteButton, and Gear & Speed, suggesting it handles functionalities related to remote control and navigation. This modular design ensures a clear separation of concerns, making the application easier to maintain and extend. The overall structure is visually represented in fig. 4.82 below.

4.80.2 Output

The graphical user interface of the robot, segmented into several functional areas for ease of operation:

1. Menu: On the left side, we have a straightforward menu with two options: ”Remote Control” and ”Task.” This menu allows users to navigate between different functionalities of the system easily (see fig. 4.83).

2. Remote Control Tab: This section is the heart of the interface and is further divided into three parts (see fig. 4.84):

    - Main Camera View: Dominating the top centre is a large grey box labelled ”Main Camera.” This is likely where the live feed from the camera appears, giving users a visual of the controlled environment.
    - Control Panel: Located below the camera view, this panel includes directional buttons (up, down, left, right) and a central button labelled ”S” for emergency stop There's also a toggle switch marked ”A” and ”M” and a speed indicator displaying ”0.00 m/s.” These controls are probably used to manoeuvre the remote vehicle or robot.

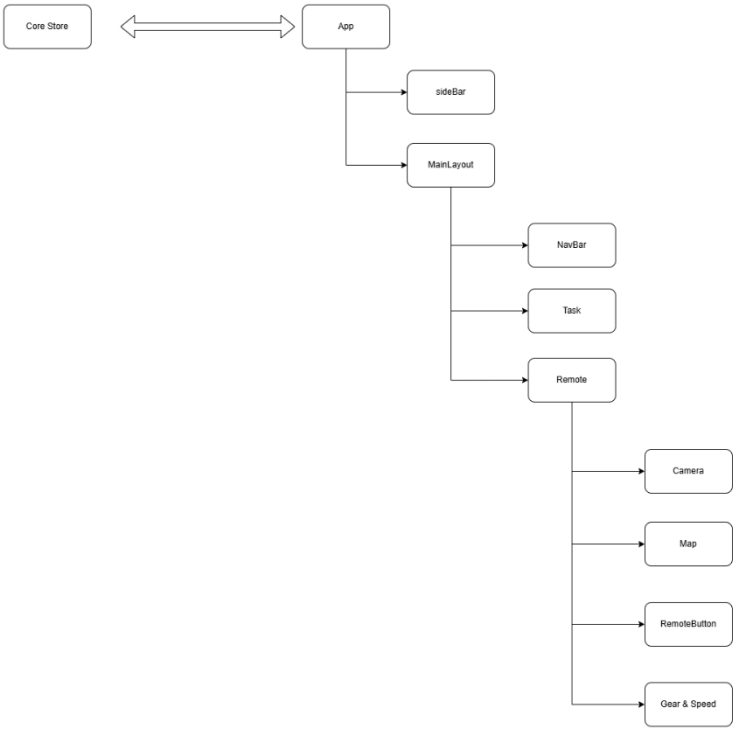


Figure 4.82: GUI hierarchy

- Map: On the right side, we see a white area with a grid of blue squares, a red and green marker, likely indicating the position of the robot or points of interest. There are two additional buttons at the bottom, a blue one with a ”+” sign and a red one with a ”-” sign, possibly for zooming in and out.

3. Task Tab: designed to manage tasks and monitor activities. The interface is divided into distinct sections for better functionality (fig. 4.85):

   - Mapping Button: This button is used to send the mapping task to the robot.
   - Task Display: Under the ”Mapping” section, there's a white text box labelled ”Task display,” which displays tasks and other relevant information.
   - Main Display Area: The majority of the screen is occupied by a large dark area that serves as the main display or workspace for the system's operations.
   - Send Task Button: At the bottom of the screen, this button allows users to send tasks to the robot.

This interface offers a clear, user-friendly design for effectively managing the robot.

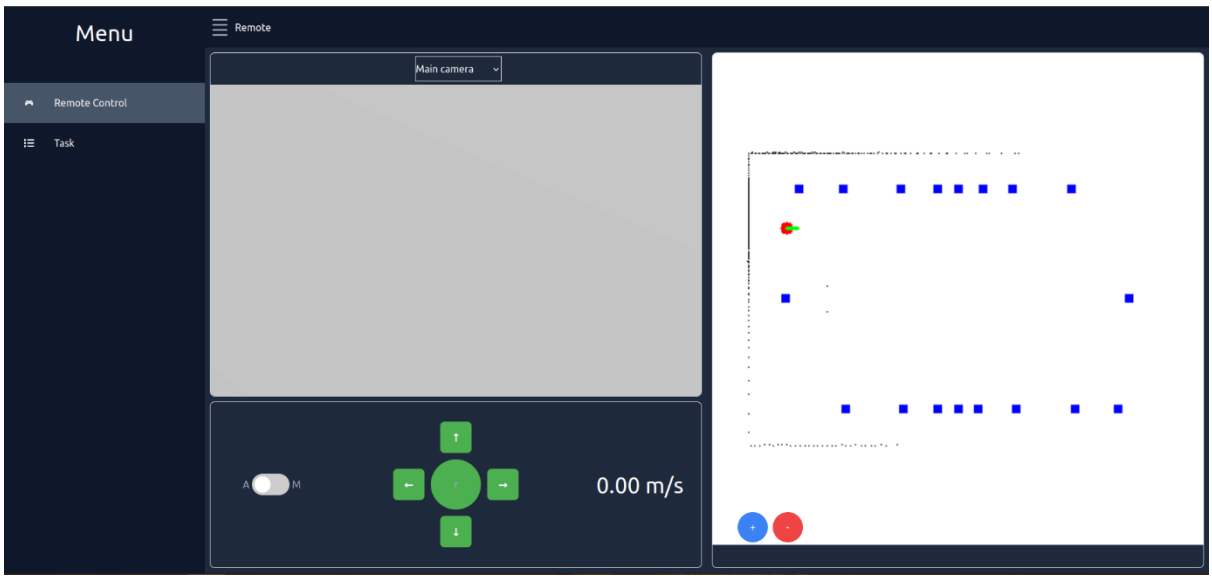


Figure 4.83: Opened menu & remote control Tab

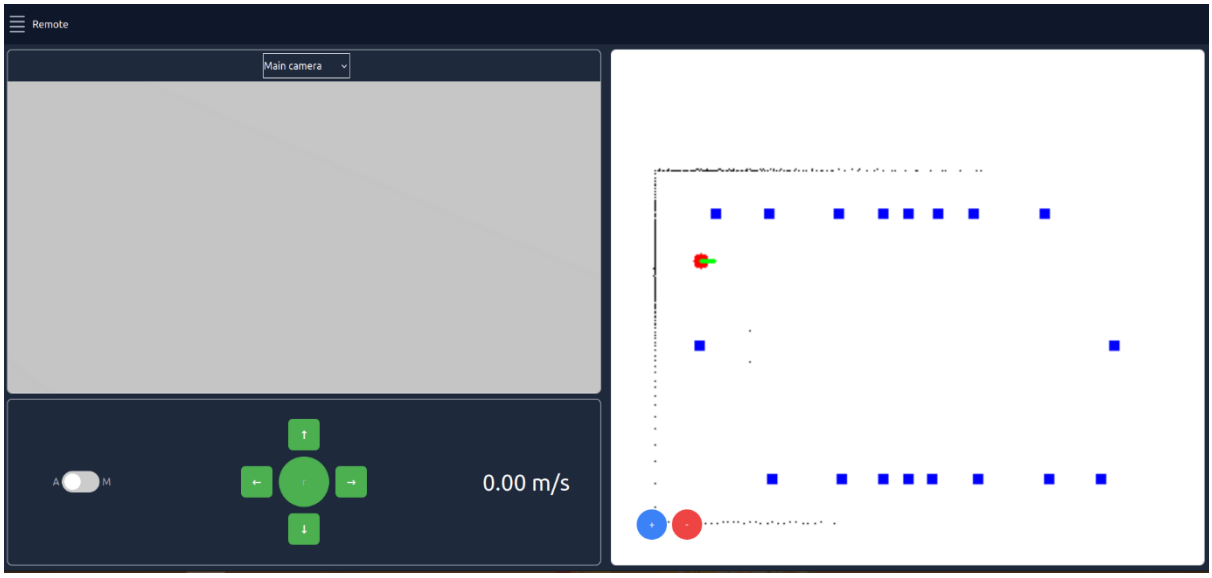


Figure 4.84: Remote control tab

Figure 4.85: Task Tab before mapping

4.80.3 Codes and background implementation

4.80.3.1 Core Store Implementation – The Most Important Element

a centralized state management system using Zustand to handle application state, WebSocket communication, and real-time data updates.

Key Responsibilities and Implementation Details:

State management was handled using Zustand by creating a global store (core, see fig. 4.82) to manage the application's state efficiently. This included tracking the connection status through connectedSocket and connectedRos, as well as managing the UI state with menu and menuOpened. Real-time data, such as cameraData, camera_qr_data, mapData, speed, gear, zone, and station, was also stored to ensure seamless updates. Additionally, the application's process state was maintained using processState. To facilitate state updates, setter functions like setmenu and setmenuOpened were implemented, allowing for specific property modifications. WebSocket integration was implemented using Socket.IO to enable real-time communication between the frontend and backend. The initializeSocket function was developed to establish a connection with the WebSocket server at `http://localhost:5000` (see fig. 4.83). It managed connection and disconnection events, ensuring the connectedSocket state was updated accordingly. Additionally, it listened for real-time data streams, including camera_feed, camera_qr_feed, map_feed, speed, gear_state, task_response, mapping_output, and processState, allowing for seamless data exchange and synchronization across the application.

Real-time data handling was implemented to ensure seamless updates and synchronization across the application. Camera feeds were processed and stored as base64-encoded

```
export const core = create((set,get) =>
({ connectedSocket : false,
    connectedRos : false,
    menu : "Remote",
    menuOpened : false,
    socket : null,
    cameraData : null,
    camera_qr_data : null,
    speed : 0,
    mapData : null,
    gear : 0,
    zone : null,
    station : null,}))

```

Figure 4.86: All states of core element with their default value

```
  const socket = io('http://localhost:5000');
  set({ socket });
```

Figure 4.87: socket connection

images in the state variables cameraData and camera_qr_data, enabling real-time visualization. The mapData state was continuously updated with real-time map images received from the backend. Additionally, the robot's speed and gear state were tracked through WebSocket events, updating the speed and gear properties accordingly. Task responses from the backend were displayed using react-hot-toast, providing instant user feedback and enhancing the overall user experience.

he frontend and backend. The sendTask function was implemented to transmit task sequences, such as loading and unloading, to the backend via WebSocket. Task data, including task_name and params, was structured and emitted through the robot_task event. For mapping, the mapping function was triggered to initiate the process by emitting a robot_task event with the necessary task data. Additionally, the mapping_output event was processed to serialize and store zone and station data in the state variables zone and station, ensuring efficient real-time updates.

Serialization of mapping data was handled through the serialize function (see fig. 4.85), which processed raw location data received from the backend. This function filtered and

```
camera_feed : async function(data){
        set({cameraData : data.image})
    },
    camera_qr_feed : async function(data){
        set({camera_qr_data : data.image})
    },
    map_feed : async function(data){
        set({mapData : data.image})
    },
```

Figure 4.88: socket connection

organized intersection and station data into structured formats, ensuring clarity and usability. The processed data was then stored in the state variables zone and station, enabling seamless integration with the UI for real-time visualization and interaction.

```
serialize : async function(locations){
      let lcs = [], st = []
      locations.forEach(location => {
        let nm = location.location.split("_")
        if(nm[0] == "intersection"){
          if (nm[2] == "x" || nm[2] == "y"){
          }else{
            let found = false
            for(let i = 0; i < lcs.length; i++){
              if (lcs[i].location == nm[1] + " " + nm[2]){
                found = true
              }
            }
            if (!found){
              lcs.push({
                location : nm[1] + " " + nm[2],
                x : location.x, y : location.y,
              })
            }
          }
        }else if (nm[0] == "station"){
          let found = false
            for(let i = 0; i < st.length; i++){
              if (st[i].location == nm[0] + " " + nm[1]){
                found = true
              }
            }
            if (!found){
              st.push({location : nm[0] + " " + nm[1],
              x : location.x, y : location.y,
            })
          }
        }
      });
      set({zone : lcs})
      set({station : st})
    },
```

Gear control was managed through the changeGear function, allowing the robot's gear state to toggle between automatic and manual modes. To ensure safe operation, gear changes were restricted while an active process was running (processState === "Processing"). Additionally, react-hot-toast was used to provide user feedback, notifying users when gear changes were blocked due to ongoing tasks.

Direction control was handled through the sendDirection function, which transmitted movement commands such as UP, DOWN, LEFT, and RIGHT to the backend via WebSocket. To maintain system integrity, movement commands were restricted during active processes (processState === "Processing"), preventing conflicts with ongoing tasks. User feedback was provided to ensure clarity when movement commands were blocked.

The outcome was the successful delivery of a scalable and efficient state management system that seamlessly integrates with WebSocket communication. This integration enabled real-time updates for critical data, including camera feeds, map data, speed, and gear state, significantly enhancing the application's interactivity and responsiveness. Additionally, the system provided a robust foundation for task management, mapping, and robot control, ensuring a smooth and intuitive user experience while maintaining high performance and reliability.

