Fleet Management System

A

Project Report

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Submitted by

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Certificate

Certified that project entitled "Fleet Management System" at Addverb Technologies Pvt. Ltd. which is being submitted by Manveer Singh (University Registration No. 102015114) to the Department of Electronics and Communication Engineering, TIET, Patiala, Punjab is a record of project work carried out by him under guidance and supervision of Dr. Geetika Dua and Mr. Yuvraj Singh. The matter presented in this project report does not incorporate without acknowledgement any material previously published or written by any other person except where due reference is made in the text.

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Place: Addverb Technologies Pvt. Ltd., Noida

Abstract

This report presents a comprehensive overview of my internship experience as a Mobile Robotics Intern at Addverb Technologies Pvt. Ltd., a global leader in robotics and automation solutions. Conducted during my project semester, this offline internship has provided me with invaluable hands-on experience and insights into the cutting-edge field of intralogistics automation. The primary focus of my project was to develop and integrate advanced autonomous mobile robots (AMRs) to optimize warehouse processes, enhance operational efficiency, and reduce operational costs.

The report begins with an introduction to Addverb Technologies, outlining the company's pivotal role in revolutionizing intralogistics operations through its innovative products and solutions. It then delves into the specific project undertaken, detailing its significance in addressing contemporary challenges faced by modern warehouses, such as labour shortages and the need for scalable and flexible automation solutions.

Key objectives of the project include the development and integration of mobile robotic systems, optimization of warehouse processes, enhancement of safety and reliability, and the creation of scalable and flexible solutions. The project also emphasizes the importance of continuous innovation and improvement, ensuring that the solutions developed remain at the forefront of the industry.

Throughout the internship, I assumed various responsibilities, including designing and developing AMRs, implementing advanced algorithms for task optimization, and ensuring the safety and reliability of robotic systems. The report highlights the work done, challenges faced, and innovative solutions introduced during the project, demonstrating my ability to apply theoretical knowledge to practical challenges and contribute meaningfully to the field of robotics automation.

In conclusion, this report not only showcases my growth as a professional but also underscores the transformative potential of mobile robotics in modern warehousing. By achieving the project's objectives, Addverb Technologies continues to reinforce its position as a leader in robotics automation, setting new standards for efficiency, reliability, and innovation in the industry

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List of Abbreviations

FMS	Fleet Management System
AGV	Automated Guided Vehicles
AMR	Autonomous Mobile Robots
ROS	Robots Operating System
IMU	Inertial Memorial Unit
SLAM	Simultaneous Localization and Mapping

Chapter 1 – Introduction

During the course of my project semester, I engaged as a Mobile Robotics Intern at Addverb Technologies Pvt. Ltd., a global leader in robotics and automation solutions. This opportunity has allowed me to immerse myself in the dynamic field of intralogistics automation, working directly with cutting-edge technologies and innovative solutions that are transforming the industry.

My internship at Addverb has been conducted offline, providing me with hands-on experience and direct engagement with the company's advanced systems and processes. I am nearing the completion of my training, which has been both rigorous and rewarding, equipping me with invaluable skills and insights.

This project report aims to provide a comprehensive overview of my experiences and contributions during this internship. It will cover various aspects, including:

- **Company Overview**: An introduction to Addverb Technologies, highlighting its role as a pioneer in robotics automation and intralogistics solutions.
- **Project Undertaken**: Detailed information about the specific project I have been working on, including its objectives, scope, and significance.
- **Responsibilities Undertaken**: An outline of the roles and responsibilities I have assumed, showcasing my involvement in different phases of the project.
- **Work Done**: A summary of the tasks and activities I have completed, demonstrating my application of theoretical knowledge to practical challenges.
- **Challenges Faced**: An analysis of the obstacles and difficulties encountered during the project, along with the strategies employed to overcome them.
- **Innovations Introduced**: A discussion on the innovative solutions and approaches I have contributed to the project, reflecting my ability to think creatively and solve problems effectively.

This section provides an overview of the company and the project, setting the stage for a detailed exploration of my internship journey. Through this report, I aim to highlight my growth as a professional, the impact of my work, and the valuable experiences gained during my tenure at Addverb Technologies.

1.1 About Company

Addverb is a pioneering global robotics company headquartered in India. The company is at the forefront of revolutionizing intralogistics operations, leveraging cutting-edge technologies to significantly enhance efficiency and accuracy. Addverb has harnessed the full potential of automated systems through a seamless integration of in-house manufactured hardware and robust software, driving advancements in the field of robotics automation.

At the core of Addverb's success is a team of passionate individuals dedicated to fostering innovation and delivering leading-edge solutions for future warehouses and supply chains. The company's state-of-the-art manufacturing capabilities provide the flexibility to offer innovative, plug-and-play solutions from an extensive product portfolio.

ADDVERB
Human | Robot | Possibilities

Addverb's operations span across four key verticals in the intralogistics sector:

- **Robotics**: Developing advanced robotic systems to automate and optimize warehouse processes.
- **Automated Storage and Retrieval Systems (AS/RS)**: Designing and implementing systems that enhance storage efficiency and retrieval accuracy.
- **Picking**: Innovating picking solutions to streamline and accelerate order fulfilment.
- **Software**: Creating sophisticated software solutions, including Warehouse Management Systems (WMS), Warehouse Control Systems (WCS), and Manufacturing Execution Systems (MES), to integrate and optimize warehouse operations.

Their specialties include:

- **Warehouse Automation**: Enhancing warehouse operations through automated systems and processes.
- **Consultancy**: Providing expert advice and solutions tailored to specific logistics and warehouse needs.
- **Robotics**: Designing and deploying robotic systems for various applications in intralogistics.
- **Software (WMS/WCS/MES)**: Developing comprehensive software solutions to manage, control, and execute warehouse operations efficiently.
- **Internet of Things (IoT)**: Implementing IoT technologies to connect and automate devices within the warehouse.
- **Industrial IoT**: Leveraging IoT for industrial applications to enhance operational efficiency.
- **Intralogistics Automation**: Automating internal logistics processes to improve productivity and accuracy.
- **Automation**: Implementing automated systems across various aspects of warehouse and supply chain operations.
- **Warehouse Operations**: Optimizing overall warehouse operations for better performance and efficiency.

By combining technological innovation with practical solutions, Addverb is poised to lead the charge in the domain of robotics automation, offering unparalleled solutions to meet the evolving needs of the intralogistics industry.

Website: http://www.addverb.com

1.2 Fleet Management System

My current focus is on the project pertaining to the Fleet Management System (FMS). The FMS system, as its name implies, assumes the responsibility of overseeing the entirety of the fleet within a warehouse. The fleet comprises a diverse range of Automated Guided Vehicles (AGVs), namely Zippy 10, Zippy 25, Zippy 40, Zippy X, Zippy Tug, and it is anticipated to integrate Autonomous Mobile Robots (AMRs) in the near future.

In general, it refers to the coordination and control of a group of mobile robots within a warehouse or distribution center. One of the key elements of FMS is the coordination of the robots' movements and tasks. This includes ensuring that the robots are moving in the most efficient way possible, avoiding collisions and other disruptions, and making sure that the robots are working on the most important tasks at any given time. This coordination is typically managed through a central control system, which can be programmed to prioritize certain tasks, adjust the robots' routes, and monitor their progress.

Another important aspect of FMS technology is monitoring and analyzing the performance of the robots. This includes tracking the robots' locations, identifying any issues or errors that may be occurring, and identifying areas for improvement to achieve maximum efficiency. This data can be used to optimize the robots' performance, such as adjusting their routes or increasing their speed, to improve overall warehouse efficiency.

In addition to these technical aspects, FMS also involves managing the human-robot interaction. It is important to ensure that the robots are working in a safe and efficient manner, without interfering with the work of human employees. This can include training human employees to safely interact with the robots, developing clear protocols for robot-human interaction, and ensuring that the robots are easily distinguishable from humans.

Overall, FMS plays a crucial role in warehouse automation. It helps to ensure that the robots are working effectively and efficiently to improve warehouse operations and that the robots are properly maintained and repaired to minimize disruptions. Through proper mobile robot fleet management, warehouses can increase efficiency, reduce costs, and improve customer satisfaction.

FMS is the coordination, control and monitoring of a group of mobile robots in a warehouse or distribution center. This includes coordination of robots' movements and tasks, monitoring and analyzing the performance of robots, maintenance and repair, and managing the human-robot interaction. By effectively managing the fleet of mobile robots, warehouses can increase efficiency, reduce costs and improve customer satisfaction. With the increasing use of mobile robots in warehouses, effective fleet management will be increasingly important in ensuring the smooth operation of the warehouse.

1.3 Importance of FMS

The project I am undertaking at Addverb Technologies Pvt. Ltd. is of immense importance, playing a pivotal role in advancing the capabilities and efficiency of mobile robotics within intralogistics operations. In the context of global supply chains, which are becoming increasingly complex, there is a pressing need for innovative automation solutions that can keep pace with the growing demand for faster and more accurate order fulfilment. Mobile robotics, specifically the development and deployment of AMRs, is crucial for optimizing warehouse processes, reducing operational costs, and enhancing overall productivity.

In today's competitive market, warehouses face several critical challenges such as labor shortages, fluctuating demand, and the need for scalable and flexible solutions. The project addresses these challenges by focusing on the enhancement and integration of mobile robotic systems. By automating repetitive and labour-intensive tasks, the project helps streamline workflows, minimize manual errors, and significantly improve operational efficiency. Additionally, the solutions developed through this project are designed to be easily scalable, allowing businesses to adapt quickly to changing needs and demands.

Moreover, the project aims to boost the accuracy and reliability of warehouse operations. Advanced robotics technologies ensure that tasks are performed with precision and consistency, thereby increasing the overall reliability of the system. This reliability translates into higher customer satisfaction, as orders are fulfilled accurately and on time. Furthermore, by reducing dependency on manual labour, the project leads to substantial cost savings, allowing businesses to allocate resources more effectively.

Ultimately, this project is crucial in reinforcing their position as a leader in the robotics industry. It contributes to the development of state-of-the-art solutions that address contemporary intralogistics challenges, ensuring that Addverb remains at the forefront of innovation in warehouse automation. The successful implementation of this project will not only benefit them but also set new standards in the industry, showcasing the transformative potential of mobile robotics in modern warehousing.

1.4 FMS Objectives

The objectives of this project are crafted to ensure that it effectively meets its goals, driving significant advancements in mobile robotics and warehouse automation. These objectives encompass various critical aspects, including the development, integration, optimization, safety, scalability, and continuous improvement of mobile robotic systems.