4.80.3.2 App Component

the root App component serves as the entry point for the application.

The application was enhanced with several key integrations to improve functionality and user experience. React Router (BrowserRouter) was integrated to enable client-side routing, allowing for seamless navigation between pages. Conditional rendering logic was added to display a loading spinner (Loader component) while waiting for the socket connection to be established, ensuring users are informed during the connection process. The layout was structured using flexbox for a responsive design, dividing the interface into a SideBar and MainLayout component for better organization. Additionally, React Hot Toast (Toaster) was integrated to provide user notifications and feedback, enhancing interactivity and responsiveness throughout the application.

The outcome:

The creation of a scalable and modular application structure, designed to support real-time communication capabilities seamlessly. By implementing loading states and real-time notifications, the application ensures a smooth user experience, keeping users informed and engaged during the connection process and throughout their interactions with the system. This structure not only enhances performance but also improves the overall user interface, making it responsive and intuitive. See fig. 4.89 for implementation.

```
function App() {
  const {initializeSocket, connectedSocket, connectedRos}= core()
  useEffect(function(){
    initializeSocket()
  },[initializeSocket])

  if(!(connectedSocket  )){
    return <Loarder/>
  }

  return (
    <BrowserRouter>
    <div className="flex flex-row w-full h-full">
        <SideBar />
        <MainLayout />
    </div>
    <Toaster></Toaster>
    </BrowserRouter>
  );
}

export default App;

```

Figure 4.89: App Component

4.80.3.3 MainLayout Component

This component manages the main content area and routing logic. See fig. 4.90 for implementation.

Key Responsibilities:

The application was structured with React Router using Routes and Route to define navigation paths. A default route (/) was set to render the Remote component, while additional routes were configured for the /remote path to display the Remote component and the /task path for the Task component. Conditional rendering was implemented to display a loading spinner (Loader component) when the socket connection is not yet established, ensuring a smooth user experience during the initial connection phase. The layout was designed to be responsive using CSS, allowing the content area to adjust dynamically based on the viewport size. Additionally, a NavBar component was integrated at the top of the layout to provide

```
const MainLayout = () => {
    const { connectedSocket, menuOpened } = core();
    return (
    <div className="w-full h-full overflow-hidden">
        <NavBar />
        <div className="w-full h-[calc(100%-64px)]">
        <Routes>
            <Route path="/" element={connectedSocket ? <Remote /> :
            ↪ <Loader />} />
            <Route
            path="/remote"
            element={connectedSocket ? <Remote /> : <Loader />}
            />
            <Route path="/task" element={connectedSocket ? <Task /> :
            ↪ <Loader />} />
        </Routes>
        </div>
    </div>
    );
};
export default MainLayout;
```

Figure 4.90: MainLayout Component

consistent navigation across the application, enhancing usability and accessibility.

Outcome:

Was the creation of a centralized and reusable layout structure for the application, promoting maintainability and scalability. By implementing proper loading states and routing, seamless navigation was ensured, allowing users to transition between different sections smoothly. This structure enhanced the overall user experience, providing consistent and responsive design elements across the application, while also ensuring that users are kept informed during the socket connection process.

4.80.3.4 Remote Component

Remote component serves as the central interface for remote control functionality.

The application features a dual-panel layout implemented using CSS Flexbox, enhancing responsiveness and user experience. The left panel integrates a live camera feed alongside a control interface equipped with directional buttons (RemoteButton) for navigation.

A gear-switching mechanism is incorporated, utilizing a toggle switch to alternate between automatic (A) and manual (M) modes. This functionality leverages React's useEffect and useRef hooks for efficient state management. Throughout, responsive and dynamic UI updates are ensured, adapting seamlessly to user interactions and state changes. See code below for implementation.

```
const Remote = (props) => {
    const {sendDirection, changeGear, gear} = core()
    const gearref = React.createRef()
    const onReset = function(e){ sendDirection("STOP") }
    const switchGear = function(e){
        e.preventDefault()
        changeGear()
    }
    useEffect(() => { gearref.current.checked = gear == 1}, [gear])
return (
<div
 ↪  className="w-full h-full overflow-hidden flex flex-row bg-slate-800">
  <section className="w-1/2 p-2">
    <div className="w-full h-2/3 flex flex-col items-center
    border rounded-lg overflow-hidden">
      <Camera/>
    </div>
    <div className="w-full h-[calc((100%/3)-8px)]
    border rounded-lg mt-2 flex flex-row">
      <div className=" w-1/4 h-full flex items-center justify-center">
        <label className="switch-label mr-1">A</label>
          <label className="switch">
            <input type="checkbox" name="switch"
            id = "switch" ref={gearref} value={gear == 1}
             ↪  onClick={switchGear}/>
              <span className="slider round"></span>
          </label>
        <label className="switch-label ml-1">M</label>
      </div>
      <div className=
       ↪  "circle-section flex items-center justify-center  w-2/4 h-full"
       ↪  >
        <div className="circle-container relative ">
          <button className="center-circle" onClick =
           ↪  {onReset}>r</button>
```

```
            <RemoteButton direction="UP"/>
            <RemoteButton direction="DOWN"/>
            <RemoteButton direction="LEFT"/>
            <RemoteButton direction="RIGHT"/>
          </div>
        </div>
        <div className=" w-1/4 h-full"><Speed/></div>
      </div>
    </section>
    <section className="w-1/2 flex items-center justify-center p-2">
      <div  className="w-full h-full border rounded-lg flex flex-col
      items-center relative overflow-hidden">
        <Map ></Map>
      </div>
            </section>
      </div>
      );
};
export default Remote;
```

4.80.3.5 Camera Component

The Camera component displays live camera feeds and enable camera switching functionality.

A dynamic camera feed display was implemented by processing base64-encoded image data from the backend, supporting both the Main Camera and QR Code Camera. React's useEffect was utilized to ensure the image source (imgRef) updated whenever new camera data (cameraData or camera_qr_data) was received (see fig. 4.91). A camera selection dropdown was added to enhance user interaction, allowing users to switch between the main camera and QR code camera views. Memory management was efficiently handled by revoking object URLs when the component unmounted or the camera data changed. The component was styled using CSS to ensure the camera feed was responsive and fit seamlessly within the layout.

```
useEffect(function(){
        if(cam === "front"){
            if (cameraData) {
                const imageUrl = `${cameraData}`
                imgRef.current.src = imageUrl;

                // Clean up the object URL when component is unmounted
                return () => {
                    URL.revokeObjectURL(imageUrl);
                };
            }
        }
        else if (cam === "back"){
            if (camera_qr_data) {
                const imageUrl =
                 ↪  `${camera_qr_data}`
                imgRef.current.src = imageUrl;

                // Clean up the object URL when component is unmounted
                return () => {
                    URL.revokeObjectURL(imageUrl);
                };
            }
        }
    },[cameraData, camera_qr_data])
```

Figure 4.91: UseEffect which update camera image each render

4.80.3.6 Map Component

This component displays and interact with a dynamic map interface. included integrating a base64-encoded map image (mapData) to display real-time map data. Zoom functionality was implemented using buttons for zooming in (+) and out (-) (see code below), as well as mouse wheel support for smooth zooming. A loading state was added to display a placeholder message while the map data was being fetched. Using useEffect, the map image was dynamically updated whenever new mapData was received (see code below), ensuring real-time updates. CSS transformations (scale) were applied to enable smooth zooming transitions, and floating zoom buttons were designed for an intuitive user experience, styled with CSS for a modern look.

```
1   const zoomIn = () => {
2       setZoom((prevZoom) => Math.min(prevZoom + 0.1, 7)); // Max zoom
        ↪ 7x
3   };
4
5   const zoomOut = () => {
6       setZoom((prevZoom) => Math.max(prevZoom - 0.1, 1)); // Min zoom
        ↪ 1x (original size)
7   };
8
9   const handleWheel = (event) => {
10      // Prevent the page from scrolling when zooming
11      event.preventDefault();
12
13      if (event.deltaY < 0) {
14          zoomIn(); // Zoom in when scrolling up
15      } else {
16          zoomOut(); // Zoom out when scrolling down
17      }
18  };
19
20  useEffect(() => {
21      if (mapData) {
22          const imageUrl = `${mapData}`;
23
24          // Set image src only if imgRef.current is available
25          imgRef.current.src = imageUrl;
26          if(!mapData){
```

```
                setLoading(true);
            }
            setLoading(false)
            return () => {
                URL.revokeObjectURL(imageUrl);
            };
        }
    }, [mapData]);

```

4.80.3.7 Task Component

the Task component manages task creation and submission for the application. It is responsible for managing task creation and submission for the application. The responsibilities included designing and implementing a task creation interface that allowed users to select zones and define tasks, such as loading or unloading. The component dynamically built and displayed task sequences based on user input and integrated validation logic (see code below) to ensure task sequences adhered to predefined rules. For example, it prevented invalid task combinations like unloading without loading first and limited the number of tasks to a maximum of six. React hooks (useState, useEffect, useCallback, useRef) were utilized for state management and user interaction handling. Toast notifications (react-hot-toast) were integrated to provide real-time feedback for errors and successful actions. A mapping button was implemented to trigger mapping functionality and dynamically display available zones. The component was styled using CSS and Tailwind CSS to achieve a clean and responsive design, ensuring a smooth and intuitive user experience while efficiently managing tasks within the application.

```
const set = () => {
        if (params.length === 6) return
         ↪  toast.error("You can't load and unload more than 6 times");
        if (selected === "") return toast.error("Select a zone");
        let type = ref.current.value === "Loading" ? "L" : "U";
        if (type === "U") {
            let param = params[params.length - 1];
            if (param) {
                let key = Object.keys(param)[0];
                if (param[key] !== "Loading") {
                    return
                     ↪  toast.error("You can't unload without loading");
```

```
                } else if (key === selected) {
                    return toast.error(
                        "You can't unload from a zone you've loaded from"
                    );
                }
            } else { return toast.error("You need to load first");}
        }else if( type === "L"){
            let param = params[params.length - 1];
            if (param) {
                let key = Object.keys(param)[0];
                if (param[key] === "Loading") {
                    return toast.error("You can't load twice");
                }
            }
        }
        setTask(`${task}${selected}(${type}) -> `);
        setParams([...params, { [selected]: ref.current.value }]);
        setSelected("");
    };
```

4.81 ROS

The Robot Operating System (ROS) serves as the robot's main controller, managing all operations seamlessly at all times and facilitating communication with the GUI.

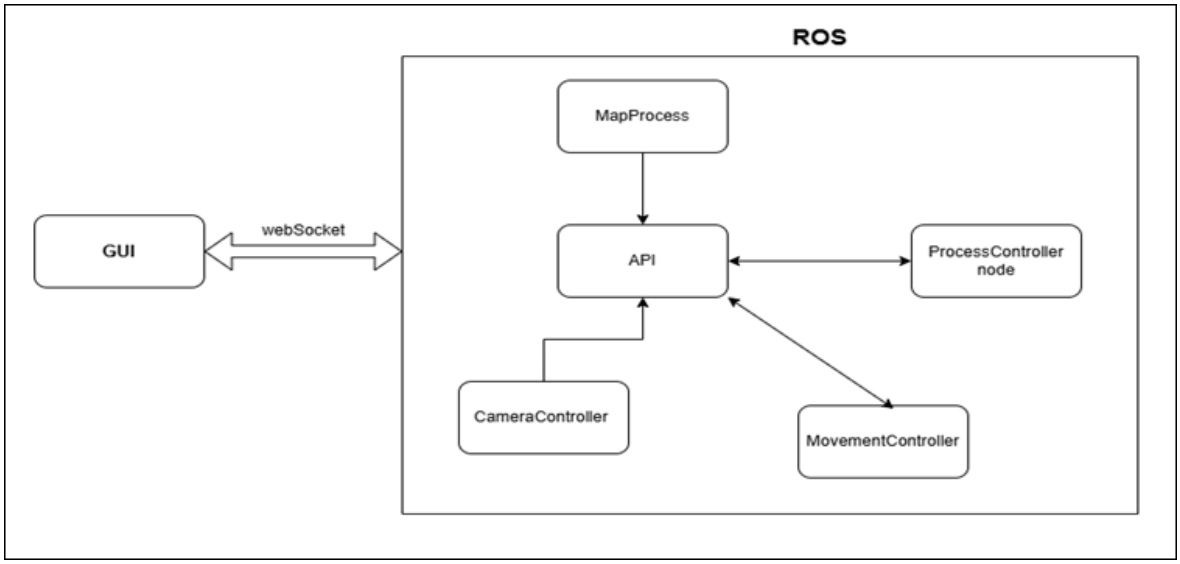


Figure 4.92: general architecture

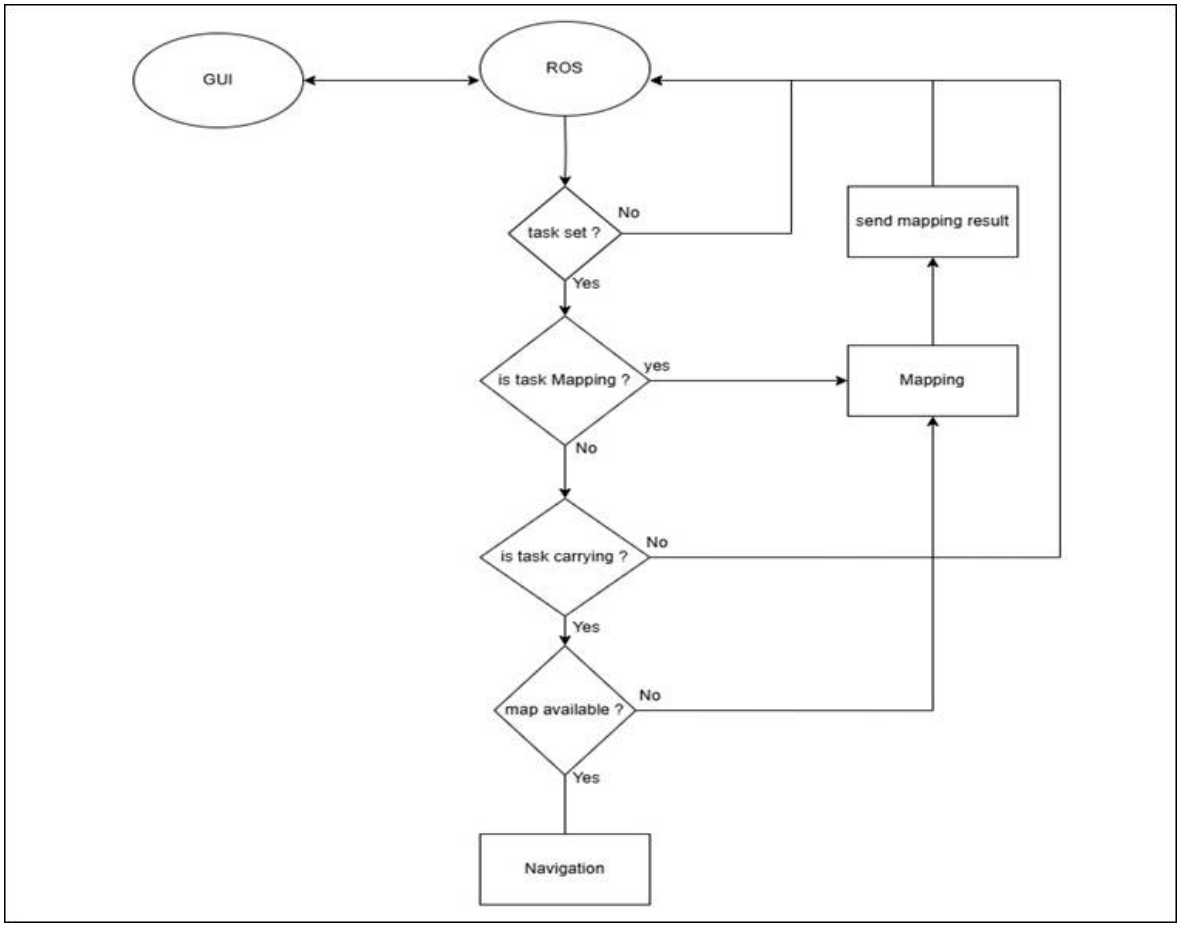


Figure 4.93: general architecture

4.81.1 Nodes

4.81.1.1 ie_API_Server

This node serves as a critical bridge between the ROS (Robot Operating System) ecosystem and a frontend application, leveraging WebSocket communication to enable seamless interaction. It facilitates real-time data streaming, robot control, and task management, ensuring smooth and efficient communication between the backend and frontend (see fig. 4.92).

The node integrates WebSocket communication using Socket.IO, establishing a real-time, bidirectional channel that supports multiple clients. This allows users to connect, disconnect, and interact with the robot in real time. The WebSocket connection is the backbone of the system, enabling instant data exchange and control commands between the frontend and the ROS backend.

```
class ie_API_Server:
  def __init__(self):
      self._bridge = CvBridge()
      self.sio = socketio.async_server.AsyncServer(async_mode='asgi',
      ↪  cors_allowed_origins="*")
      self.app = socketio.asgi.ASGIApp(self.sio)
      self.mc_pub = rospy.Publisher("manual_controller", Int32,
      ↪  queue_size=10)
      self.cam_sub = rospy.Subscriber("camera_feed", Image,
      ↪  self.run_async_cameraFeedCallback)
      self.cam_qr_sub = rospy.Subscriber("camera_qr_code_feed", Image,
      ↪  self.run_async_cameraQrFeedCallback)
      self.sensors_sub = rospy.Subscriber("sensor_data", SensorDataMap,
      ↪  self.sensorsCallback)
      self.speed_sub = rospy.Subscriber("speed_value", Float32,
      ↪  self.run_async_speedCallback)
      self.map_sub = rospy.Subscriber("map_feed", Image,
      ↪  self.run_async_mapFeedCallback)
      self.process_sub = rospy.Subscriber("ProcessState", String,
      ↪  self.run_async_processState)
      rospy.Service('output', taskMessage, self.run_async_taskFinished)
      rospy.Service('mapping_output', mappingOutput,
      ↪  self.run_async_mappingOutput)
      rospy.Service('gear_changed', robotGear,
      ↪  self.run_async_gearChanged)
      self.sio.on("connect", self.onConnect)
      self.sio.on("disconnect", self.onDisconnect)
      self.sio.on("moveDirection", self.movement)
      self.sio.on("message", self.message)
      self.sio.on("robot_task", self.taskCallback)
      self.sio.on("robot_gear", self.gearCallback)
```

Figure 4.94: API initial value

For real-time data streaming, the node subscribes to various ROS topics to capture and process critical information. It subscribes to camera_feed and camera_qr_code_feed to receive live camera images, which are then converted from ROS Image messages to OpenCV format using CvBridge. These images are encoded as base64 strings and streamed to the frontend via WebSocket. Similarly, the node subscribes to the map_feed topic to receive

```
  # Register event handlers
self.sio.on("connect", self.onConnect)
self.sio.on("disconnect", self.onDisconnect)
self.sio.on("moveDirection", self.movement)
self.sio.on("message", self.message)
self.sio.on("robot_task", self.taskCallback)
self.sio.on("robot_gear", self.gearCallback)
```

Figure 4.95: API initial value

real-time map images, processes them, and streams them to the frontend in the same manner. Additionally, it subscribes to the speed_value topic to capture the robot's speed and emits speed updates to the frontend in real time, ensuring users have up-to-date information on the robot's movement.

The node also handles robot control by listening for specific events from the frontend. For movement control, it listens for moveDirection events (e.g., UP, DOWN, LEFT, RIGHT, STOP) and translates these into corresponding commands published to the manual_controller ROS topic, enabling direct control of the robot's movement. For gear control, it listens for robot_gear events to toggle between automatic and manual modes. This is achieved by calling the change_gear ROS service and emitting the updated gear state to the frontend, ensuring the user interface reflects the current state of the robot.

Task management is another key functionality of the node. It listens for robot_task events from the frontend, which trigger tasks such as loading, unloading, or mapping. The node converts task data into a ROS-compatible format (using the TaskData message) and calls the robot_task service to execute the task(see fig. 4.95). It also listens for task feedback from the ROS backend via the output service, emitting task responses (e.g., success or failure messages) to the frontend. This ensures users receive timely updates on task progress and outcomes, enhancing transparency and usability.

For mapping functionality, the node listens for mapping data from the ROS backend via the mapping_output service. It processes and serializes this data, which includes information such as locations and coordinates, and emits it to the frontend. This allows users to visualize the robot's environment and track its movements in real time.

Finally, the node monitors the robot's process state by subscribing to the ProcessState topic. It captures updates on the robot's current state (e.g., Processing, Stationary) and emits these updates to the frontend in real time. This ensures users are always aware of the robot's operational status, enabling better decision-making and control.

```
async def taskCallback(self, sid, task):
      t = TaskData()
      t.task_name = task['task']["task_name"]
      t.params =  [Param(zone=key,type=value) for key, value in
       ↪  task['task']["params"].items()]
      rospy.wait_for_service('robot_task')
      robot_task = rospy.ServiceProxy('robot_task', robotTask)
      robot_task.wait_for_service(10)
      try:
          response = robot_task(t)
          print(response)
          await self.sio.emit("task_response", {"response":
           ↪  response.message}, to=sid)
      except rospy.ServiceException as exc:
          print("Service did not process request: " + str(exc))

  def run_async_taskFinished(self,output):
      try:
          loop = asyncio.new_event_loop()
          asyncio.set_event_loop(loop)
          loop.run_until_complete(self.taskFinished(output))
      except Exception as e:
          rospy.logerr(f
           ↪  "Error before proccessing and emitting taskFinished: {e}
           ↪  ")

      return taskMessageResponse(True)

  async def taskFinished(self, output):
      await self.sio.emit("task_response", {"response":
       ↪  output.message})

  def run_async_mappingOutput(self,output):
      try:
          loop = asyncio.new_event_loop()
          asyncio.set_event_loop(loop)
          loop.run_until_complete(self.mappingOutput(output))
      except Exception as e:
          rospy.logerr(f
           ↪  "Error before proccessing and emitting taskFinished: {e}
           ↪  ")
```

```
35
36          return mappingOutputResponse(True)
37
38      async def mappingOutput(self, output):
39          print(output)
40          data = [{"location" :kv.location, "x": kv.x, "y":kv.y} for kv in
             ↪  output.locations]
41          print(data)
42          await self.sio.emit("mapping_output", {"locations": data})
```

4.81.1.2 movementController

This node manages the robot's movement in both manual and autonomous modes. It processes control commands, handles gear switching, and ensures smooth transitions between states.

Key Features and Functionality:

The node supports two modes of operation:

- Manual Mode: The robot is controlled via user commands, such as increasing or decreasing linear or angular velocity.
- Autonomous Mode: The robot is controlled by an external system, like a navigation stack, with manual control disabled.

To facilitate seamless switching between these modes, the twist_mux package can be utilized. This package subscribes to multiple cmd_vel topics.

The Movement Control component was designed to subscribe to the manual_controller topic to receive movement commands, such as UP, DOWN, LEFT, RIGHT, and STOP. The component adjusted the robot's linear and angular velocity based on the received commands and then published the resulting velocity commands to the cmd_vel topic.

Gear Switching system provides a ROS service (change_gear) to switch between manual and autonomous modes, updates the gear state and notifies the GUI via another ROS service (gear_changed) (see fig. 4.92). Velocity Interpolation Implements smooth interpolation for angular velocity to prevent abrupt changes in robot movement. Uses a waiting period and linear interpolation to gradually reduce angular velocity to zero.

Process State Monitoring Subscribes to the ProcessState topic to monitor the robot's current state (e.g., Processing, Stationary). Resets movement commands if the robot is in a Processing state. Speed Calculation Calculates the robot's total velocity by combining linear

and angular velocity components. Publishes the calculated speed to the speed_value topic for real-time monitoring.

Technical Details:

- ROS Integration:
  - Publishers:
    - cmd_vel: Publishes velocity commands for the robot.
    - speed_value: Publishes the robot's current speed.
  - Subscribers:
    - manual_controller: Receives movement commands.
    - ProcessState: Monitors the robot's state.
    - cmd_vel: Receives velocity commands from the autonomous system.
  - Services:
    - change_gear: Handles gear switching between manual and autonomous modes.
- Data Structures:
  - cmd_vel Struct: Stores the robot's linear and angular velocity (see fig. 4.95) components.Manages interpolation and waiting states for smooth velocity transitions.Provides methods to increase/decrease velocity and reset commands.
- Interpolation Logic: Uses timestamps (ros::Time) to track the last update time and interpolation duration. Implements a waiting period (wait_duration) before starting interpolation. Linearly interpolates angular velocity towards zero over a specified duration (interpolation_duration), see fig. 4.94 for implementation.
- Velocity Calculation: Combines linear and angular velocity components to calculate the robot's total velocity. Accounts for the robot's wheel radius (radius) to convert angular velocity to linear velocity.
- Error Handling: Logs warnings for invalid commands or attempts to control the robot in autonomous mode. Ensures smooth transitions between states to prevent abrupt movements.

```
1   bool changeGear (ie_communication::robotGear::Request &req,
    ↪  ie_communication::robotGear::Response &res){
2     movedata.gear = req.state;
3     if(movedata.gear == 0){
4         std::cout <<
          ↪  "The robot is in autonomous mode, manual control is disabled"
          ↪   <<
          ↪  std::endl;
5     }else{
6         std::cout <<
          ↪  "The robot is in manual mode, autonomous control is disabled"
          ↪   <<
          ↪  std::endl;
7     }
8
9     ros::NodeHandle n;
10    ros::ServiceClient client =
      ↪  n.serviceClient<ie_communication::robotGear>("gear_changed");
11    ie_communication::robotGear srv;
12
13    srv.request.state = movedata.gear;
14
15    if(client.call(srv)){
16
17    }else{
18        ROS_ERROR("Failed to update the gear to GUI");
19    }
20
21    res.message = true;
22    return true;
23  }
```

Figure 4.96: Gear shift

```
void updateAngular() {
      ros::Time current_time = ros::Time::now();
      ros::Duration time_since_update = current_time -
       ↪  last_update_time;

      if (waiting_to_interpolate) {
          if (time_since_update.toSec() >= wait_duration) {
              // Start interpolation after waiting period
              angular_start = az;
              interpolation_start_time = current_time;
              angular_interpolating = true;
              waiting_to_interpolate = false;
          }
      }

      if (angular_interpolating) {
          ros::Duration time_since_start = current_time -
           ↪  interpolation_start_time;
          float t = time_since_start.toSec() / interpolation_duration;

          if (t >= 1.0) {
              az = 0.0; // Stop interpolation after duration
              angular_interpolating = false;
          } else {
              az = angular_start * (1.0 - t); // Linearly interpolate
               ↪  towards zero
          }
      }
  }