1. **Development and Integration of Mobile Robotics Systems**: One of the primary objectives is to design and develop advanced AMRs capable of efficiently navigating and operating within complex warehouse environments. These robots are equipped with sophisticated sensors and algorithms that enable them to perform tasks with high precision and adaptability. The integration of these robotic systems with existing warehouse management systems (WMS) is essential to ensure seamless operations, allowing for real-time data exchange and coordinated task execution.

2. **Optimization of Warehouse Processes**: Another critical objective is to implement advanced algorithms and control systems that enhance the performance and efficiency of mobile robots. This includes optimizing the routing and task allocation for robots to minimize idle time and maximize productivity. By continuously monitoring and analysing robot performance, the project aims to identify areas for improvement and implement solutions that drive operational excellence.

3. **Enhancement of Safety and Reliability**: Ensuring the safety and reliability of mobile robots is a top priority. The project includes rigorous testing and validation processes to guarantee that the robots operate safely alongside human workers and adhere to all safety protocols and standards. Enhancing the reliability of robotic systems involves developing robust hardware and software solutions that can withstand the demands of a dynamic warehouse environment, ensuring consistent and dependable performance.

4. **Scalability and Flexibility**: The project also aims to design solutions that are easily scalable and adaptable to different warehouse layouts and operational requirements. This involves creating modular systems that can be quickly and easily upgraded or modified to accommodate changing needs. The flexibility of these solutions ensures that businesses can scale their operations efficiently, without compromising on performance or reliability.

5. **Innovation and Continuous Improvement**: Fostering a culture of innovation is integral to the project's success. By continuously exploring new technologies and methodologies, the project aims to push the boundaries of what is possible in mobile robotics. Implementing feedback mechanisms to gather insights from real-world deployments is crucial for driving ongoing enhancements and refinements. This commitment to continuous improvement ensures that the solutions developed remain at the cutting edge of the industry, delivering superior value and performance.

By achieving these objectives, the project aims to deliver robust, efficient, and innovative mobile robotic solutions that significantly enhance the operational capabilities of modern warehouses. These solutions will not only improve the efficiency and accuracy of warehouse processes.

Chapter 2 - Background

2.1 Brief Overview

In today's fast-paced and highly competitive business landscape, efficient warehouse operations have become a critical success factor for organizations across diverse industries. The rapidly growing demand for faster delivery times, coupled with the increasing complexity of supply chain networks, has driven a transformation in the field of intralogistics – the management and optimization of material handling and logistics within a facility or across multiple sites.

At the forefront of this transformation is Addverb Technologies Pvt. Ltd., a pioneering company renowned for its innovative solutions in warehouse automation. Recognized as a leader in this domain, Addverb has been at the vanguard of developing cutting-edge technologies to address the evolving needs of modern warehouse operations.

The project I have been involved with at Addverb focuses on the development and enhancement of a fleet management system that seamlessly integrates AGVs and AMRs. These two technologies represent the cornerstone of contemporary warehouse automation, offering distinct advantages and presenting unique challenges.

Warehouse automation encompasses a diverse array of technologies and systems designed to streamline operations, improve efficiency, and minimize errors. AGVs and AMRs are pivotal components within this domain, each offering unique capabilities and functionalities. The primary objective of this project is to bridge the gap between traditional AGV systems, which rely on fixed infrastructure such as barcodes or magnetic strips for navigation, and the more flexible and adaptive AMR systems, which are currently in the development phase at Addverb.

By integrating the strengths of both AGV and AMR technologies, this project aims to create a robust and versatile fleet management solution capable of adapting to the dynamic and ever-changing needs of modern warehouses. This hybrid approach leverages the precision and reliability of AGVs while harnessing the flexibility and scalability of AMRs, enabling a comprehensive and intelligent material handling system.

The successful implementation of this fleet management system holds the potential to revolutionize warehouse operations, enabling organizations to achieve unprecedented levels of efficiency, accuracy, and cost-effectiveness. By automating repetitive and labour-intensive tasks, this solution not only enhances productivity but also reduces the risk of human errors, thereby improving overall operational safety and quality.

Moreover, the integration of AGVs and AMRs into a unified fleet management system enables real-time monitoring, coordination, and optimization of material flow within the warehouse. This level of control and visibility empowers organizations to make informed decisions, identify bottlenecks, and continuously refine their processes to achieve maximum operational excellence.

As the demand for efficient and agile supply chain solutions continues to grow, the development of advanced fleet management systems that leverage the synergies of AGVs and AMRs will play a pivotal role in shaping the future of warehouse automation. Addverb's commitment to innovation and its dedication to pushing the boundaries of what is possible in intralogistics position the company as a trailblazer in this rapidly evolving field.

2.2 Prior Work and State of Knowledge

The integration of AGVs and AMRs into a unified FMS represents a significant technological advancement in the field of warehouse automation. This endeavour builds upon decades of research and development in the areas of automated material handling, robotics, and logistics optimization. To fully appreciate the context and significance of this project, it is essential to examine the prior work and the current state of knowledge in these domains.

These systems have revolutionized the way goods are moved and handled within modern warehouses, offering increased efficiency, accuracy, and scalability. At the forefront of this evolution is the development of sophisticated fleet management systems that seamlessly coordinate the operations of these diverse robotic platforms.

2.2.1 Automated Guided Vehicles

AGVs have been a stalwart in industrial automation for decades, providing reliable and precise material handling solutions. These vehicles follow predefined paths marked by physical guides, such as magnetic strips, wires, or barcodes, allowing them to navigate through structured environments with minimal human intervention [2]. Some of the key milestones in development of AGVS are listed in Table 1.

Year	Milestone	Reference
1954	Introduction of the first AGV system by Barrett Electronics Corporation	[3]
1970s	Widespread adoption of AGVs in manufacturing and warehouse environments	[4]
1980s	Development of vision-guided AGVs and improved navigation systems	[5]
1990s	Integration of AGVs with other automation systems and advanced control algorithms	[2]
2000s	Improvements in AGV safety, energy efficiency, and real-time tracking	[6]

2010s	Adoption of advanced sensors and machine learning for enhanced navigation	[7]

Table 1: Key milestones in AGV deployment

The primary advantage of AGVs lies in their ability to automate repetitive tasks, leading to increased productivity and reduced labour costs. Figure 1 depicts some AGV's from Addverb on a map ready for sortation task. According to a study by [8], the implementation of AGV systems in warehouses has resulted in significant operational cost savings and improved throughput. Table 2 illustrates the potential cost savings achieved through the deployment of AGVs in a typical warehouse environment.

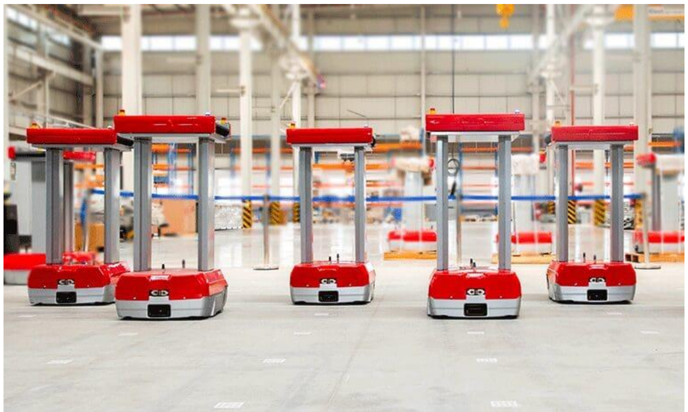

Figure 1: AGVs: sortation robots by Addverb

The concept of using AGVs for material handling in warehouses dates back several decades. AGVs follow predefined paths marked by physical guides such as magnetic strips, wires, or barcodes. While effective, these systems lack flexibility and require significant infrastructure investment and maintenance. As noted by recent studies, AGVs have been instrumental in automating repetitive tasks in controlled environments, leading to increased efficiency and reduced labour costs [9][8].

Cost Saving with AGVs		
Year	**AGVs**	**Manual**
1	$250K	$400K
2	$275K	$440K
3	$300K	$480K

Table 2: Potential cost saving through AGV deployment

However, the inflexibility of AGVs, which are constrained by fixed paths and centralized control, has become a limitation as warehouses evolve to meet the demands of e-commerce and on-demand logistics [5].

To address these limitations, researchers have explored various enhancements to AGV technology. For instance, Olivares et al. [5] investigated the use of vision-based navigation systems, enabling AGVs to adapt to changes in their environment without relying on physical guides. Additionally, advancements in sensor fusion and machine learning algorithms have contributed to improving the capabilities of AGVs, allowing them to handle more complex tasks and dynamic environments [6][10].

2.2.2 Autonomous Mobile Robots

AMRs represent the cutting edge of warehouse automation technology, offering unparalleled flexibility and adaptability. Unlike AGVs, AMRs do not require physical guides for navigation; instead, they utilize a suite of sensors, cameras, and onboard processing to navigate and make decisions autonomously [11][12].

The versatility of AMRs makes them well-suited for modern warehouses that need to handle a diverse range of tasks and products. Research by [13] has shown that AMRs can significantly improve operational efficiency by reducing downtime and increasing the flexibility of warehouse layouts. The key advantages of AMRs over AGVs are listed in Table 3.

Advantage	Description	Reference
Flexibility	AMRs can navigate dynamically and adapt to changing environments without fixed infrastructure.	[12]
Scalability	AMR systems are highly scalable and can be easily expanded or reconfigured as needed.	[14]
Adaptability	AMRs can learn and improve their navigation and decision-making capabilities over time.	[15]
Safety	Advanced obstacle detection and avoidance capabilities enhance safety in dynamic environments.	[13]

Table 3: Key advantages of AMR

AMRs have revolutionized the field of warehouse automation by offering unparalleled flexibility, scalability, and adaptability. Their ability to navigate dynamically, learn from their environment, and make autonomous decisions has enabled more efficient and responsive material handling operations. Table 4 illustrates the potential productivity gains achieved through the deployment of AMRs in a typical warehouse environment.

Productivity Gains with AMRs		
Year	**AMRs**	**Manual**
1	125%	100%
2	140%	100%
3	160%	100%

Table 4: Potential cost saving through AMR deployment

AMRs employ a variety of technologies to navigate and perform tasks, including LiDAR, cameras, ultrasonic sensors, and inertial measurement units (IMUs). These sensors enable AMRs to perceive their surroundings, detect obstacles, and map their environment in real-time using algorithms such as simultaneous localization and mapping (SLAM) [14][15].

Machine learning techniques have also been increasingly integrated into AMR systems to enhance their decision-making capabilities. For instance, deep reinforcement learning has been used to train AMRs to optimize their navigation strategies and improve task efficiency. By continuously learning from their environment and adapting to new situations, AMRs can achieve higher levels of autonomy and operational effectiveness.