```

Figure 4.97: Linear interpolation

```
struct cmd_vel {
  int gear = 0;
  float lx = 0.0;
  float ly = 0.0;
  float lz = 0.0;
  float ax = 0.0;
  float ay = 0.0;
  float az = 0.0;

  ros::Time last_update_time; // Last time angular velocity was updated
  ros::Time interpolation_start_time; // Time when interpolation starts
  bool angular_interpolating = false; // Flag to indicate interpolation
  bool waiting_to_interpolate = false; // Flag to indicate waiting
   ↪ period
  float angular_start = 0.0; // Starting value for interpolation
  float interpolation_duration = 0.8; // Duration for interpolation (in
   ↪ seconds)
  float wait_duration = 0.3; // Time to wait before starting
   ↪ interpolation (in seconds)
  float radius = 0.16;
  void changeGear(const std_msgs::Int32::ConstPtr& msg) {
      gear = msg->data;
  }
  void increaseLinear() {
      lx += 0.01;
  }

  void decreaseLinear() {
      lx -= 0.01;
  }

  void increaseAngular() {
      az += 0.1;
      updateAngularState();
  }

  void decreaseAngular() {
      az -= 0.1;
      updateAngularState();
  }
```

```
38
39      void reset() {
40          lx = 0.0;
41          ly = 0.0;
42          lz = 0.0;
43
44          ax = 0.0;
45          ay = 0.0;
46          az = 0.0;
47
48          angular_interpolating = false;
49          waiting_to_interpolate = false;
50      }
51
52      void updateAngularState() {
53          last_update_time = ros::Time::now();
54          angular_interpolating = false; // Stop interpolation if active
55          waiting_to_interpolate = true; // Set waiting state
56      }
57
58
59      float getVelocity(){
60          if (gear == 1){
61              float linear_velocity_rotational = az * radius;
62              float tVelocity = sqrt((pow(lx, 2) +
                ↪  pow(linear_velocity_rotational, 2)));
63              return std::round(tVelocity * 100.0f) / 100.0f;
64          }else{
65              float linear_velocity_rotational = acvl.angular.z * radius;
66              float tVelocity = sqrt((pow(acvl.linear.x, 2) +
                ↪  pow(linear_velocity_rotational, 2)));
67              return std::round(tVelocity * 100.0f) / 100.0f;
68          }
69      }
70  };
71
```

Figure 4.98: Cmd_vel structure

4.81.1.3 CameraController

This node functions as a camera feed manager, playing a crucial role in subscribing to raw camera feeds, processing them, and publishing the processed feeds to other ROS topics for further use, such as display or analysis. It subscribes to two raw camera feeds: /camera/rgb/image_raw, which is the primary camera feed used for general purposes like navigation or object detection, and /camera_2/camera_2/image_raw, the secondary camera feed often utilized for specialized tasks such as QR code detection. The node then publishes the processed feeds to two ROS topics: camera_feed for the primary camera feed and camera_qr_code_feed for the secondary camera feed. This ensures that downstream nodes or applications have access to the necessary camera data for their respective tasks, see **??** for implementation.

The node also incorporates camera state management to ensure efficient operation. It uses a boolean flag (_camState) to enable or disable feed publishing, ensuring that feeds are only published when the camera is active and data is available. Additionally, it tracks camera availability (_cam_available) to prevent publishing when no data is being received. This state management mechanism helps optimize resource usage and prevents unnecessary processing. To handle potential issues, the node implements robust error handling for image conversion and publishing. Errors, such as failed image conversions or publishing failures, are logged using rospy.logerr, making it easier to debug and maintain the system.

From a technical perspective, the node integrates seamlessly with the ROS ecosystem. It subscribes to /camera/rgb/image_raw and /camera_2/camera_2/image_raw to receive raw images from the primary and secondary cameras, respectively. It then publishes the processed images to camera_feed and camera_qr_code_feed for further use. For image processing, the node uses CvBridge to convert ROS Image messages into OpenCV-compatible formats. While the node processes and publishes the images, it does not apply additional filtering or transformations, ensuring the images remain in their original state unless modified by downstream nodes.

To ensure smooth operation and responsiveness, the node is initialized in a separate thread. This threading approach allows the node to handle image processing and publishing without blocking the main thread, ensuring efficient performance even under high workloads. By combining ROS integration, state management, error handling, and threading, this camera feed manager node provides a reliable and efficient solution for managing and streaming real-time camera data within the ROS ecosystem. Its design ensures that downstream applications receive the necessary camera feeds promptly and accurately, making it an essential component for systems that rely on real-time visual data.

```python
  import rospy
from ie_communication.srv import camState, camStateResponse
import cv2
from cv_bridge import CvBridge
from sensor_msgs.msg import Image

class CameraController:

    def __init__(self):
        self._pubcam1 = rospy.Publisher("camera_feed", Image,
        ↪  queue_size=10)
        self._pubcam2 = rospy.Publisher("camera_qr_code_feed", Image,
        ↪  queue_size=10)
        rospy.Subscriber("/camera/rgb/image_raw",Image,
        ↪  self._camera1Process)
        rospy.Subscriber("/camera_2/camera_2/image_raw",Image,
        ↪  self._camera2Process)
        self._bridge = CvBridge()
        self._camState = True
        self._cam_available = False
        self._cam1Frame = None
        self._cam2Frame = None

    def _camera1Process(self, data):
        try:
            self._cam1Frame = data
            self._cam_available = True
            self._provideCamFeed()
        except Exception as e:
            rospy.logerr(f"Error converting image: {e}")

    def _camera2Process(self, data):
        try:
            self._cam2Frame = data
            self._cam_available = True
            self._provideCam2Feed()
        except Exception as e:
            rospy.logerr(f"Error converting image: {e}")

    def _provideCamFeed(self) -> None:
```

```
37          if self._camState and self._cam_available:
38              try:
39                  self._pubcam1.publish(self._cam1Frame)
40              except Exception as e:
41                  rospy.logerr(f"Error publishing image feed: {e}")
42
43      def _provideCam2Feed(self) -> None:
44          try:
45              self._pubcam2.publish(self._cam2Frame)
46          except Exception as e:
47              rospy.logerr(f"Error publishing image from cam2 feed: {e}")
```

Figure 4.99: CameraProcess node

4.81.1.4 map_process

This node is responsible for processing laser scan data, robot position, and QR code positions to generate and publish a dynamic map for visualization and navigation. It subscribes to the /scan topic to receive laser scan data, which is processed to detect obstacles and update the local map. The robot's position and orientation are tracked using TF2, which retrieves the robot's translation and rotation in the map frame. These coordinates are then converted into pixel coordinates for visualization on the map. Additionally, the node integrates QR code positions by reading them from an SQLite database (qr_code.db) every 5 seconds. These QR code positions are displayed on the map as blue rectangles, providing a comprehensive view of the environment.

```
def update_map_from_scan(self):
  if self.robot_position is None or self.robot_rotation is None:
     return
  yaw = self.get_yaw_from_quaternion(self.robot_rotation)

  for i, range_val in enumerate(self.latest_scan.ranges):
      if range_val < self.latest_scan.range_min or range_val >
       ↪  self.latest_scan.range_max:
          continue  # Skip invalid range values

angle=self.latest_scan.angle_min+i* self.latest_scan.angle_increment

      endpoint_x = self.robot_position.x + range_val * np.cos(yaw +
       ↪  angle)
      endpoint_y = self.robot_position.y + range_val * np.sin(yaw +
       ↪  angle)

      endpoint_x_pixel = int((endpoint_x - self.map_origin_x) /
       ↪  self.map_resolution)

      endpoint_y_pixel = int((endpoint_y - self.map_origin_y) /
       ↪  self.map_resolution)

      if 0 <= endpoint_x_pixel < self.map_width and 0 <=
       ↪  endpoint_y_pixel < self.map_height:

              self.map_image[endpoint_y_pixel, endpoint_x_pixel] = 0

```

Figure 4.100: Update Map from Scan Function

The node generates a 2D map image that includes several key elements: obstacles derived from laser scan data (represented as black pixels), the robot's current position (shown as a red circle) and orientation (indicated by a green line), QR code positions (displayed as blue rectangles), and the robot's path (traced as a green line over time). This map image is published to the map_feed topic, enabling real-time visualization for users or other nodes. The map is dynamically updated at a fixed rate of 10 Hz using a timer callback, ensuring it reflects the latest scan data, robot position, and QR code positions. The map parameters, such as resolution (5 cm per pixel), dimensions (400x400 pixels), and origin (-10.0, -10.0 meters), are predefined, and the map is initialized as free space (white pixels) before being updated with obstacles (black pixels) from laser scans.

In summary, this node provides a dynamic and real-time map visualization by integrating laser scan data, robot position, and QR code positions. Its robust processing and integration capabilities ensure accurate and up-to-date map generation, making it a vital component for navigation and visualization tasks in the ROS ecosystem.

```
def process_scan(self):
      self.map_image.fill(255)

      robot_x_pixel = int((self.robot_position.x - self.map_origin_x)
       ↪  / self.map_resolution)
      robot_y_pixel = int((self.robot_position.y - self.map_origin_y)
       ↪  / self.map_resolution)

      if not (0 <= robot_x_pixel < self.map_width and 0 <=
       ↪  robot_y_pixel < self.map_height):
          return
    self.update_map_from_scan()
    map_image_color=cv2.cvtColor(self.map_image, cv2.COLOR_GRAY2BGR)

    if len(self.path_history) > 1:
        for i in range(1, len(self.path_history)):
              cv2.line(map_image_color, self.path_history[i - 1],
               ↪  self.path_history[i], (0, 255, 0), 2)

    for qr_x, qr_y in self.qr_code_positions:
        qr_x_pixel=int((qr_x-self.map_origin_x)/ self.map_resolution)
        qr_y_pixel=int((qr_y-self.map_origin_y)/ self.map_resolution)
          if 0 <= qr_x_pixel < self.map_width and 0 <= qr_y_pixel <
           ↪  self.map_height:
```

```
                cv2.rectangle(map_image_color,
(qr_x_pixel - self.qr_code_size, qr_y_pixel -
 ↪ self.qr_code_size),(qr_x_pixel + self.qr_code_size, qr_y_pixel +
 ↪ self.qr_code_size),(255, 0, 0), -1)

        cv2.circle(map_image_color, (robot_x_pixel, robot_y_pixel), 5,
         ↪ (0, 0, 255), -1)
        yaw = self.get_yaw_from_quaternion(self.robot_rotation)
        robot_x_end = robot_x_pixel + int(np.cos(yaw) * 10)
        robot_y_end = robot_y_pixel + int(np.sin(yaw) * 10)
        cv2.line(map_image_color, (robot_x_pixel, robot_y_pixel),
         ↪ (robot_x_end, robot_y_end), (0, 255, 0), 2)

        map_image_color = np.flipud(map_image_color)
        map_image_color = cv2.rotate(map_image_color,
         ↪ cv2.ROTATE_90_COUNTERCLOCKWISE)
        output_path = "/tmp/robot_map_with_position.png"
        cv2.imwrite(output_path, map_image_color)
        self.send_image(output_path)
```

Figure 4.101: Function Drawing Map

4.81.2 Classes

4.81.2.1 Task

The Task class is a base class that encapsulates common functionality for robot tasks, such as: Robot control (movement, turning, stopping), Obstacle detection and avoidance using LIDAR data, Image processing for line following and QR code detection, State management for task execution and transitions.

Key Features and Functionality:

The robot control system offers a comprehensive set of methods for managing basic robot movements. These include _move_forward, which propels the robot forward at a constant speed, as well as _turn_left and _turn_right for executing left and right turns, respectively. Additionally, the system features a _U_turn method for performing a 180° turn and a _move function that adjusts the robot's movement based on error, particularly useful for tasks like line following. To halt the robot, the stop method is available.

For obstacle detection and avoidance, the system subscribes to the /scan topic to receive LIDAR data, enabling it to monitor the surroundings. It employs the check_for_obstacles function (see fig. 4.99) to detect obstacles in the robot's path. When an obstacle is detected,

the system utilizes a contouring algorithm called contour_obstacle(see fig. 4.99) to navigate around it. This algorithm involves turning 90° left, moving forward, turning 90° right, and then returning to the original path. To ensure precise turns, the system tracks the robot's orientation using odometry data, accessed through the _get_yaw method. This combination of movement control and obstacle avoidance ensures efficient and accurate navigation in dynamic environments.

```
  def check_for_obstacles(self, event):
    if self.scan_data is None or len(self.scan_data.ranges) == 0:
      return

print("Checking for obstacles using LIDAR data")
  front_angle_range = 30  # Degrees
    front_angle_range_rad = np.deg2rad(front_angle_range)
    angle_increment = self.scan_data.angle_increment
    num_ranges = len(self.scan_data.ranges)
    min_angle = self.scan_data.angle_min
    start_index = max(0, int((min_angle - front_angle_range_rad / 2) /
     ↪  angle_increment))
    end_index = min(num_ranges - 1, int((min_angle +
     ↪  front_angle_range_rad / 2) / angle_increment))
    min_distance = float('inf')
    for i in range(start_index, end_index):
      if 0 < self.scan_data.ranges[i] < min_distance and
       ↪  np.isfinite(self.scan_data.ranges[i]):
          min_distance = self.scan_data.ranges[i]
          obstacle_distance_threshold = 0.3
    if min_distance < obstacle_distance_threshold:
        self._obstacleInFront = True
        rospy.loginfo(f"Obstacle detected at {min_distance:.2f} meters!")
        self.stop()  # Stop the robot
        self._obstacleChecker += 1

    if self._obstacleChecker >= 5:
      rospy.loginfo(
       ↪  "Obstacle is still present. Calling contour_obstacle function."
       ↪  )
      self._obstacleChecker = 0

    if not self._contourningObstacle:
```

```
29            self._contourningObstacle = True
30            self.contour_obstacle()
31        else:
32            self._obstacleInFront = False
33            self._obstacleChecker = 0
34            rospy.loginfo("No obstacle detected. Moving.")
```

Figure 4.103: Obstacle Detection

```
def contour_obstacle(self):
      self._contourningStep += 1
      if self.timer:
          self.timer.shutdown()
      self.stop()  # Stop the robot

      if self._contourningStep == 1:
          rospy.loginfo("Contouring obstacle: Step 1")
          self.turn_angle(90)
          self.contour_obstacle()
      elif self._contourningStep == 2:
          rospy.loginfo("Contouring obstacle: Step 2")
          self._move_forward()
          while not self.is_obstacle_behind():
              rospy.sleep(0.1)
          self.turn_angle(-90)  # Turn right 90°
          self.contour_obstacle()
      elif self._contourningStep == 3:
          rospy.loginfo("Contouring obstacle: Step 3")
          self._move_forward()
          while not self.is_obstacle_behind():
              rospy.sleep(0.1)
          self.turn_angle(-90)
          self.contour_obstacle()
      elif self._contourningStep == 4:
          rospy.loginfo("Contouring obstacle: Step 4")
          self._move_forward()
          self._turnSide = "left"
          self.moveToTurnPosition = True
          self._obstacleInFront = False
```

Figure 4.102: Obstacle avoidance procedure

```python
def is_obstacle_behind(self):
      if self.scan_data is None:
          return False
      robot_length = 0.52
      obstacle_distance_threshold = robot_
      sector_start_angle = np.deg2rad(225)  # 225 degrees
      sector_end_angle = np.deg2rad(270)   # 270 degrees
      angle_increment = self.scan_data.angle_increment
      num_ranges = len(self.scan_data.ranges)
      start_index = int((sector_start_angle - self.scan_data.angle_min)
      ↪ / angle_increment)
      end_index = int((sector_end_angle - self.scan_data.angle_min) /
      ↪ angle_increment)
      min_distance = float('inf')
      for i in range(start_index, end_index):
          if 0 < self.scan_data.ranges[i] < min_distance:
              min_distance = self.scan_data.ranges[i]
      print(f"min distance : {min_distance}")
      return min_distance > obstacle_distance_threshold and
      ↪ min_distance < (obstacle_distance_threshold + 0.5)
```

Figure 4.104: Function checking if the robot overpass the obstacle

The image processing component of the system is designed to enhance the robot's navigation and interaction capabilities by subscribing to multiple camera topics, such as /camera/rgb/image_raw and /camera_qr_code_feed. This allows the robot to perform tasks like line following and QR code detection. For line following, the system detects black lines using techniques such as thresholding and contour detection, enabling the robot to accurately track and follow predefined paths. Additionally, the system incorporates QR code detection using the QReader library, which decodes QR codes to extract relevant information or commands. To ensure precise alignment with detected lines, the system implements the _adjust_orientation method, which dynamically adjusts the robot's movement based on real-time line detection data. Together, these features enable the robot to navigate complex environments and interact with visual markers effectively.

The task state management system is responsible for monitoring and controlling the execution of tasks. It tracks the task's current state using the _running variable, which indicates whether the task is active or inactive. The system provides two key methods: start to initiate the task and stop to halt it, ensuring flexibility and control over task execution. Additionally, it emits signals such as finishedSignal and failedSignal to notify the system when a task has been successfully completed or has encountered a failure. These signals enable the system to respond appropriately, whether by transitioning to the next task or handling errors, ensuring smooth and efficient operation.

The system incorporates robust error handling to manage potential issues across various components, including ROS callbacks, image processing, and task execution. Errors and task statuses are logged using rospy.loginfo for informational messages and rospy.logerr for error reporting, ensuring transparency and ease of debugging.

To enhance efficiency and responsiveness, the system leverages asynchronous execution through the asyncio library. The _execute method is designed to run tasks in a non-blocking manner, allowing the robot to perform multiple operations simultaneously without interruptions. This approach ensures smooth operation and maintains system responsiveness, even during complex or time-consuming tasks.

Technical Details:

The system is tightly integrated with ROS (Robot Operating System) to facilitate seamless communication and control. It utilizes subscribers to receive critical data from various sensors and topics:

- /odom: Provides odometry data, enabling the system to track the robot's position and orientation.
- /scan: Delivers LIDAR data, which is essential for obstacle detection and avoidance.
- /camera/rgb/image_raw, /camera_qr_code_feed, and other camera topics: Supply image

feeds for tasks like line following and QR code detection.

On the output side, the system employs publishers to send commands and data:

- /cmd_vel: Publishes velocity commands to control the robot's movement, such as forward motion, turns, and stops.
- /error: Publishes error values for debugging and monitoring system performance.
- /position_joint_controller/command: Sends commands to control lifting mechanisms or other actuators, if applicable.

This integration ensures efficient data flow and real-time control, enabling the robot to perform complex tasks with precision and reliability.

Navigation system The navigation system is composed of three key functions: _adjust_orientation, check_side_pixels, and check_straight_pixels. These methods work together to enable the robot to follow lines and detect junctions effectively, ensuring smooth and accurate navigation in its environment.
The _adjust_orientation method is responsible for adjusting the robot's orientation based on the detected line and the number of black pixels in the camera image. It ensures the robot stays centered on the line or makes appropriate turns at junctions. This method takes several input parameters, including the error (deviation of the line from the center of the image), the angle of the detected line, the number of black pixels in the region of interest, the binary mask of the image, and the dimensions of the bounding box around the detected line. If the robot is moving to a lift position, it adjusts its orientation to reach the target. Otherwise, it checks the number of black pixels to determine the robot's position relative to the line. If the number of black pixels is within a defined threshold, the robot moves forward while adjusting its orientation based on the error. If the number of black pixels exceeds the threshold, the robot uses check_side_pixels and check_straight_pixels to determine if it's at a junction. Based on the detected line configuration, the robot decides whether to turn left, right, or move forward. The method then publishes velocity commands to the /cmd_vel topic to adjust the robot's movement.

```
1    def _adjust_orientation(self, error, angle, pixels, mask , w_min,
     ↪  h_min):
2        if self._obstacleInFront:
3            return None
4        if self.moveToTurnPosition:
```

```
            self._move(error)
            return
        if self._making_turn:
            print("error", error)
            if error < 60 or error > -60:
                self.stop()
                self._making_turn = False
            return
        if self._making_u_turn:
            print("error", error)
            if error < 60 or error > -60:
                self.stop()
                self._making_u_turn = False
            return
        if (w_min < 100 and h_min < 100):
            self._move_forward()
            return None
        if (pixels <= self._black_pixels + (self._black_pixels *
        ↪  self._threshold)) and  (pixels >= self._black_pixels -
        ↪  (self._black_pixels * self._threshold)):
            self._move(error)
            return None
        if pixels > (self._black_pixels + (self._black_pixels *
        ↪  self._threshold)):
            left_pixels, right_pixels, onLeft, onRight =
            ↪  self.check_side_pixels(mask)
            if onLeft or onRight:
                top_pixels_remaining, top_pixels_side,
                ↪  bottom_pixels_side, onTop, hastoStop =
                ↪  self.check_straight_pixels(mask)
                if hastoStop:
                    self.needMakeDecision = True
                    self.junction_decision(onLeft, onRight, onTop)
                    if top_pixels_remaining == 0:
                        self._move_forward()
                    return [left_pixels, right_pixels,
                    ↪  top_pixels_remaining, top_pixels_side,
                    ↪  bottom_pixels_side]
                self._move_forward()
                return [left_pixels, right_pixels, 0, 0, 0]
```

```
37              elif pixels < (self._black_pixels - (self._black_pixels *
                ↪ self._threshold)):
38                  self._move(error)
39                  return None
40          self._move(error)
41          return None
```

Figure 4.105: Adjust Orientation Function

The check_side_pixels method checks the number of black pixels on the left and right sides of the image to detect junctions or turns. It takes the binary mask of the image as input and divides the image into left and right halves, excluding the middle region. It counts the number of black pixels in each half and determines if the number of black pixels on either side exceeds a threshold, indicating a potential turn. The method returns the number of black pixels on the left and right sides, along with flags indicating whether a turn is detected. This information is used by _adjust_orientation to make decisions at junctions.

The check_straight_pixels method checks the number of black pixels in the top and bottom halves of the image to detect straight paths or junctions. It also takes the binary mask of the image as input and divides the image into top and bottom halves, excluding the middle region. It counts the number of black pixels in each half and determines if the number of black pixels in the bottom half exceeds the top half, indicating a potential junction. If a junction is detected, it checks the continuity of the line in the top half to determine if the robot should move forward. The method returns the number of black pixels in the top and bottom halves, along with flags indicating whether the robot should stop or move forward.

```python
def check_side_pixels(self, mask):
    onLeft = False
    onRight = False
    height, width = mask.shape

    # Defining middle region of the mask
    middle_start = (width // 2) - (self._middle_width // 2)
    middle_end = (width // 2) + (self._middle_width // 2)

    # Create a mask for the middle region and remove it from the original
    ↪ mask
    middle_mask = np.zeros_like(mask)
    middle_mask[:, middle_start:middle_end] = 255
    masked_binary = cv2.bitwise_and(mask, cv2.bitwise_not(middle_mask))

    # Split the masked binary into left and right halves
    left_half = masked_binary[:, :width // 2]
    right_half = masked_binary[:, width // 2:]

    # Count the black pixels in both halves
    left_pixels = np.sum(left_half == 255)
    right_pixels = np.sum(right_half == 255)

    # Define a threshold for the number of black pixels to consider left
    ↪ or right
    threshold_lr = (self._black_pixels // 3) - 20

    # Check if the left or right region has sufficient black pixels
    if left_pixels > threshold_lr:
        onLeft = True
    if right_pixels > threshold_lr:
        onRight = True

    return left_pixels, right_pixels, onLeft, onRight

```

Figure 4.106: Check Side Pixels Function

```
def check_straight_pixels(self, mask):
    onTop = False
    hastoStop = False
    height, width = mask.shape
    middle_start = (width // 2) - (self._middle_width // 2)
    middle_end = (width // 2) + (self._middle_width // 2)

    # Create a mask for the middle region and remove it from the original
    ↪ mask
    middle_mask = np.zeros_like(mask)
    middle_mask[:, middle_start:middle_end] = 255
    masked_binary = cv2.bitwise_and(mask, cv2.bitwise_not(middle_mask))

    # Split the masked binary into top and bottom halves
    top_half = masked_binary[:height // 2, :]
    bottom_half = masked_binary[height // 2:, :]

    # Count the white pixels in the top and bottom halves
    top_pixels = np.sum(top_half == 255)
    bottom_pixels = np.sum(bottom_half == 255)

    # Check if bottom pixels are greater than or equal to top pixels,
    ↪ implying a need to stop
    if bottom_pixels >= top_pixels:
        hastoStop = True
        middle_line = mask[:, middle_start:middle_end]
        height, _ = middle_line.shape

        # Split the middle line into top and bottom portions
        top_half = middle_line[:height // 2, :]
        bottom_half = middle_line[height // 2:, :]

        # Zero out the black pixels in the bottom portion
        bottom_half[bottom_half == 255] = 0

        # Count remaining white pixels in the top half
        top_pixels_remaining = np.sum(top_half == 255)
        continuity_threshold = 0.3 * self._black_pixels

        # Check if top pixels remaining are above the threshold
```

```
        if top_pixels_remaining >= continuity_threshold:
            onTop = True

    return top_pixels_remaining, top_pixels, bottom_pixels, onTop,
    ↪ hastoStop

```

Figure 4.107: Check Straight Pixels Function

Together, these methods form a robust navigation system that allows the robot to follow lines accurately and make informed decisions at junctions. The _adjust_orientation method continuously adjusts the robot's movement based on real-time data, while check_side_pixels and check_straight_pixels provide critical information about the robot's surroundings. This combination ensures the robot can navigate complex environments with precision and reliability, adapting its behavior based on the detected line and junction configurations.

Interaction Between Methods: Line Following: The _adjust_orientation method uses check_side_pixels and check_straight_pixels to determine if the robot is at a junction or should continue following the line. If the robot is on a straight path, it adjusts its orientation based on the error and moves forward.
Junction Detection: When the number of black pixels exceeds the threshold,
check_side_pixels and check_straight_pixels are called to detect junctions. Based on the results, the robot makes a decision to turn left, right, or move forward.
Navigation: The junction_decision method (in child classes like Mapping and Carrying) uses the output of check_side_pixels and check_straight_pixels to navigate junctions and reach goal zones.