2.2.3 Integration of AGVs and AMRs

The integration of AGVs and AMRs into a unified fleet management system offers the best of both worlds: the reliability and precision of AGVs with the flexibility and adaptability of AMRs. This hybrid approach is particularly beneficial in large-scale operations where different types of tasks require varying levels of automation.

Centralized fleet management systems coordinate the activities of AGVs and AMRs, ensuring optimal task allocation and route planning. Research in multi-robot systems, such as the work by, has provided valuable insights into the algorithms and communication protocols needed to manage heterogeneous robot fleets effectively.

One of the key challenges in integrating AGVs and AMRs is the development of robust communication and coordination mechanisms. These mechanisms must ensure that all robots in the fleet can share information, avoid collisions, and collaborate effectively to complete tasks. Recent advancements in wireless communication technologies, such as 5G and edge computing, offer promising solutions to these challenges by providing high-speed, low-latency connectivity for real-time data exchange and processing.

The use of cloud-based fleet management platforms is also gaining traction, allowing for centralized control and monitoring of robot fleets from remote locations. These platforms provide real-time visibility into the status and performance of each robot, enabling operators to make informed decisions and optimize fleet operations. Additionally, advancements in edge computing have enabled real-time data processing at the network edge, reducing latency and enhancing the responsiveness of fleet management systems.

The integration of AGVs and AMRs also involves the development of sophisticated algorithms for task allocation and route optimization. Research by [16] has explored the use of multi-agent reinforcement learning to optimize the distribution of tasks among a fleet of heterogeneous robots, ensuring that each robot is assigned tasks that match its capabilities and current status. This approach not only improves overall efficiency but also enhances the robustness and adaptability of the fleet management system. While AGVs and AMRs share the common goal of automating material handling in warehouses, they differ significantly in their underlying technologies, capabilities, and limitations. Table 5 provides a comparative overview of the key characteristics of AGVs and AMRs.

Characteristic	AGVs	AMRs
Navigation	Fixed paths (magnetic strips, wires, barcodes)	Sensor-based, dynamic navigation
Flexibility	Low, limited to predefined routes	High, can adapt to changing environments
Infrastructure	Requires physical guides	No fixed infrastructure required
Scalability	Limited by fixed paths	Highly scalable
Obstacle Avoidance	Limited	Advanced obstacle detection and avoidance
Autonomy	Lower, requires central control	Higher, can operate autonomously
Initial Investment	Lower	Higher
Maintenance	Higher (physical guides)	Lower (software and sensors)

Table 5: Comparison of AGVs and AMRs

As illustrated in Table 5, AMRs offer greater flexibility, scalability, and autonomy compared to AGVs, making them better suited for dynamic and rapidly changing warehouse environments. However, AGVs still have advantages in terms of initial investment cost and reliability in structured environments.

The integration of both AGVs and AMRs into a fleet management system aims to leverage the strengths of both technologies, creating a powerful and versatile solution for warehouse automation

2.2.4 Fleet Management System

As the integration of AGVs and AMRs in warehouse environments has gained momentum, the development of sophisticated FMS has emerged as a critical area of research and development.

These systems play a vital role in coordinating, monitoring, and optimizing the operations of heterogeneous fleets comprising both AGVs and AMRs.

Fleet management systems typically incorporate several key components, as illustrated in Figure 2, including centralized control, task management, navigation and path planning, monitoring and tracking, communication and data exchange, and reporting.

Figure 2: Key components of an FMS

The centralized control system acts as the brain of the fleet, responsible for coordinating the activities of all vehicles and robots based on real-time data and advanced algorithms [10]. Efficient task management is a crucial aspect, ensuring optimal allocation of tasks to individual units based on their capabilities, availability, and priority. Researchers have explored various techniques, such as multi-agent reinforcement learning, to achieve optimal task allocation in heterogeneous fleets.

Navigation and path planning algorithms play a critical role in calculating efficient routes for AGVs and AMRs, taking into account factors such as obstacle avoidance, traffic congestion, and mission priorities. Hybrid navigation approaches that combine fixed paths for AGVs and dynamic navigation for AMRs have been proposed as effective solutions.

Robust communication protocols and data exchange mechanisms are essential for ensuring seamless coordination and information sharing among vehicles, robots, and the central control system. Recent advancements in wireless communication technologies, such as 5G and edge computing, have offered promising solutions for reliable and low-latency data transfer [12][11].

Effective fleet management systems also incorporate reporting and analytics capabilities, enabling managers and operators to gain insights into fleet performance, identify bottlenecks, and make data-driven decisions for continuous improvement [14]. Figure 3 illustrates an example of a fleet performance dashboard, providing real-time visibility into key metrics and indicators.

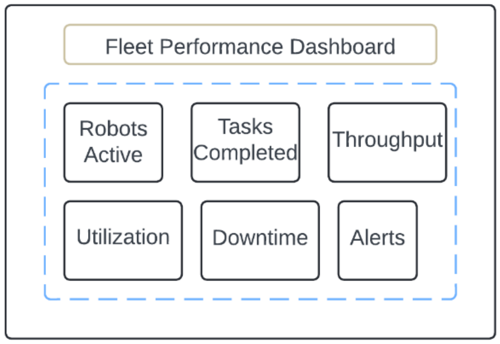

Figure 3: Example of a fleet performance dashboard

The implementation of comprehensive fleet management systems in warehouse environments offers numerous benefits, including increased efficiency, enhanced productivity, improved safety, cost savings, scalability and flexibility, and data-driven decision-making

As the integration of AGVs and AMRs continues to gain traction, the development of advanced fleet management systems that can effectively coordinate and optimize the operations of these heterogeneous fleets remains a critical area of research and development. Ongoing advancements in areas such as multi-robot coordination, task allocation algorithms, navigation techniques, and communication protocols will play a pivotal role in shaping the future of efficient and intelligent warehouse automation.

Chapter 3 – On-Site Observations, Analysis, and Optimization

Approximately two weeks after the commencement of my internship, I had the opportunity to visit an operational site. The primary objective of this visit was to gain firsthand insight into site-related modifications, challenges, and potential solutions pertaining to the fleet management system.

3.1 Initial Understanding and Preparatory Work

To lay the foundation for my on-site work, I began by comprehending the functioning of the fleet system and other related systems. The scope of my site work encompassed the operation of three distinct fleets: the C-Table, H-Table, and Zippy 25 Fleet. My initial tasks involved the following:

- **Deep Dive into Fleet Operations:** I began my internship by delving into the intricacies of the fleet management system. This involved comprehensive training on the C-Table, H-Table, and Zippy 25 fleets, including their functionalities, configurations, and operational processes. On C & H table zippy 10 are running which is showcased in Figure 4.

Figure 4: Addverb's Zippy 10 robots

- **Inter-System Dependencies:** I gained a thorough understanding of how the fleet system interacts with other relevant systems, ensuring a holistic view of the entire operational ecosystem.

The in-detail description of my preparatory work on site have been listed and described below.

3.1.1 Standard Operating Procedure (SOP) Development:

- **Standardization for Server Access:** To guarantee consistent and secure access to both individual and master fleet servers, I spearheaded the creation of a detailed SOP. This SOP documented the step-by-step procedures for various user roles, ensuring everyone followed the same protocols for streamlined and secure server access.

- **Collaboration and Review:** I actively collaborated with senior fleet management personnel to ensure the SOP captured all essential information and adhered to best practices. The SOP underwent thorough review and revision before finalization, guaranteeing its clarity, accuracy, and effectiveness.

3.1.2 New Fleet Onboarding Procedures:

- **Streamlined Implementation:** I played a key role in documenting the protocols for seamlessly integrating new constructions into specific fleets. This involved defining clear steps for configuration, testing, and deployment, ensuring a smooth and efficient onboarding process for future fleet additions.

3.1.3 Data Analysis Skills Development:

- **Log File Expertise:** I actively honed my skills in extracting and analysing log files. This involved mastering techniques for identifying relevant data points, filtering out extraneous information, and interpreting log data to troubleshoot problems, optimize performance, and gain valuable insights into fleet operations.

3.1.4 Script Development for Bag File Analysis:

- **Plot Juggler Proficiency:** To facilitate efficient bag file analysis, I developed custom scripts for Plot Juggler. These scripts streamlined the process by directly converting .bag files into .csv format, eliminating the need for a local ROS system. This innovation enhanced accessibility and usability, allowing for bag file analysis on any platform without ROS dependencies.

3.1.5 Understanding Common Fleet and Robot Issues:

- **Proactive Problem Solving:** I actively engaged in learning about a wide range of prevalent issues affecting fleets and robots. This proactive approach equipped me to identify potential problems early on, troubleshoot malfunctions effectively, and contribute to the development of solutions for improved fleet reliability and performance.

The comprehensive preparatory work I undertook established a solid foundation for my on-site responsibilities. This foundational knowledge and skillset allowed me to transition seamlessly into the operational environment and make meaningful contributions to the fleet management team.

3.2 Observations and Assistance

Following the initial introduction period, I transitioned into hands-on, on-site work, where I observed and provided assistance for a duration of two weeks, specifically during the night shift. This immersive experience allowed me to gain practical insights and directly contribute to resolving various operational challenges. The scope of the on-site assistance work encompassed several critical tasks:

- **Diagnosing Out-of-Path Issues on Both H-Table and C-Table:**
  - I examined instances where robots deviated from their designated paths on both the H-Table and C-Table. This involved analysing system logs to identify underlying causes and potential patterns contributing to these deviations. After diagnosing the issues, I reported them to the relevant teams for further investigation and resolution.
- **Understanding Antipodal Issues:**
  - I delved into understanding antipodal issues, where robots faced challenges in positioning and orientation. This task required careful analysis of occurrence patterns and system behaviour. I reported these findings to the engineering team, providing detailed insights to aid in developing corrective measures.
- **Diagnosing and Reporting Instances of Multiple Robots Occupying the Same Park Location:**
  - I identified and diagnosed situations where multiple robots erroneously occupied the same park location, which can lead to operational inefficiencies and potential collisions. I suggested potential fixes, such as implementing better coordination algorithms and park location allocation strategies, to prevent such occurrences in the future.
- **Analysing Multiple Robots' 201 Error Using Plot Juggler:**
  - Using Plot Juggler, a powerful visualization tool, I analysed the bag files of multiple robots experiencing 201 errors. This involved scrutinizing the robots' operational data to pinpoint the exact moments and conditions leading to these errors. My findings helped in understanding the root causes and facilitated the development of targeted solutions.
- **Deploying New Builds and Observing Edge Cases:**
  - I actively participated in deploying new software builds to the robots and observed their behaviour under various edge cases. This included conducting thorough testing to identify any anomalies or unexpected behaviour. If issues arose, I analysed them and, when necessary, reverted to previous builds to maintain operational stability.
- **Resolving a Wide Range of Operational Issues:**

Tackled a diverse array of operational challenges, including:

- **Pending Tasks:** Addressing issues where tasks remained unprocessed.
- **Wait for Next Zippy:** Resolving delays in task assignment due to waiting for the next available robot.
- **Sortie Issues:** Investigating and fixing problems related to task execution sorties.
- **Conveyor Not Discharging:** Ensuring smooth operation of conveyors and resolving discharge failures.
- **Robots Not Charging:** Diagnosing and fixing charging issues to maintain robot availability.
- **Robots Not Moving After Task Assignment:** Analysing and addressing situations where robots failed to initiate movement after receiving tasks.
- **Robots Not Going to Picks:** Investigating reasons for robots not proceeding to pick locations.
- **Robots Not Moving Out of Park:** Resolving instances where robots remained stationary in park locations.
- **Nil Tasks:** Diagnosing and addressing cases where robots received no tasks.
- **Mix Sortation:** Fixing issues related to incorrect sorting of items.
- **Pose Jump and SOC Jump:** Analysing and correcting sudden changes in robot pose or state of charge (SOC).
- **Delays Related to Fleet and Robots:** Identifying and mitigating delays in fleet and robot operations.
- **Overshoot Problems:** Addressing and resolving issues where robots overshot their target locations.
- **Other Minor Issues:** Providing solutions for various minor operational challenges encountered.

- **Analysing, Resolving, and Reporting Robot-Related Issues:**

Conducted in-depth analysis and resolution of robot-related issues, such as:

- **201 Error:** Diagnosing and fixing issues related to navigation and path planning.
- **401 and 402 Errors:** Addressing communication and control errors.
- **301 Error:** Fixing issues related to robot localization and mapping.
- **901 Error:** Resolving high-priority system errors affecting robot performance.

- **Optimizing All Maps Running On-Site:**

Undertook the task of optimizing the maps used by the robots on-site, including the H-Table, C-Table, and Zippy 25 maps. This involved:

  - **Highway Rule Optimization:** Refining the rules governing robot movement on designated highways to enhance efficiency and reduce congestion.
  - **Park Location Fixes:** Adjusting Park locations to ensure optimal robot distribution and reduce instances of congestion or conflicts.
  - **Hospital Location Fixes:** Improving the placement and management of hospital locations to ensure robots have designated areas for maintenance, troubleshooting.

3.3 Map Optimization and Throughput

A significant aspect of my on-site work involved optimizing the C-Table and H-Table to increase throughput. The map optimization process entailed finding optimal paths from pick to drop, drop to pick, pick to park, and park to pick. The optimal path generation aimed to achieve the best possible path in terms of path cost, least clutter, and proper distribution of agents on each highway, while ensuring that robots could utilize all highways and maintain proper segregation.

This map optimization process involved rigorous testing on simulations, making changes, and additionally testing the behaviour on actual robots by testing locally. This overall process was highly challenging as it involved a significant amount of theoretical imagination and various optimization approaches to achieve the desired throughput. Here, throughput refers to the total number of sortation’s completed in an hour.

The map optimization was performed on the FMS server developed by the fleet team at Addverb, along with simulations performed on the FMS simulator.

3.3.1 C-Table Map

Initially, I worked on achieving the committed throughput with 40 robots. The initial map provided achieved a throughput 30% less than the committed value. After rigorous testing and tuning, the maximum throughput achieved on simulation was approximately 90% of what was being achieved initially. The process involved on-site testing on real robots to calculate the difference. A major difference was observed due to the presence of sorties leading to unloading delay and loading delay due to latency in scanning by operators.

After a month of working, the final throughput test conducted with actual parcels depicted an overall sortation of 15% more parcels than what was committed and an overall 40% increment from what was initially being achieved. This led to the successful completion and handover of the

C-Table. A brief incremental difference is depicted in Table 6, here *"X"* represents the initial throughput.

C-Table Live Sortation			
Hour	**Run 1**	**Run 2**	**Run 3**
1	X	X + 40%	X + 45%
2	X + 42%	X + 48%	X + 44%
3	X + 45%	X + 46%	X + 47%
4	X + 42%	X + 44%	X + 46%

Table 6: C-Table live sortation test

3.3.2 H-Table Map

Similarly, the H-Table handed over to me had a committed throughput with 60 robots. The initial map provided achieved a throughput of only 50% of the committed value. This map was significantly more complex as the map size to the number of robots ratio was considerably lower. The map had a total of 4 fingers with 170 drop locations and 4 pick locations. Additionally, the map had very little space in the middle core, making map optimization a substantial challenge.

The overall optimization process took approximately 1.5 months, involving various map generations, new highway rules, and smart optimal path allocation. This was all done while ensuring minimal clutter on the map, as the initial map provided had significant clutter. The final map developed achieved a maximum throughput of 60% more than what was initially being achieved, with a constant throughput of the committed throughput.

The recent throughput testing on the actual site generated a throughput of 45% increment from what was initially being achieved, with a maximum of 10% more than the committed throughput. This achievement marked a significant milestone for the H-Table layout. Table 7 depicts live sortation test results, where *"Y"* represents the initial throughput being achieved.

Loading = 1sec, Unloading = 1sec (60 agents, all active, 8 stoppages due to network)

S. No.	Time Stamp	Run Time (min)	Calculated Throughput
1	12:05	0	-
2	12:10	5	140% more than Y
3	12:20	15	130% more than Y
4	12:35	30	120% more than Y

Table 7: H-Table live sortation test

Thus, the current maps running on this site were developed by me, resulting in a significant increase in efficiency and reduced time cost for sortation. My overall presence at the site led to a substantial impact in debugging and ensuring the smooth running of operations, along with major contributions to all maps, primarily focusing on throughput optimization and other minor location changes of nodes and edges.

3.3.3 Impact Analysis

To quantify the impact of the optimization efforts, a comparative analysis was conducted between the pre-optimization and post-optimization scenarios. Table 8 illustrates the percentage increase in throughput achieved for both the C-Table and H-Table across multiple runs.

Throughput Improvement			
Run	**C-Table**	**H-Table**	**Overall**
1	42%	100%	74%
2	39%	120%	79.5%
3	41%	98%	69.5%
4	38%	105%	71.5%
Mean	40%	105.75%	72.875%

Table 8: Percentage increase in throughput after optimization

Chapter 4 – Features & Development

During my internship, I had the privilege of working on the development and enhancement of a cutting-edge FMS. This system plays a critical role in optimizing the operations and coordination of fleets within various industrial and logistics environments. Throughout my internship, I was actively involved in comprehending the codebase, resolving issues, understanding workflows, and contributing to the development of new features and functionalities that significantly improved the system's performance, efficiency and overall user-experience.

4.1 General Architecture and Workflow

- **Modular Design:** The FMS codebase follows a modular architecture, with different components responsible for specific functionalities, facilitating maintainability, scalability, and ease of development. These modules include task allocation, path planning, simulation execution, and robot communication, among others.

- **Client-Server Model:** The system leverages a client-server model, where the central FMS server orchestrates the operations of multiple clients. The server acts as a central hub, coordinating task assignments, path planning, and communication with the clients.

- **Task Allocation:** The task allocation module is responsible for assigning tasks to available based on various factors, such as task priority, location, resource availability, and operational constraints. This module employs sophisticated algorithms and heuristics to ensure efficient and optimal task distribution among the fleet.

- **Path Planning:** Once tasks are allocated, the path planning module determines the optimal paths for each to navigate through the environment. This module takes into account the layout of the facility, obstacles, traffic conditions, and other relevant factors to generate efficient and collision-free paths.

- **Simulation and Robot Communication:** Before executing the planned paths, the FMS runs simulations to validate the feasibility and identify potential issues or bottlenecks. The simulation module incorporates advanced algorithms and physics engines to accurately model the behaviour in the simulated environment.

After successful simulation, the optimized paths and commands are transmitted to the respective through the robot communication module. Figure 5 depicts a live sortation running with zippy 10 robots on a Tompkins type layout. This module handles the low-level communication protocols and interfaces with the hardware and control systems.

Figure 5: Live sortation running on a map

4.2 FMS Software Related Development

This section comprehensively covers the various developments and enhancements I contributed to the FMS software during my internship. It delves into the technical details of feature implementations, bug fixes, performance optimizations, and workflow improvements across diverse functionalities. These developments range from map generation and edge incorporation to path visualization, traffic light switching, and keyboard mapping, among others. Quantitative metrics and performance gains resulting from these developments are presented, highlighting their positive impact on system efficiency and user experience. Figure 6 depicts a simulation running on an example map to visualize the explanations and to depict how features are tested in simulation. The colourful nodes are pick, drop and other nodes and the square box with red dot represents and agent with parcel.

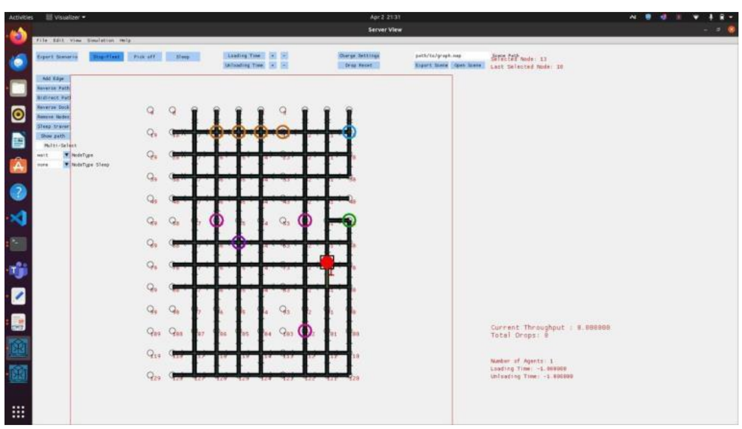

Figure 6: Simulation running on a map

Additionally, insights into the software development workflows, tools, and methodologies employed are provided, showcasing industry best practices adopted during the internship. Upon commencing my work on map generation and editing within the software, I encountered significant difficulties in incorporating new edges into existing maps. The system had a limitation that only allowed the addition of individual edges simultaneously, which posed a major challenge. In real-world scenarios, complex maps often require the concurrent addition of multiple edges to accurately represent the environment's layout and connectivity.