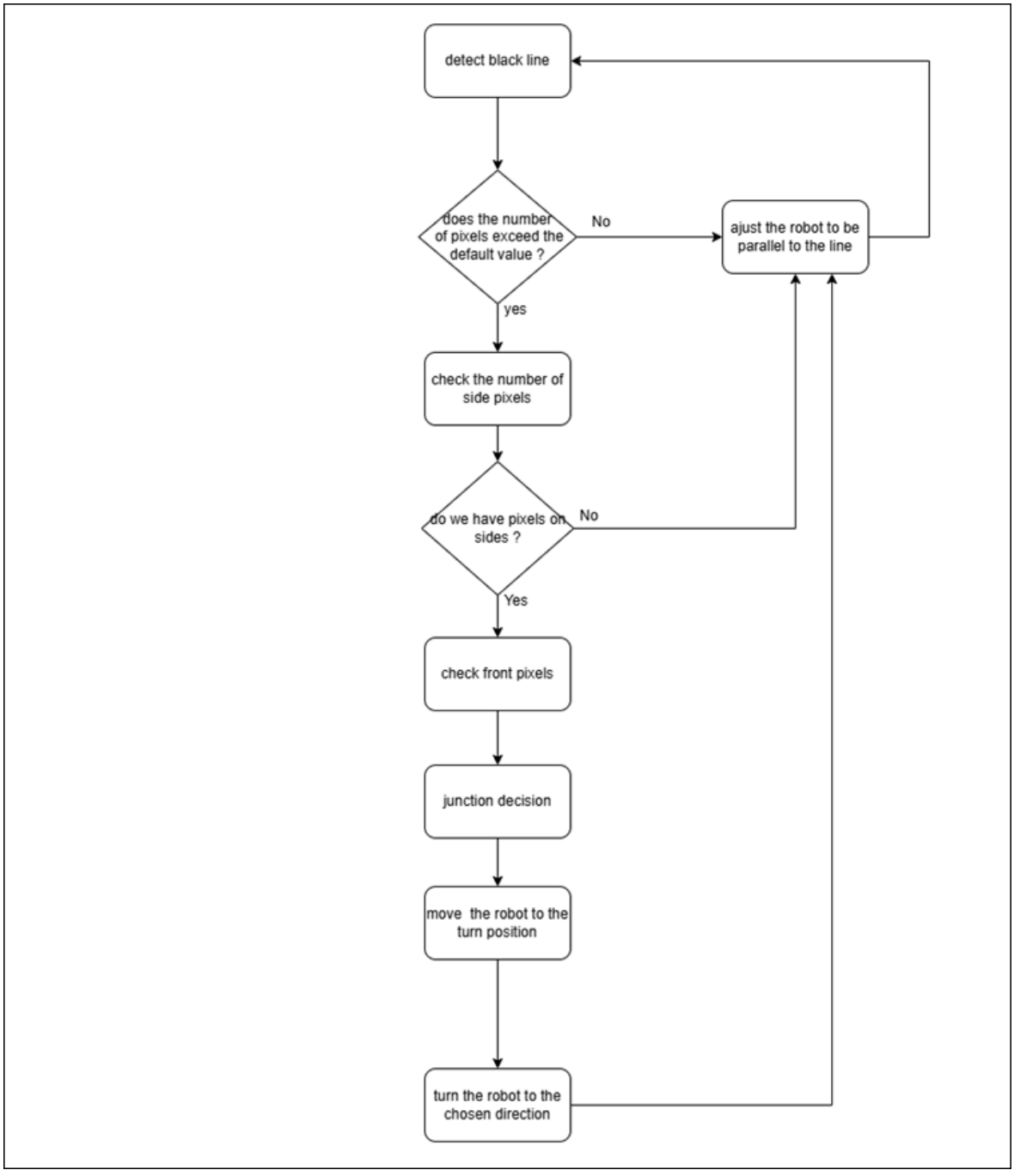


Figure 4.108: line following & junction flowchart

Example Scenario

- Following a Straight Line: The robot detects a line with a small error and a number of black pixels within the threshold. The _adjust_orientation method adjusts the robot's orientation and moves it forward (see fig. 4.107 Robot following the line and detecting a junction) .
- Approaching a Junction: The robot detects a significant increase in black pixels, indicating a junction. The check_side_pixels method detects more black pixels on the left side, suggesting a left turn. The check_straight_pixels method confirms that the robot should stop and make a decision. The junction_decision method instructs the robot to turn left, so the robot move to the turn positrion (see fig. 4.108 the robot is at the turn position), and turn to the choosen direction (see fig. 4.109 The robot turns to the chosen direction).
- Navigating a Complex Path: The robot uses a combination of check_side_pixels, check_straight_pixels, and junction_decision to navigate through multiple junctions and reach its goal.

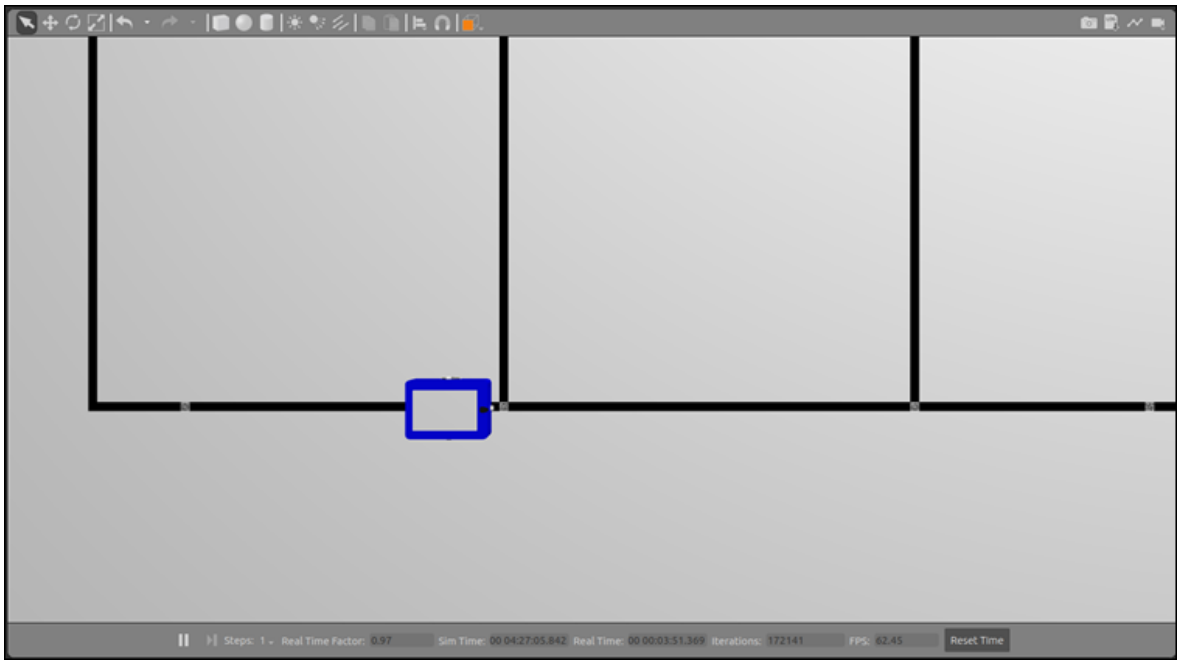


Figure 4.109: Robot following the line and detecting a junction

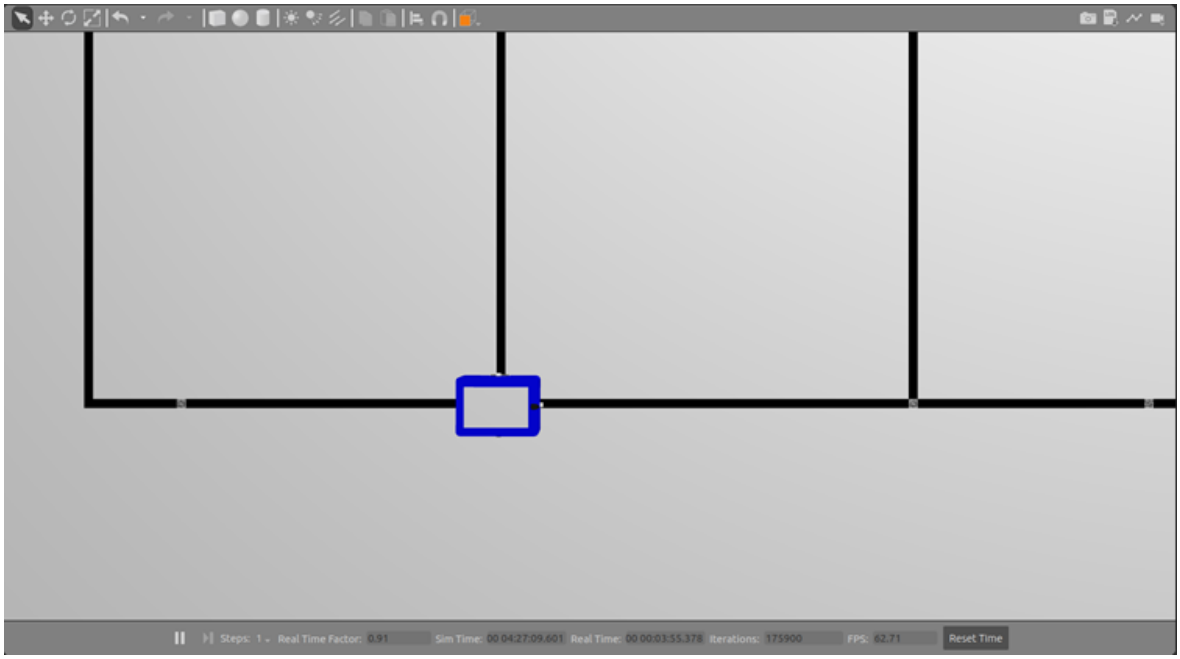


Figure 4.110: the robot is at the turn position

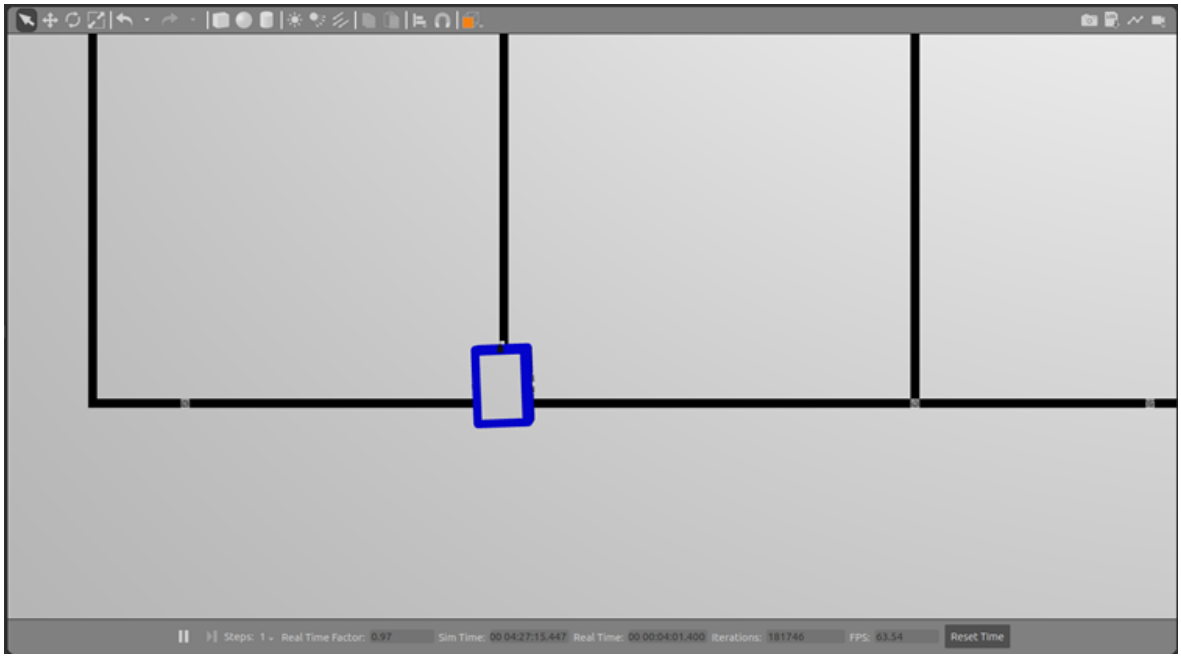


Figure 4.111: The robot turns to the chosen direction

Essentials parameters The parameters (self.param, self._black_pixels, self._sideBlackPixels, self._threshold, self._middle_width, self.distanceToQr, and obstacle_distance_threshold) are critical to the functionality of the Task class. These values were carefully tuned through extensive testing and experimentation to ensure optimal performance. Let's break down each parameter, its purpose, and how it was determined:
_black_pixels: Represents the expected number of black pixels in the camera image when the robot is following a straight the line. With a default Value of 493850, this value was determined by analyzing the camera image when the robot is perfectly aligned on the line. This parameter is used as a reference value for line-following logic. If the number of black pixels deviates significantly from this value, the robot adjusts its orientation.
_sideBlackPixels: Represents the expected number of black pixels on the sides of the camera image when the robot is approaching a turn. Its Value is 414556, Determined by analysing the camera image when the robot is approaching a junction or turn.
It's used to detect when the robot should initiate a turn (e.g., when the number of black pixels on one side exceeds this threshold).
_threshold: Defines the acceptable deviation from self._black_pixels for line-following.
The correct value found after test is 0.119 (11.9%). This parameter determined through experimentation to balance sensitivity and robustness. If the number of black pixels deviates by more than 11.9% from self._black_pixels, the robot adjusts its orientation.
_middle_width: Defines the width of the region of interest (ROI) in the camera image for line detection. Its value is 580 (pixels width). Set to focus on the central portion of the camera image, where the line is most likely to be.Adjusted to ensure the robot can detect the line even if it deviates slightly from the center.
distanceToQr: Represents the distance (in meters) from the robot to the QR code when it is detected. With a value of 0.3869 meters, determined by measuring the distance at which the QR code is reliably detected and decoded and ensures the robot stops at an appropriate distance from the QR code for accurate processing.
obstacle_distance_threshold: Defines the minimum distance (in meters) at which an obstacle is considered too close and requires avoidance. Its value is 0.3 (meters).
Determined through testing to balance safety and efficiency. A smaller value could risk collisions, while a larger value could cause unnecessary detours.