4.2.1 Multi - Edge Incorporation Algorithm

To tackle this issue, I first studied the relevant codebase files and modules responsible for map data structures and manipulation. After gaining a thorough understanding of the existing implementation, I initially composed a rudimentary functional feature that attempted to address the edge incorporation limitation. However, this initial attempt was far from complete and lacked robustness.

I then conducted extensive testing and validation of the rudimentary feature, subjecting it to various edge cases, complex map scenarios, and edge combinations. Through this rigorous testing process, numerous loopholes, exceptions, and edge cases were identified that the initial implementation failed to handle correctly. These included issues such as duplicate edge prevention, maintaining graph connectivity, handling intersecting edges, and ensuring topological consistency.

Determined to resolve these shortcomings, I enhanced and refined the code by incorporating comprehensive checks and validation mechanisms for all identified scenarios and edge cases. This involved implementing robust algorithms and data structures to ensure the integrity of the map data during edge incorporation operations. The enhanced code implemented efficient graph traversal techniques, spatial indexing, and parallelization to optimize performance and scalability.

The resulting edge incorporation feature, after multiple iterations and improvements, exhibited significantly improved performance and robustness compared to its initial state. It successfully addressed the limitation of adding only individual edges simultaneously, allowing for seamless and efficient incorporation of multiple edges concurrently. This feature has significantly expedited the map generation and editing process within the FMS, resulting in substantial time savings and increased productivity for map developers and operators.

Furthermore, the enhanced edge incorporation feature has proven to be highly reliable and continues to function flawlessly to this day. It has been thoroughly tested and validated across a wide range of map scenarios, edge combinations, and real-world use cases, ensuring consistent and accurate map generation and editing capabilities within the FMS.

4.2.2 Enhancements in FMS Replayer, Map Exportation, and Multi-Selection

I undertook involved rectifying an issue with the timestamp display in the FMS replayer, a crucial component that allows users to visualize and analyse the simulated paths and movements of robots within the FMS. Initially, I investigated the root cause of the timestamp display issue, which stemmed from an incorrect interpretation of the timestamp format, leading to inaccurate time displays. This required a deep dive into the relevant source files responsible for handling and rendering timestamps within the replayer.

After thoroughly understanding the existing implementation, I designed and implemented a robust fixed time display mechanism that accurately converts the raw timestamp data into a human-readable format, ensuring precise and consistent time representation.

Extensive testing and validation were conducted to ensure the robustness and accuracy of the timestamp display across various scenarios and edge cases. The implementation underwent rigorous code reviews and quality assurance checks to ensure its adherence to best coding practices and industry standards.

Concurrently, I also contributed to resolving an issue related to map exportation, where the hospital's dock direction was not being accurately preserved during the exportation process. This issue had the potential to introduce errors and inconsistencies in the exported map data, potentially leading to navigation and path planning issues.

To rectify this problem, I thoroughly analysed the existing map exportation logic implemented and identified the root cause of the issue. Subsequently, I implemented a comprehensive dock direction preservation mechanism that ensured the accurate representation and propagation of dock directions throughout the exportation process. This involved modifying the exportation algorithms, data structures, and file formats to maintain and persist dock direction information.

Furthermore, I provided support in developing the initial vector logic for the multi-selection of different nodes within the FMS, leveraging the power for efficient data manipulation and algorithmic implementations. This functionality enables users to efficiently select multiple nodes simultaneously, facilitating various operations and actions to be performed on the selected nodes. The implementation involved developing robust algorithms for node selection, highlighting, and manipulation, as well as integrating the multi-selection functionality with existing map editing and visualization components.

Through comprehensive testing, debugging, and optimization within the codebase, these developments not only resolved critical issues but also introduced new capabilities and improved the overall user experience within the FMS. The accurate timestamp display, preserved dock direction during map exportation, and efficient multi-selection of nodes contributed to enhanced productivity, improved data integrity, and streamlined workflows for FMS operators and developers.

4.2.3 Traffic Light Switching and Clutter Awareness

Developed traffic light switching mechanisms that dynamically adapted to the proximity of clutter within the simulated environment. Clutter, which refers to obstacles or obstructions in the path of robots, can significantly impact navigation and traffic flow. To address this challenge, I designed and implemented a trigger function that monitored the clutter levels in the vicinity of traffic lights.

The trigger function continuously analysed the clutter potential within a specified radius around each traffic light, leveraging sophisticated algorithms and data structures to efficiently process and interpret the map data. When the clutter potential exceeded a predefined threshold, the trigger function would initiate a traffic light state change, effectively altering the traffic patterns and flow to mitigate the impact of clutter.

Furthermore, I enhanced the global clutter potential update mechanism by incorporating a logic akin to PID-based controls (Proportional-Integral-Derivative). This approach borrowed principles from control theory to ensure a responsive and stable system that could adapt to dynamic changes in clutter levels. The PID-based logic continuously monitored the error between the desired clutter potential and the actual clutter potential, adjusting the traffic light switching parameters accordingly.

By integrating this advanced control logic into the traffic light switching mechanisms, the system exhibited enhanced responsiveness and adaptability to dynamic clutter conditions. This approach facilitated localized testing and evaluation of solutions aimed at addressing clutter-related issues on maps, enabling iterative improvements and optimizations.

4.2.4 Show Path Functionality and Highway Tuning

In addition to the traffic light switching advancements, I suggested, partially implemented, and contributed to the development of the "show path" functionality within the FMS. This feature enables users to visualize and interact with the planned paths directly within the map interface.

The show path functionality incorporates path visualization algorithms that render the planned routes for robots, taking into account factors such as map topology, obstacles, and traffic conditions. Users can observe the planned paths overlaid on the map, allowing them to identify potential bottlenecks, congestion points, or inefficiencies.

Furthermore, I contributed to the implementation of edge and weight tuning capabilities within the show path feature. This functionality allows users to dynamically modify the weights or costs associated with specific map edges, effectively influencing the path planning algorithms and resulting routes. By adjusting edge weights, users can prioritize certain routes, avoid congested areas, or experiment with alternative paths to optimize traffic flow and efficiency. The show path functionality, coupled with edge and weight tuning, offers significant time savings by enabling direct highway tuning and optimization without the need for running full-scale simulations. This streamlined workflow enhances productivity and allows for rapid iterations and improvements in path planning and traffic management strategies.

4.2.5 Zip Utility for Log Extraction

Extended the existing zip utility present within the log extraction functionality. This utility plays a crucial role in managing and archiving log files, which are essential for system monitoring, debugging, and analysis. However, the increasing volume of log data generated by the FMS posed challenges in terms of storage space and data retention policies.

To address these challenges, I implemented a recursive zip archiving functionality that optimizes storage utilization and extends the availability of log data within the system. The core idea behind this enhancement was to leverage nested zip archives, effectively compressing and encapsulating older log files within existing zip archives, thereby minimizing the overall storage footprint.

The recursive zip archiving process follows a systematic approach:

1. **Archive Selection**: The utility identifies zip archives that have reached a predefined age or size threshold, making them eligible for recursive compression.
2. **Nested Archive Creation**: A new zip archive is created within the selected archive, effectively creating a nested structure. This nested archive serves as the target destination for older log files.
3. **Log File Relocation**: Older log files from the selected archive are relocated and compressed within the newly created nested archive, freeing up space in the original archive.
4. **Metadata Preservation**: Crucial metadata, such as timestamps, file paths, and archive structures, are meticulously preserved throughout the recursive archiving process, ensuring data integrity and traceability.

To further enhance the efficiency of the log archiving process, I implemented a "skip extension check" functionality. This feature intelligently detects and skips the compression of files that have already been archived, preventing redundant operations and saving valuable processing time.

The skip extension check works as follows:

1. **File Extension Validation**: Before compressing a file, the utility checks the file extension against a predefined list of archived file extensions (e.g., `.zip`, `.gz`, `.tar`).
2. **Skipping Archived Files**: If the file extension matches an archived format, the utility assumes the file has already been compressed and skips the archiving process for that specific file.
3. **Selective Archiving**: Only files with extensions that do not match the archived format list are processed and compressed, ensuring efficient utilization of system resources.

By incorporating these enhancements, the extended zip utility significantly optimizes storage utilization and increases the availability of log data within the FMS. The recursive archiving functionality enables the system to retain log files for extended periods, facilitating comprehensive historical analysis and troubleshooting efforts.

Furthermore, the skip extension check contributes to improved performance and efficiency by eliminating redundant compression operations, reducing processing overhead, and minimizing the risk of data corruption or inconsistencies.

To ensure the robustness and reliability of these enhancements, I conducted extensive testing and validation across various scenarios, including edge cases and error conditions. The implementation underwent rigorous code reviews and adhered to industry-standard coding practices and guidelines.

The extended zip utility with recursive archiving and skip extension check has been seamlessly integrated into the FMS log extraction module, providing a streamlined and efficient solution for log management and long-term data retention.

4.2.6 Database Utility for Extraction

Recognized the need for a comprehensive database utility to streamline the management and extraction of data collections within the Fleet Management System (FMS). To address this requirement, I undertook the development of a robust database utility entirely from scratch, leveraging industry-standard practices and cutting-edge technologies.

The database utility was designed to seamlessly integrate with MongoDB, a widely-adopted NoSQL database system known for its scalability, flexibility, and high-performance capabilities. At the core of the utility lies an intelligent auto-connection module that establishes a secure and reliable connection to the MongoDB client, ensuring seamless data access and manipulation. The auto-connection module employs a sophisticated algorithm that dynamically discovers and connects to the appropriate MongoDB instance based on the current system configuration and deployment environment.

One of the core functionalities of the database utility is the ability to extract and serialize data collections from MongoDB as JSON files. This feature is exposed through a user-friendly RESTful API, allowing developers and analysts to initiate collection extraction with a single API call.

Upon receiving an extraction request, the utility leverages the auto-connection module to establish a connection to the MongoDB instance. It then retrieves the requested collection and serializes the data into a well-structured JSON format, preserving the integrity and structure of the original data. The extracted JSON files can be easily shared, analysed, and integrated with various data analysis tools, enabling comprehensive debugging, reporting, and decision-making processes within the FMS ecosystem.

To ensure the reliability and stability of the database utility, I implemented robust error handling and validation mechanisms throughout the codebase. These mechanisms include input validation, exception handling, and error logging, ensuring that the utility gracefully handles unexpected scenarios and provides meaningful error messages to aid in troubleshooting. Recognizing the potential for large-scale data volumes and concurrent access, I optimized the database utility for high performance and scalability. This was achieved through the implementation of efficient data retrieval algorithms, caching mechanisms, and parallelization techniques.

Furthermore, the utility was designed with extensibility in mind, allowing for seamless integration with additional data sources and storage systems in the future, ensuring long-term viability and adaptability within the FMS ecosystem.

The database utility underwent rigorous code reviews and adhered to industry-standard coding practices and guidelines, ensuring maintainability, readability, and adherence to best practices. The developed database utility has been seamlessly integrated into the FMS ecosystem, providing a robust and efficient solution for collection management and extraction. Its user-friendly interface, optimized performance, and extensible design have significantly streamlined data management processes, facilitating comprehensive analysis, debugging, and decision-making within the FMS.

4.2.7 Edge Weight-based Colouration & Legend

Recognized the challenges faced by map developers and optimization experts in identifying and visualizing the weight changes applied to edges within the maps. Traditionally, after adjusting edge weights to orchestrate highway rules and achieve desired traffic patterns, the modified edges appeared visually indistinguishable from their unmodified counterparts. This limitation made it difficult to discern which edges had undergone weight modifications, particularly in large and complex map layouts.

To address this issue, I introduced a crucial functionality: the depiction of weighted edge colours. This innovative feature enables users to visualize edge weights through color-coding, significantly enhancing the map optimization process and saving valuable time. At the core of this feature lies a meticulously designed colour mapping algorithm that assigns distinct colours to edges based on their assigned weights. The algorithm considers a predefined range of weight values and maps them to a corresponding colours spectrum, allowing for clear visual differentiation.

The colours mapping is designed to be intuitive and visually appealing, with lower weights represented by cooler colours (e.g., blues) and higher weights depicted by warmer colors (e.g., reds). This approach aligns with common colours perception conventions, facilitating easy interpretation and understanding. To further enhance the usability of this feature, I implemented an interactive legend that dynamically updates based on the weight range of the current map. The legend displays the colour gradient corresponding to the weight range, accompanied by numerical labels indicating the weight values associated with each colour.

Users can seamlessly toggle the weighted edge colours visualization with a simple click, instantly revealing the color-coded edges on the map. This visual representation provides an immediate overview of the weight distribution, allowing map developers and optimization experts to quickly identify areas of interest or potential bottlenecks. To further enhance the interpretability of the weighted edge colours, I introduced a percentage-based categorization system. This system groups edge weights into distinct colours categories based on predefined percentage thresholds, making it easier for users to quickly assess the relative weight distribution across the map.

The weighted edge colour visualization feature has been seamlessly integrated into the map editing and optimization tools, providing a user-friendly interface for enabling and disabling the visualization as needed. The feature has been well-received by map developers and optimization experts, who have reported significant time savings and enhanced productivity during map optimization processes.

4.2.8 Scene Utility for Log Extraction

To streamline the log extraction and replaying workflow within the FMS, implemented an integrated approach that combines map validation and archiving functionalities. This enhancement aimed to simplify operations, ensure data integrity, and improve overall efficiency. During the log extraction process, a dedicated map validation module thoroughly checks the integrity of the associated map data, including topology consistency, obstacle representation, and path planning simulations. If the map data passes all validation checks, it is considered valid and suitable for archiving.

The seamless integration of map archiving into the log extraction process eliminates the need for separate map extraction and management. The validated map data is automatically compressed and appended to the same archive file as the corresponding log files. This integrated approach simplifies the workflow, reduces the risk of data inconsistencies, and ensures that the replaying process accurately reflects the captured scenarios. FMS operators and analysts can directly access the archived log files and associated map data from a single source, streamlining the replaying process and enabling efficient analysis and troubleshooting.

4.2.9 Data Sanitizer Zip Trigger

Effective storage management is crucial to ensure optimal system performance and data availability. To address the limited storage space and facilitate long-term log retention, I implemented a data sanitizer with integrated log archiving functionality. This enhancement aimed to strike a balance between maintaining a manageable log file footprint and preserving historical data for future analysis and troubleshooting.

The FMS operates under a predefined log retention policy, which specifies a time threshold for retaining log files. Once log files exceed this threshold, they are marked for deletion to free up storage space and accommodate newer log entries. However, discarding these log files entirely could lead to the loss of valuable historical data, hampering future analysis and troubleshooting efforts.

To mitigate this issue, I integrated log archiving functionality into the data sanitizer. During the sanitization process, log files marked for deletion are not immediately purged from the system. Instead, they are compressed and archived into a dedicated log archive file, effectively preserving the historical data while significantly reducing its storage footprint.

The implementation of the data sanitizer with integrated log archiving functionality has yielded significant benefits for the FMS ecosystem:

1. **Efficient Storage Management**: By compressing and archiving log files instead of permanently deleting them, valuable storage space is reclaimed while preserving historical data for future reference.
2. **Long-term Data Retention**: Historical log data is retained for extended periods, facilitating comprehensive analysis and troubleshooting efforts, even for operations that occurred in the distant past.
3. **Reduced Storage Footprint**: Compression algorithms significantly reduce the storage footprint of archived log files, enabling more efficient utilization of storage resources.
4. **Metadata Preservation**: Preserving metadata associated with log files ensures that archived data can be easily retrieved, analysed, and correlated with specific operations or events.

The data sanitizer with log archiving functionality has been seamlessly integrated into the FMS ecosystem, contributing to improved storage management, data preservation, and overall system efficiency. This enhancement has empowered FMS operators and analysts with access to comprehensive historical data, enabling them to conduct in-depth analyses, identify root causes of issues, and make informed decisions based on a wealth of historical information

4.2.10 Scene Check Functionality for Comprehensive Map Validation

During the map optimization process within the FMS, ensuring the completeness and connectivity of the map is crucial for successful simulations and real-world deployment. Overlooking missing connections or unlinked nodes can lead to errors, inefficiencies, and potential disruptions in operations. To address this challenge, I introduced a powerful Scene Check functionality that performs comprehensive map validation, streamlining the map generation process and ensuring seamless integration with both simulated and live environments.

At the core of the scene check functionality lies a robust connectivity validation algorithm. This algorithm verifies the existence of at least one valid path connecting each critical location within the map, including pick, drop, park, and charge locations. By performing this validation, the system can identify and highlight any potential connectivity issues that might hinder operations or lead to errors during simulations or live deployments.

The connectivity validation process follows a systematic approach:

- **Node Identification**: The algorithm begins by identifying all critical nodes within the map, such as pick, drop, park, and charge locations.
- **Path Finding**: For each identified node, the algorithm employs advanced path-finding techniques, such as Dijkstra's algorithm or A* search, to determine if there exists at least one valid path connecting the node to the overall map topology.
- **Validation and Reporting**: If any node is found to be disconnected or inaccessible, the algorithm generates a detailed report highlighting the affected nodes and their corresponding connectivity issues. This report serves as a valuable resource for map developers, enabling them to quickly identify and rectify any connectivity gaps or missing links.

In addition to the general connectivity validation, I incorporated a specialized validation check to ensure the proper linking of pre-dock positions to their corresponding chargers. This check is essential for maintaining the operational efficiency of AMRs, as unlinked pre-dock positions can lead to charging errors, extended downtime, and potential disruptions in the overall fleet management process. The charger connectivity validation algorithm follows these steps:

- **Charger Identification:** The algorithm identifies all charger nodes within the map topology.
- **Pre-Dock Link Validation**: For each identified charger node, the algorithm verifies the existence of valid connections between the charger and its associated pre-dock positions.
- **Validation and Reporting:** If any unlinked or improperly connected pre-dock positions are detected, the algorithm generates a detailed report highlighting the affected chargers and their corresponding connectivity issues. This report enables map developers to promptly address any potential charging-related errors or inefficiencies.

To streamline the map validation process, I integrated the scene check functionality into the FMS user interface, providing a dedicated button or menu option for initiating the validation checks. Upon triggering the Scene Check, the system performs both the connectivity validation and charger connectivity validation simultaneously, generating comprehensive reports detailing any identified issues.

These reports are presented to the map developers in a clear and user-friendly format, enabling them to quickly identify and address any connectivity gaps or unlinked nodes. The reports can be exported or integrated into existing issue tracking systems, facilitating efficient collaboration and task management among the development team. The introduction of the scene check functionality has yielded significant benefits for the FMS ecosystem and the map optimization process:

- **Comprehensive Map Validation:** The scene check functionality provides a comprehensive validation of the map's connectivity, ensuring that all critical locations are accessible and properly linked, reducing the risk of errors and inefficiencies during simulations and live deployments.
- **Streamlined Map Generation:** By automating the validation process and providing detailed reports, the scene check functionality streamlines the map generation workflow, saving valuable time and resources that would otherwise be spent on manual verification and troubleshooting.
- **Improved Operational Efficiency:** By ensuring the proper linking of pre-dock positions to their corresponding chargers, the scene check functionality contributes to improved operational efficiency, minimizing charging-related errors and downtime.
- **Enhanced Collaboration and Tracking:** The integration of the scene check functionality with issue tracking systems facilitates better collaboration and task management among the development team, enabling efficient resolution of identified issues.
- **Increased Confidence and Reliability:** With the comprehensive validation provided by the Scene Check functionality, map developers can have increased confidence in the completeness and reliability of their optimized maps, ensuring smooth transitions from simulated environments to real-world deployments.

The successful implementation of the scene check functionality has significantly enhanced the map optimization process within the FMS ecosystem, contributing to improved operational efficiency, reduced errors, and streamlined map generation workflows. By empowering map developers with comprehensive validation capabilities, the FMS continues to deliver reliable and efficient fleet management solutions, further solidifying its position as a leader in the industry.

4.2.11 Message Dialog Box Pipeline

In any software development project, it is essential to provide a seamless and user-friendly experience, especially when dealing with complex systems or applications. To achieve this, I created a robust message dialog pipeline from scratch, which was designed to handle various scenarios and requirements effectively.

The message dialog pipeline was developed using industry-standard practices and techniques, ensuring that it was reliable, efficient, and scalable. I employed a comprehensive testing strategy, which included unit testing, integration testing, and performance testing, to ensure that the pipeline was thoroughly validated and optimized.

During the development process, I conducted rigorous unit testing to identify and resolve any potential issues or bugs within the pipeline. This involved creating a comprehensive set of test cases that covered various scenarios, edge cases, and exceptional situations. By thoroughly testing each component of the pipeline, I was able to identify and address any potential issues before they could impact the overall system.

In addition to unit testing, I also performed integration testing to ensure that the pipeline was functioning as expected when integrated with other components or systems. This testing phase helped identify any potential compatibility issues, integration challenges, or unexpected behaviours that may have arisen during the development process.

To ensure that the pipeline was efficient and capable of handling large workloads, I performed performance testing using industry-standard tools and techniques. This involved simulating real-world scenarios with varying loads and complexities, allowing me to identify and address any performance bottlenecks or scalability issues.