How These Values Were Determined:

- Iterative Testing: Each parameter was initially set to a rough estimate based on theoretical calculations or prior experience. The robot was then tested in various scenarios (e.g., line following, obstacle avoidance, QR code detection) to observe its behaviour.

- Incremental Adjustments: Parameters were adjusted incrementally to improve performance. For example: Adjusting self._threshold to reduce oscillations during line following.
- Real-World Validation: The robot was tested in real-world environments (e.g., with varying lighting conditions, uneven surfaces, and different obstacle configurations) to ensure robustness.
- Trade-Offs: Some parameters required trade-offs. For example: A larger obstacle_distance_threshold increases safety but may result in longer detours.

Child Classes: Mapping and Carrying The child classes (Mapping and Carrying) will extend the Task class to implement task-specific logic.
Mapping: Focuses on exploring the environment, detecting QR codes, and building a map.
Carrying: Focuses on transporting items between specified zones.

4.81.2.2 Mapping

The Mapping class is designed to explore the environment, detect QR codes, and store their positions in a database. It inherits from the Task class, leveraging its core functionality such as robot control, obstacle avoidance, and line following, while adding mapping-specific logic to fulfill its unique role. This inheritance allows the Mapping class to reuse existing methods and focus on extending functionality for environment exploration and QR code detection.
One of the key features of the Mapping class is QR code detection, which is handled by the _check_qr method. This method detects QR codes using image processing techniques and stores the detected QR codes along with their positions in a dictionary (self.qrcodes). To prevent duplicate detections, the class compares new QR codes with the last detected one (self._lastQrCode), ensuring that each QR code is only recorded once. This avoids redundancy and improves the efficiency of the mapping process.
For environment exploration, the class utilizes the junction_decision method to navigate junctions systematically. When a junction is detected (e.g., left, right, or top), the robot makes a decision to turn or move forward based on the exploration strategy. This ensures that the robot explores all possible paths in the environment, leaving no area unmapped. The systematic approach guarantees comprehensive coverage, which is essential for accurate mapping.
The Mapping class also integrates with an SQLite database (qr_code.db) to store detected QR codes and their positions. The _store method is responsible for inserting QR code data into the database, while the _checkExistingQrCodes method checks for existing QR codes to avoid redundant entries. This ensures that the database remains up-to-date and free of duplicates. The database schema includes a table named qr_code with columns for id (primary

key), name (QR code identifier), position_x (X-coordinate), and position_y (Y-coordinate), providing a structured way to store and retrieve mapping data.
When the mapping process is complete, the class emits a signal (fsignal) containing the detected QR codes, notifying other system components of the task's completion. It also calls the parent class's _task_finished method to clean up resources and notify the system, ensuring a smooth transition to the next task. The use of the signalslot library enables decoupled communication between the Mapping class and other components, enhancing modularity and flexibility.
The class implements robust error handling to manage potential issues during database operations, such as table creation or data insertion. Errors are logged using rospy.logerr, providing detailed information for debugging and maintenance. Additionally, the class ensures that the database connection is properly closed, preventing resource leaks and ensuring data integrity.

How It Works The Mapping class operates through a well-defined workflow that ensures systematic environment exploration, QR code detection, and data storage. Here's how it works in detail:
Initialization
The Mapping class begins by initializing itself through the parent class's constructor using super().__init__("mapping"). This sets up the core functionality inherited from the Task class, such as robot control, obstacle avoidance, and line following. Additionally, the class initializes the fsignal, a signal used to notify other components when the mapping task is complete. This signal is essential for decoupled communication within the system.
Start Mapping
The mapping process is initiated by calling the start method. This method first checks for existing QR codes in the SQLite database using the _checkExistingQrCodes method. If QR codes are already present in the database, the task completes immediately by emitting the fsignal with the existing data. This avoids redundant mapping and saves time. If no QR codes are found, the robot begins exploring the environment, systematically navigating through the space to detect and record new QR codes.
QR Code Detection
QR code detection is handled by the _check_qr method. When a QR code is detected, the method processes it by converting its position to global coordinates using the _calculate_distance function. This ensures that the QR code's location is accurately recorded relative to the robot's environment. The detected QR code and its position are then stored in the self.qrcodes dictionary. To prevent duplicate detections, the method compares the new QR code with the last detected one (self._lastQrCode). If the QR code has

```
def _check_qr(self, decoded_text):
  if not self._processQrCode :
    self._processQrCode = True
    if decoded_text[0] == "None" or decoded_text[0] is None:
        self._processQrCode = False
        return
    if decoded_text[0] != self._lastQrCode:
        if len(self.qrcodes) >= 1:
          if (decoded_text[0] == list(self.qrcodes.keys())[0]):
              self._processQrCode = False
              self._task_finished(message="Mapping process finished")
              return
        self.hasDetectedQrRecently = False
        position = self._calculate_distance(self.robot_pose)
        self.qrcodes[decoded_text[0]] = position
        self._lastQrCode = decoded_text[0]
        self._processQrCode = False
    self._processQrCode = False

```

Figure 4.112: Mapping Qr Code Checker

already been recorded, it is ignored, ensuring that only unique QR codes are stored.

Junction Navigation

The junction_decision method plays a critical role in navigating the robot through the environment. When the robot encounters a junction, this method determines the appropriate action based on the type of junction detected:

- If a top junction is detected, the robot moves forward to continue exploration.
- If a left or right junction is detected, the robot prepares to turn, ensuring that all paths are systematically explored. This method ensures comprehensive coverage of the environment, leaving no area unmapped.

Task Completion

Once the mapping process is complete, the _task_finished method is called to wrap up the task. This method performs several key actions:

1. It stores the detected QR codes in the SQLite database using the _store method, ensuring that the data is saved for future use.

```
def junction_decision(self, onLeft, onRight, onTop):
    tm = 3
    if onTop:
    print("On top")
    tm = 1
    self._move_forward()
    self.timer= rospy.Timer(rospy.Duration(tm),self.resume_processing)
    elif onLeft:
        self._turnSide = "left"
        self.moveToTurnPosition = True
    elif onRight:
        self._turnSide = "right"
        self.moveToTurnPosition = True

```

Figure 4.113: Junction decision of mapping class

2. It emits the fsignal with the QR code data, notifying other system components that the task is complete.

3. It calls the parent class's _task_finished method to clean up resources and notify the system, ensuring a smooth transition to the next task.

Impact on the System The Mapping class enables the robot to autonomously explore its environment, detect QR codes, and store their positions for future use. It leverages the parent class's functionality for robot control and obstacle avoidance, demonstrating the power of inheritance and code reuse. The integration with SQLite ensures persistent storage of mapping data, enabling other tasks (e.g., carrying) to use this information.

4.81.2.3 Carrying

The Carrying class is a specialized child class of the Task class, designed to handle the transportation of items between specified zones. It extends the parent class by adding carrying-specific functionality, such as QR code navigation, lifting mechanism control, and complex junction navigation. By leveraging the core functionality of the Task class—such as robot control, obstacle avoidance, and line following—the Carrying class focuses on implementing logic tailored to item transportation tasks.

Key Features and Functionality Task Initialization:

The Carrying class initializes by accepting a list of tasks (params) that specify the zones and actions to be performed, such as loading or unloading. It calls the parent class's constructor with the task name "carrying" to set up the core functionality. This initialization ensures the robot is ready to execute the carrying task with the necessary parameters.

QR Code Navigation:

The class uses QR codes to navigate to goal positions. It implements the _check_qr method to detect QR codes and determine if the robot has reached a goal zone. By comparing the detected QR code with the target zone, the robot can confirm its location and proceed with the next action, such as loading or unloading.

Lifting Mechanism:

The Carrying class controls a lifting mechanism to handle items during loading and unloading. The _lift method is responsible for interpolating the lifting motion over a specified duration, ensuring smooth and precise movement. Commands for the lifting mechanism are published to the /position_joint_controller/command topic, enabling real-time control.

Junction Navigation:

The class extends the junction_decision method to handle complex navigation decisions. When the robot encounters a junction, it determines the best direction to reach the goal zone based on QR code positions and intersections. The class uses a shortest path algorithm to choose between turning left, right, or making a U-turn, ensuring efficient navigation.

Task Completion:

The class tracks the progress of the task using self._currentTask. Once all goals have been reached, the task is marked as complete, and a signal (fsignal) is emitted to notify the system. This ensures that other components are aware of the task's completion and can take appropriate action.

How It Works Initialization:

The Carrying class initializes by calling the parent class's constructor and setting up the task parameters. It prepares the robot for the carrying task by loading QR code positions and configuring the lifting mechanism.

Navigation and QR Code Detection.

The robot navigates through the environment using QR codes as markers. The _check_qr method detects QR codes and determines if the robot has reached a goal zone. If the target zone is reached, the robot proceeds with loading or unloading.

Lifting Mechanism Control:

The _lift method controls the lifting mechanism, interpolating its motion to ensure smooth

operation. This method is called during loading and unloading to handle items efficiently.
Junction Navigation:
The junction navigation is a critical component of the Carrying class, responsible for handling navigation decisions at junctions. Its purpose is to determine the best action—such as turning left, right, or moving forward—based on the detected QR codes, the robot's current position, and the goal zone. This method ensures the robot navigates efficiently and reaches its destination while avoiding unnecessary detours.
The method takes three key parameters: onLeft Indicates whether a left turn is detected, onRight Indicates whether a right turn is detected and onTop Indicates whether a straight path is detected. These parameters provide information about the robot's immediate environment, helping it decide the best course of action.
The method's logic is divided into two main scenarios: when no QR code is detected and when a QR code is detected.
No QR Code Detected: If no QR code has been scanned recently, the robot makes a decision based on the detected junctions:

- If a left or right turn is detected, the robot prepares to turn in the corresponding direction.
- If a straight path is detected, the robot moves forward to continue its journey.

This logic ensures the robot continues exploring or navigating even when no QR codes are present, maintaining progress toward its goal.
QR Code Detected: If a QR code has been scanned, the robot checks whether it corresponds to a goal zone or an intersection:

- If the QR code is a goal zone, the robot moves to the lifting position and performs the required action, such as loading or unloading. This marks a key milestone in the task.
- If the QR code is an intersection, the robot uses the _chooseSide or _chooseSideToGo method to determine the best direction to reach the goal zone. These methods calculate the optimal path based on the robot's current position, the goal zone's location, and the available routes.