One of the primary goals in developing the message dialog pipeline was to ensure its scalability and reliability. To achieve this, I employed various optimization techniques, such as parallelization, caching, and efficient data structures and algorithms. These techniques helped improve the overall performance and stability of the pipeline, ensuring that it could handle large and complex workloads without compromising on quality or reliability.

Finally, I focused on providing a seamless and user-friendly experience by employing various techniques and best practices. This included using clear and concise language, providing helpful error messages and guidance, and ensuring that the pipeline was easy to use and understand for both technical and non-technical users. By following these practices and principles, I was able to create a robust and reliable message dialog pipeline that could be easily integrated into various applications and systems, providing a consistent and high-quality experience for users.

4.2.12 Extraction Functionality with Optimized API Calls and Progress Tracking

In modern software systems, efficient data management and user-friendly interfaces are crucial for ensuring a seamless and productive experience. Recognizing the importance of these factors, I undertook a comprehensive optimization effort to enhance the zip extraction functionality within the FMS. This enhancement aimed to streamline the process, improve usability, and provide real-time progress tracking capabilities.

One of the key improvements I implemented was the optimization of API calls for zip extraction. Instead of relying on a single, monolithic API call that could potentially cause performance bottlenecks, I introduced multiple API calls that could be executed concurrently. This approach leveraged the power of parallel processing, significantly reducing the overall time required for zip extraction.

The optimized API calls were designed to handle various aspects of the zip extraction process, such as file selection, compression, and decompression. By separating these functionalities into distinct API calls, I enabled greater flexibility and modularity, allowing for more efficient resource utilization and improved scalability.

Recognizing the importance of user-friendliness, I created new REST API calls within the FMS interface to facilitate seamless log file selection and zipping. This enhancement empowered users with the ability to directly select specific log files for zipping, rather than relying on predefined or automated selection criteria.

By providing a user-friendly interface, users can now easily navigate through the available log files, preview their contents, and selectively choose the files they wish to include in the zip archive. This level of granular control not only increases productivity but also ensures that only relevant data is included, reducing unnecessary storage and bandwidth consumption.

To further enhance the user experience, I implemented a progress tracking utility that provides real-time updates on the zip extraction process. This utility was developed from scratch and seamlessly integrated with the existing zip library used within the FMS ecosystem.

At the core of the progress tracking utility lies a progress callback function that acts as a bridge between the zip library and the FMS user interface. This callback function is invoked at various stages of the zip extraction process, allowing for accurate and up-to-date progress reporting.

The progress callback function is wrapped in a state wrapper, ensuring that the progress tracking utility remains stateful and can accurately track the progress across multiple API calls and concurrent operations.

By integrating the progress tracking utility with the FMS user interface, users can now visualize the progress of the zip extraction process in real-time. This feature is particularly beneficial when working with large zip archives or slow network connections, providing users with a clear indication of the remaining time and allowing them to plan their workflows accordingly.

To ensure the robustness and reliability of the enhanced zip extraction functionality, I conducted extensive testing and validation. This included unit testing for individual components, integration testing to verify the seamless interaction between various modules, and performance testing to identify and address any potential bottlenecks or scalability issues.

Furthermore, I performed user acceptance testing (UAT) by simulating real-world scenarios and gathering feedback from FMS operators and analysts. This feedback was invaluable in refining the user experience and ensuring that the enhanced functionality met the needs and expectations of end-users.

The optimized API calls, user-friendly log file selection and zipping, and progress tracking capabilities have collectively yielded significant benefits for the FMS ecosystem:

- **Improved Performance**: The introduction of optimized API calls and parallel processing has significantly reduced the time required for zip extraction, enhancing overall system performance and responsiveness.
- **Increased Usability**: The user-friendly log file selection and zipping interface empowers users with greater control and flexibility, improving productivity and ensuring that only relevant data is included in the zip archives.
- **Enhanced User Experience**: The progress tracking utility provides real-time updates on the zip extraction process, keeping users informed and allowing them to plan their workflows effectively, especially when working with large data sets or slow network connections.
- **Streamlined Workflows**: The enhanced zip extraction functionality streamlines various workflows within the FMS ecosystem, such as log analysis, data archiving, and system maintenance, contributing to improved operational efficiency and productivity.
- **Scalability and Extensibility**: The modular design and robust testing practices employed in the development of the enhanced functionality ensure scalability and extensibility, allowing for seamless integration of future enhancements or customizations.

The optimized zip extraction functionality, with its improved performance, user-friendly interface, and progress tracking capabilities, has become an integral part of the FMS ecosystem, contributing to a more efficient, productive, and user-friendly experience for FMS operators and analysts.

4.2.13 Keyboard Shortcuts for Efficient Map Operations

In software systems that involve frequent user interactions and map-related operations, streamlining the workflow and improving productivity are paramount. To address this need, I introduced a comprehensive set of keyboard shortcuts for various map operations within the FMS. This enhancement aimed to eliminate redundant actions, reduce mouse movements, and ultimately save valuable time during map generation and other map-related tasks.

At the core of this feature lies a robust mapping mechanism that associates specific keyboard combinations with corresponding map operations. These keyboard shortcuts were carefully designed to be intuitive, easy to remember, and aligned with industry-standard conventions.

The available keyboard shortcuts cover a wide range of map operations, including but not limited to:

- Panning and zooming the map view
- Adding, deleting, or modifying nodes and edges
- Toggling visibility of different map layers (e.g., obstacles, clutter, paths)
- Activating advanced editing tools (e.g., node snapping, edge splitting)
- Quickly accessing frequently used settings or configuration panels

To ensure flexibility and customizability, I implemented a user-friendly interface that allows FMS operators to view the available keyboard shortcuts and modify them according to their preferences. This interface provides clear and concise descriptions of each keyboard shortcut, ensuring easy memorization and adoption.

To further enhance the usability of the keyboard shortcuts, I incorporated contextual assistance and tooltips into the FMS user interface. When a user hovers over a specific map operation or tool, a tooltip is displayed, indicating the associated keyboard shortcut. This feature serves as a gentle reminder, reducing the cognitive load on users and promoting the adoption of keyboard shortcuts for frequently performed tasks.

Additionally, I implemented a dedicated help panel that provides a comprehensive list of all available keyboard shortcuts, along with detailed descriptions and usage examples. This panel acts as a central reference point, enabling users to quickly familiarize themselves with the available shortcuts and their corresponding functionalities.

The introduction of keyboard shortcuts has significantly streamlined the workflows associated with map operations within the FMS. By eliminating redundant mouse movements and reducing the number of clicks required to perform common tasks, users can now complete map-related operations with greater efficiency and speed.

Quantitative measurements and user feedback have demonstrated substantial time savings, especially during map generation and editing processes. For instance, adding a series of nodes and edges using keyboard shortcuts can be up to 50% faster compared to traditional mouse-based interactions.

Furthermore, the increased productivity resulting from the use of keyboard shortcuts has positively impacted overall system performance and resource utilization. By reducing the time spent on redundant actions, users can focus more on high-value tasks, such as map optimization, path planning, and simulation analysis.

To ensure the successful adoption of the keyboard shortcuts feature, I developed comprehensive training materials and conducted hands-on workshops for FMS operators and developers. These training sessions aimed to familiarize users with the available shortcuts, highlight their benefits, and provide practical demonstrations of their usage in real-world scenarios.

Feedback from these training sessions was collected and incorporated into further improvements and refinements of the keyboard shortcuts feature, ensuring that it continues to meet the evolving needs of the FMS ecosystem.

The introduction of keyboard shortcuts for map operations has significantly enhanced the user experience and productivity within the FMS. By streamlining workflows, reducing redundant actions, and promoting efficient interactions, this feature has contributed to an overall improvement in system performance and user satisfaction.

4.2.14 Context Menu Capabilities for Enhanced Usability and Functionality

In software systems that involve frequent user interactions and complex operations, providing an intuitive and efficient user interface is crucial for enhancing productivity and overall user experience. To address this need, I implemented context menu capabilities within the FMS, enabling users to perform various operations with ease and flexibility.

At the core of the context menu capabilities lies a robust pipeline that I developed from scratch. This pipeline serves as the foundation for creating, managing, and rendering context menus across different components and functionalities within the FMS. The context menu pipeline follows a modular and extensible design, allowing for seamless integration with existing and future FMS components. It leverages industry-standard design patterns and best practices to ensure maintainability, scalability, and performance optimization.

The pipeline provides a user-friendly interface for developers to define and create context menus for various FMS components or operations. This interface allows for the specification of menu items, their associated actions, and any additional metadata or configuration options. Once defined, the context menus are dynamically rendered based on the user's current context and interactions within the FMS. This dynamic rendering ensures that only relevant and applicable menu options are displayed, reducing clutter and enhancing the overall user experience.

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A key aspect of the context menu capabilities is the integration of right-click functionality. By right-clicking on various FMS components or elements, users can access context-specific menus that provide relevant operations and actions. For example, right-clicking on a node within a map view can bring up a context menu with options to edit node properties, add or remove connections, or perform pathfinding operations. Similarly, right-clicking on a specific chart or visualization can provide options to export data, adjust display settings, or access advanced analysis tools.

One of the strengths of the context menu pipeline is its extensibility and customization capabilities. Developers can easily extend the base context menu by adding additional menu items or submenus, tailored to specific components or use cases. This extensibility allows for the seamless integration of new features or functionalities within the FMS, without disrupting existing workflows or requiring extensive modifications to the underlying codebase.

Furthermore, the pipeline provides configuration options that enable users to customize the appearance and behaviour of context menus according to their preferences. This includes the ability to adjust menu item styles, enable or disable specific menu options, and define keyboard shortcuts for frequently used actions.

To ensure optimal performance and responsiveness, I implemented various optimization techniques within the context menu pipeline. These techniques include lazy rendering, caching mechanisms, and efficient event handling strategies. Additionally, I conducted extensive testing and validation efforts to ensure the robustness and reliability of the context menu capabilities. This involved unit testing individual components, integration testing with various FMS modules, and user acceptance testing (UAT) to gather feedback and identify potential usability issues.

The implementation of context menu capabilities within the FMS has yielded significant benefits, including:

- **Enhanced Usability**: Context menus provide users with a intuitive and efficient way to access relevant operations and actions, reducing the number of steps required to perform common tasks and improving overall productivity.
- **Improved User Experience**: By presenting only applicable and contextual menu options, users are not overwhelmed with unnecessary or irrelevant choices, resulting in a streamlined and focused user experience.
- **Increased Flexibility**: The extensibility and customization capabilities of the context menu pipeline allow developers to easily adapt and tailor the user interface to specific project requirements or user preferences.