This logic ensures the robot makes informed decisions at intersections, minimizing travel time and energy consumption.
Based on the decision-making process, the method publishes velocity commands (self.msg) to the /cmd_vel topic. These commands execute the chosen action, such as turning left, turning right, or moving forward. This ensures the robot's movements are precise and aligned with the navigation strategy.

```
def junction_decision(self, onLeft, onRight, onTop):
    print("Making decision")
    print(self.hasDetectedQrRecently)
    self.stop()
    tm = 3
    current = self._params[self._currentTask]

    if not self.hasDetectedQrRecently:  # no qrCode has been scanned
        if onLeft and (not onTop) and (not onRight):
            self._turnSide = "left"
            self.moveToTurnPosition = True
        elif onRight and (not onTop) and (not onLeft):
            self._turnSide = "right"
            self.moveToTurnPosition = True
        elif onTop:
            tm = 2
            self._move_forward()
            self.timer = rospy.Timer(rospy.Duration(tm),
             ↪  self.resume_processing, oneshot=True)
        else:  # if the robot can't go straight, failed the task
            self._task_failed("The robot is stuck : should go straight")

    elif self._lastQrCode:  # qrCode has been scanned
        if self._lastQrCode in self.qrcodes:
            if self._isStationSide(self._lastQrCode):
                tm = 2
                self._move_forward()
                self.timer = rospy.Timer(rospy.Duration(tm),
                 ↪  self.resume_processing, oneshot=True)
            else:
                if self.goal_in_db:
                    current = self._params[self._currentTask]
                    zArr = current["zone"].split(" ")
                    goal = f"{zArr[0]}_{zArr[1]}_center"
                    goalPos = self.qrcodes.get(goal, (None, None))
                    side = self._chooseSideToGo(onTop, onRight, onLeft,
                     ↪  goalPos)
                    if side == "S":
                        tm = 2
                        self._move_forward()
```

```
                    self.timer = rospy.Timer(rospy.Duration(tm),
                    ↪ self.resume_processing, oneshot=True)
                elif side == "R":
                    self._turnSide = "right"
                    self.moveToTurnPosition = True
                elif side == "L":
                    self._turnSide = "left"
                    self.moveToTurnPosition = True
                elif side == "B":
                    tm = 6
                    self._U_turn()
                    self.timer = rospy.Timer(rospy.Duration(tm),
                    ↪ self.resume_processing, oneshot=True)
                elif side == "0":
                    return
            else:
                intersections =
                ↪ self._getIntersection(current['zone'])
                if self._lastQrCode in [intersections[0][0],
                ↪ intersections[1][0]]:
                    if onLeft:
                        self._turnSide = "left"
                        self.moveToTurnPosition = True
                    elif onRight:
                        self._turnSide = "right"
                        self.moveToTurnPosition = True
                    else:
                        self._task_failed(
                        ↪ "The robot is stuck : should turn")
                else:
                    if onLeft and (not onTop) and (not onRight):
                        self._turnSide = "left"
                        self.moveToTurnPosition = True
                    elif onRight and (not onTop) and (not onLeft):
                        self._turnSide = "right"
                        self.moveToTurnPosition = True
                    else:
                        print("Not a corner, using shortest path")
                        side = self._chooseSide(onTop, onRight,
                        ↪ onLeft, intersections)
```

```
72                              if side == "S":
73                                  tm = 2
74                                  self._move_forward()
75                                  self.timer =
                                     ↪  rospy.Timer(rospy.Duration(tm),
                                     ↪  self.resume_processing, oneshot=True)
76                              elif side == "R":
77                                  self._turnSide = "right"
78                                  self.moveToTurnPosition = True
79                              elif side == "L":
80                                  self._turnSide = "left"
81                                  self.moveToTurnPosition = True
82                              elif side == "B":
83                                  tm = 6
84                                  self._U_turn()
85                                  self.timer =
                                     ↪  rospy.Timer(rospy.Duration(tm),
                                     ↪  self.resume_processing, oneshot=True)
86                              elif side == "0":
87                                  tm = 6
88                                  self._U_turn()
89                                  self.timer =
                                     ↪  rospy.Timer(rospy.Duration(tm),
                                     ↪  self.resume_processing, oneshot=True)
90                                  rospy.logerr("Wrong direction")
91                                  return
92          else:
93              tm = 2
94              self._move_forward()
95              self.timer = rospy.Timer(rospy.Duration(tm),
                 ↪  self.resume_processing, oneshot=True)
96              rospy.logerr("The robot is stuck : doesn't know what to do")
```

Figure 4.114: Junction Decision Function Of Carrying Process

Task Completion: Once all goals have been reached, the task is marked as complete, and the fsignal is emitted to notify the system. The parent class's cleanup methods are called to ensure resources are released and the system is ready for the next task.

Interaction Between Methods

- Junction Detection: The junction_decision method detects junctions and determines if the robot should turn left, right, or move forward. If a QR code is detected, it uses _chooseSide or _chooseSideToGo to determine the best direction to reach the goal zone.
- Path Planning: The _chooseSide method calculates the shortest path to the goal zone based on the positions of intersections. The _chooseSideToGo method calculates the shortest path to a specific target position (e.g., a goal zone).
- Navigation:
  - Based on the chosen direction, the robot executes the corresponding action (e.g., turn left, turn right, move forward).

Example Scenario

1. Approaching a Junction: The robot detects a junction with options to turn left, right, or move forward. The junction_decision method calls _chooseSide to determine the best direction to reach the goal zone.
2. Calculating the Shortest Path: The _chooseSide method calculates the Euclidean distance to each intersection and chooses the direction with the minimum distance. If the goal zone is directly ahead, the robot moves forward. If it's to the left or right, the robot turns accordingly.
3. Executing the Action: The robot executes the chosen action (e.g., turn left, turn right, move forward) and continues navigating toward the goal zone.

```python
def _adjust_orientation(self, error, angle, pixels, mask, w_min, h_min):

        if not self.isLifting :
            if self.moveToLiftPosition:
                if self._distanceToLifePosition() > 0.005:
                    self._move(error)
                    return None
                else:
                    print("Lift position reached")
                    self.stop()
                    self.isLifting = True
                    self._lift()
                return None
            else:
                return super()._adjust_orientation(error, angle, pixels,
                 ↪  mask, w_min, h_min)

```

Figure 4.115: Adjust Orientation Function of Carrying Class

Impact on the System

- These methods enable the robot to autonomously navigate junctions and reach goal zones efficiently, ensuring reliable and efficient task execution.
- They demonstrate the importance of path planning and decision-making algorithms in robotics, showcasing your ability to implement complex navigation logic.

```python
def _lift(self, duration=3):
    current = self._params[self._currentTask]
    liftType = current["type"]
    start = 0 if liftType == "Loading" else 1
    end = 1 if liftType == "Loading" else 0

    start_time = rospy.Time.now()
    end_time = start_time + rospy.Duration.from_sec(duration)
    rate = rospy.Rate(100)
    while rospy.Time.now() < end_time and not rospy.is_shutdown():
        current_time = rospy.Time.now()
        elapsed = (current_time - start_time).to_sec()
        fraction = elapsed / duration
        fraction = min(fraction, 1.0)  # Fixed the missing parenthesis
        ↪ here
        current_value = start + fraction * (end - start)
        self.liftPub.publish(current_value)
        rate.sleep()

    self.liftPub.publish(end)
    self.isLifting = False
    self.moveToLiftPosition = False

    self._currentTask += 1
    if(self._currentTask == len(self._params)):
        self.stop()
        self._task_finished(message="All goals have been reached")
```

Figure 4.116: Lift function

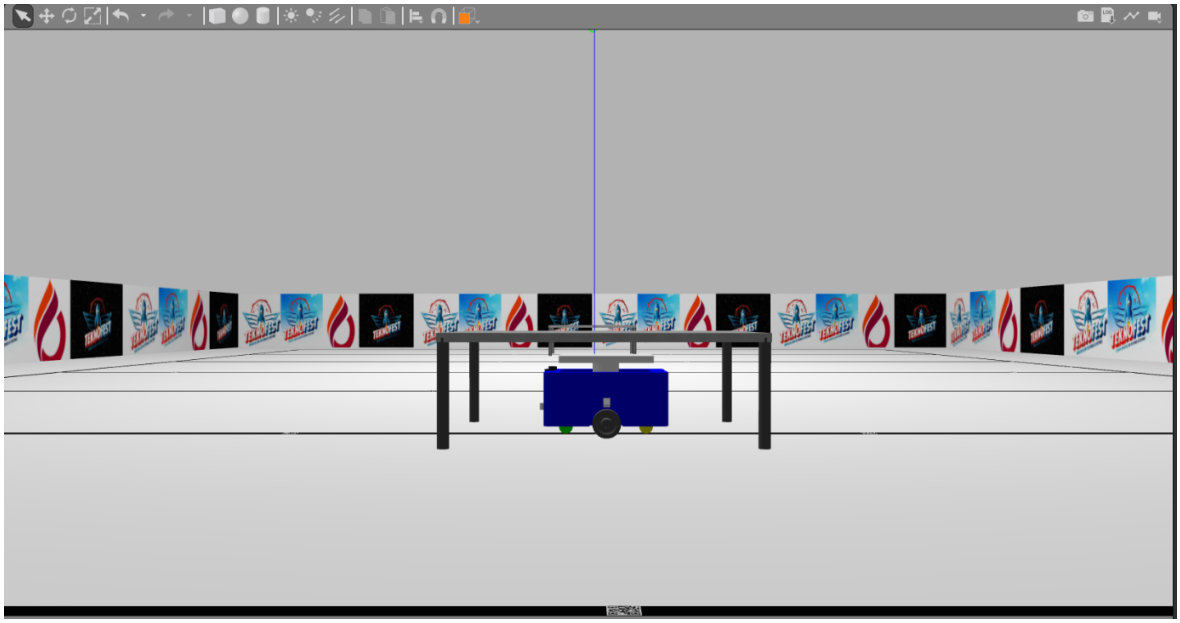


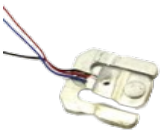
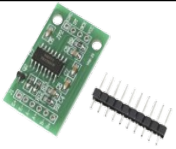
Figure 4.117: the robot ready to lift a charge

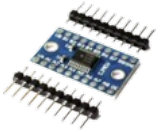
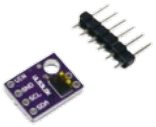
Chapter 5

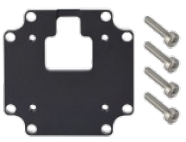
CONCLUSION AND FUTURE WORKS

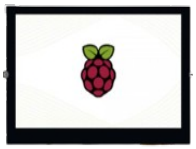
5.1 COST

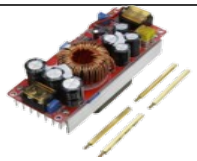
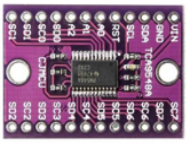
Table 5.1: here is the list of components

Components	Quantity	Price(per Unit)	ref
Raspberry Pi 4 8GB RAM	1	3127.03 ₺	
ESP32-S3-DevKitC-1-N8R8 - ESP32-S3-WROOM-1	2	1220 ₺	
Closed Loop Stepper Driver V4.1 0-8.0A 24-48VDC CL57T	2	1186 ₺	
Motorobit Weight Sensor 120 kg	2	768.2 ₺	
Weight Sensor - Load Sensor 50Kg.	4	29.7 ₺	
Load Cell Amplifier - HX711	4	27.3 ₺	

BTS7960B 40 Amp Motor Driver Board	1	188.82 ₺	
Barcode Scanner Module 1D/2D Codes Reader	1	1261.83 ₺	
QTRXL-MD-01A Reflectance Sensor Array	4	90.57 ₺	
Gravity: HUSKYLENS	1	1723.14 ₺	
IMU Sensor / 9 Axis MPU9255 IMU and Barometric Sensor (Low Power)	1	1058.31 ₺	
RPLIDAR - 360 degree Laser Scanner Development Kit	1	5029.72 ₺	
TXS0108E 8 Channel Voltage Level Transducer	4	40 ₺	
The VL53L0X is a time-of-flight (ToF) distance sensor	10	101.76 ₺	
UV Solder Mask	3	180.78 ₺	
LM2596HV/LM2576 Voltage Regulator for Multiple power supply	4	36.09 ₺	

Aluminum heatsink	2	439 ₺	
5V 8 Channel Relay Card	1	154.68 ₺	
P Series Nema 23 Closed Loop Stepper Motor 2Nm(283.28oz.in) with Electromagnetic Brake	2	2971.78 ₺	
EG Series Planetary Gear-box Gear Ratio 20:1 Backlash 20arc-min for 10mm Shaft Nema 23 Stepper Motor	2	1642 ₺	
Shaft Sleeve Adaptor 11mm to 8mm for NMRV30 Worm Gearbox	4	35 ₺	
Single Output Shaft for NMRV30 Worm Gearbox	4	121.37 ₺	
Double Output Shaft for NMRV30 Worm Gearbox	4	121.37 ₺	
NEMA 23 Stepper Motor Vi-bration Damper	4	243.74 ₺	
Nema 23 Bracket for Stepper Motor	4	243.74 ₺	
Nema 23 Flange for ISC And ISD Series Drivers	3	175.28 ₺	

AWG 20 High-flexible with Shield Layer Stepper Motor Cable	2	43.25 ₺	
TP-Link TL-WR840N	1	569 ₺	
Raspberry Pi 4.3 Inch Capacitive Touch Screen DSI Interface 800”480	1	1750.28 ₺	
Nema 8R 5W 87dB 90X39mm Speaker	1	108.11 ₺	
Nema RS232 to Bluetooth Series Adapter	2	455 ₺	
12V 70 AH AGM BATTERY	1	5000 ₺	
Battery Chargers 6V/2A 12V/2A Full Automatic Smart Battery	1	642.99 ₺	
RS232 Adapter Cable to USB 2.0	2	453.65 ₺	
Motor and encoder extension cable kit	2	351 ₺	
DC 12V Electric Linear Actuator Force 6000N	1	2479 ₺	

WM-045 DC-DC 150W Voltage Booster	1	521.04 ₺	
Motorobit DC-DC 1500W 30A Voltage Boost Module	1	881.76 ₺	
TCA9548A I2C Çoklayıcı / Multiplexer Kartı	1	40.66 ₺	
3B Printer Limit Switch	2	37.07 ₺	
Drn956 16mm Acil - Stop Switch (Kafa 27mm)	1	145.08 ₺	

APPENDIX

Bearing Specifications

- Bearing Type: Deep Groove Ball Bearing (NSK 6201)
- Inner Diameter: 12 mm
- Outer Diameter: 32 mm
- Load Capacity: 7.28 kN

Material Properties

- AISI 1045 Steel: Yield Strength = 530 MPa, Ultimate Tensile Strength = 625 MPa
- AISI 52100 Chrome Steel: High Hardness (Rockwell C 60-67), Wear Resistance

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