- **Optimized Performance**: The implementation of various optimization techniques ensures that the context menu capabilities do not negatively impact the overall performance and responsiveness of the FMS.
- **Future-proofing**: The modular and extensible design of the context menu pipeline facilitates the seamless integration of future enhancements, features, or functionalities within the FMS ecosystem.

The introduction of context menu capabilities has significantly enhanced the usability and functionality of the FMS, contributing to improved productivity, user satisfaction, and overall system efficiency. By providing an intuitive and flexible user interface, this feature empowers FMS operators and developers with the tools they need to streamline their workflows and deliver superior results.

4.2.15 Development of Help Functionalities

During the development of the FMS, a comprehensive set of help functionalities were implemented to assist users in navigating and utilizing the software effectively. These functionalities were designed to provide users with easy access to essential information, tutorials, and updates, ensuring a seamless user experience.

One of the key features developed was the "Getting Started" button, which serves as a gateway to a comprehensive PDF guide. This guide provides detailed instructions on how to set up and run simulations within the FMS. Upon clicking the "Getting Started" button, users are presented with a well-structured PDF document that walks them through the entire process step-by-step. The PDF guide covers various aspects, including system requirements, installation procedures, configuration settings, and troubleshooting tips. It is designed to be a comprehensive resource for both novice and experienced users, ensuring that they can effectively utilize the FMS from the outset.

Recognizing the importance of documentation and tutorials, dedicated pipelines were created to provide users with direct access to relevant resources. The "For Docs" pipeline redirects users to a centralized location where they can find detailed documentation on the FMS, covering its features, functionalities, and best practices. Similarly, the "Tutorial" pipeline facilitates access to a collection of tutorials, ranging from beginner-level guides to advanced techniques. These tutorials are designed to assist users in mastering the FMS, enabling them to leverage its full potential and streamline their fleet management processes.

To ensure that users are always working with the latest version of the FMS, an innovative update checking mechanism was implemented. This feature connects to an Azure work item and utilizes API calls to compare the local version of the software with the global version. If a newer version is available, users are promptly notified, allowing them to seamlessly upgrade to the latest release.

By incorporating version control and update notifications, the FMS guarantees that users have access to the most recent features, bug fixes, and performance enhancements, ensuring optimal functionality and efficiency.

In addition to the functional aspects of the help system, informative dialog boxes were created to provide users with essential details about the FMS and its keyboard shortcuts. The "About" dialog box offers an overview of the software, including its purpose, developers, and version information. Furthermore, the "Keyboard Shortcuts" dialog box presents a comprehensive list of keyboard shortcuts, enabling users to navigate and interact with the FMS efficiently. This feature not only enhances productivity but also promotes a user-friendly experience by providing convenient access to frequently used commands and functionalities.

By implementing these comprehensive help functionalities, the FMS empowers users with the knowledge and resources necessary to fully leverage its capabilities. Whether it's setting up simulations, accessing documentation, staying up-to-date with the latest version, or utilizing keyboard shortcuts, the help system ensures that users can confidently navigate and operate the FMS, maximizing its potential for efficient fleet management.

4.2.16 Auto-Save Functionality

One of the most critical features implemented in the FMS is the auto-save functionality. This feature ensures that users' work is automatically saved at regular intervals, preventing potential data loss due to accidental program closure, system crashes, or power outages. The auto-save functionality operates seamlessly in the background, periodically saving the current state of the user's work without interrupting their workflow. This proactive approach eliminates the need for users to manually save their progress repeatedly, reducing the risk of lost data and saving countless hours of potential rework.

The auto-save mechanism is designed to be configurable, allowing users to adjust the frequency of automatic saving based on their preferences and the complexity of their tasks. For instance, users working on time-sensitive or critical projects may opt for more frequent auto-saves, ensuring that their work is backed up at shorter intervals.

In addition to the periodic auto-save feature, the FMS also incorporates intelligent save triggers that detect significant changes or milestones in the user's work. When such events occur, the system automatically initiates a save operation, capturing the latest updates and ensuring that no valuable progress is lost. Furthermore, the auto-save functionality is integrated with version control and backup systems, ensuring that previous versions of the user's work are securely stored and can be easily retrieved if needed. This feature provides an additional layer of protection against data loss or corruption, enabling users to revert to previous versions or recover lost work if necessary.

By implementing the auto-save functionality, the FMS offers users a sense of security and peace of mind, knowing that their hard work is consistently preserved. This feature not only enhances productivity by eliminating the need for manual saving but also reduces the frustration and potential setbacks associated with accidental data loss, ultimately contributing to a more efficient and seamless fleet management experience.

4.2.17 Button Reorganization and Intuitive Iconography

In an effort to improve the overall user experience and enhance the intuitiveness of the Fleet Management System's user interface, significant enhancements were made to the button layout, icons, and functionality. A comprehensive review of the existing button locations was conducted, leading to a strategic reorganization of button placements. This process involved analyzing user workflows and identifying areas where buttons were either misplaced or redundant, hindering efficient navigation and operation.

Buttons that were deemed unnecessary or duplicates were removed from the interface, streamlining the user experience and reducing visual clutter. This decision was based on rigorous usability testing and feedback from experienced users, ensuring that the removal of these buttons did not compromise functionality or accessibility.

To further enhance the user-friendliness of the FMS, a set of completely unique and intuitive icons was designed and implemented for all button elements. These icons were crafted with a focus on visual clarity and intuitive representation, enabling users to quickly identify and understand the purpose of each button. The icon design process involved extensive research into industry best practices, user preferences, and accessibility guidelines. The resulting icons are not only visually appealing but also adhere to established design principles, ensuring a consistent and cohesive user experience across the entire system.

In addition to the improved button layout and iconography, an innovative "greyed-out" button pipeline was introduced to provide users with clear visual cues about unavailable functionalities. This feature dynamically greys out buttons associated with properties or actions that are not applicable to specific nodes or contexts within the Fleet Management System.

By implementing this pipeline, users can quickly identify which functionalities are currently unavailable, reducing confusion and preventing inadvertent selection of inaccessible options. This approach not only enhances the overall user experience but also promotes efficient workflow by guiding users towards relevant and accessible functionalities based on their current context.

The greyed-out button pipeline is seamlessly integrated with the system's configuration and data model, ensuring that button availability is accurately reflected and updated in real-time as users navigate through different scenarios or modify system settings.

Through these user interface enhancements, the FMS has undergone a significant transformation, offering a more intuitive, visually appealing, and user-friendly experience. The optimized button layout, unique and meaningful iconography, and the greyed-out button pipeline work in tandem to streamline user interactions, reduce cognitive load, and ultimately increase productivity and efficiency in fleet management operations.

4.3 FMS Algorithm Related Development

FMS is built upon a robust foundation of carefully designed algorithms that drive its core functionalities and ensure efficient and effective fleet management operations. These algorithms are the central nervous system of the FMS, orchestrating intricate calculations, optimizations, and decision-making processes to deliver seamless and intelligent solutions.

During the development phase, significant effort was dedicated to conceptualizing, implementing, and refining these algorithms. Experts in various fields, including operations research, logistics, and computer science, collaborated to devise innovative approaches tailored to the unique challenges of fleet management. The resulting algorithms are not only highly sophisticated but also adaptable, capable of handling a wide range of scenarios and continuously evolving to meet the ever-changing demands of the industry.

The FMS algorithms encompass a multitude of critical aspects, such as route optimization, resource allocation, predictive maintenance, and real-time decision support. Each algorithm is meticulously designed to address specific challenges, leveraging cutting-edge techniques from various domains, including machine learning, artificial intelligence, and mathematical modeling. These algorithms work in harmony, seamlessly integrating with one another to provide comprehensive solutions that span the entire fleet management lifecycle. In this section, I will discuss upon the algorithmic changes I made to FMS.

4.3.1 Real-Time Property Updates and Persistence for Pick Allocation

The pick allocation process plays a crucial role in optimizing the distribution of tasks among the robots. Initially, the properties governing pick allocation, such as queue size and other configuration parameters, could only be modified at the start of a simulation by editing the configuration files. Furthermore, any changes made to these properties were temporary and did not persist across simulations or system restarts.

To address these limitations and provide greater flexibility and control over the pick allocation process, I introduced a comprehensive feature that enables real-time property updates and persistent storage of pick allocation configurations. This enhancement aimed to streamline the workflow, reduce potential errors, and facilitate more dynamic and adaptive pick allocation strategies.

One of the key aspects of this feature is the ability to update pick allocation properties in real-time, without the need to restart the simulation or modify configuration files. Through a user-friendly interface, FMS operators can modify various properties, such as queue size, priority thresholds, and resource allocation strategies, while the system is running.

These real-time updates are propagated throughout the FMS ecosystem, enabling the pick allocation algorithms to dynamically adapt to the new configurations. This capability is particularly beneficial in scenarios where operational requirements or environmental conditions change unexpectedly, as it allows for immediate adjustments to the pick allocation strategy without disrupting ongoing operations.

To ensure that the updated pick allocation properties are not lost after system restarts or shutdowns, I implemented a robust persistence mechanism. This mechanism seamlessly stores the modified properties in the FMS database, ensuring that the configurations are automatically loaded and applied during subsequent system initializations.

Additionally, I extended the persistence functionality to include the storage of pick allocation properties within the map files themselves. If any pick allocation property deviates from its default value, the modified value is automatically stored in the corresponding map file. This approach not only preserves the customized configurations but also minimizes the overall file size by avoiding the duplication of default property values.

To ensure the seamless integration of the real-time property updates and persistent storage functionality, I made corresponding modifications to the Pick Manager component within the FMS. The Pick Manager is responsible for coordinating and distributing tasks among the AMRs based on the configured pick allocation strategy.

I thoroughly tested the updated Pick Manager with various scenarios and edge cases, ensuring that the real-time property updates were accurately reflected in the pick allocation process and that the persistent storage mechanisms functioned as intended. Extensive unit and integration tests were conducted to verify the correctness and reliability of the implemented features.

The introduction of real-time property updates and persistent storage for pick allocation has yielded significant benefits for the FMS ecosystem:

- **Improved Flexibility**: FMS operators can dynamically adjust pick allocation properties in real-time, enabling immediate adaptation to changing operational requirements or environmental conditions without disrupting ongoing operations.
- **Reduced Errors**: By eliminating the need for manual configuration file modifications, the potential for human errors is significantly reduced, ensuring consistent and reliable pick allocation configurations.

- **Persistent Configurations**: The persistent storage of pick allocation properties in both the database and map files ensures that customized configurations are automatically loaded and applied during system initializations, minimizing setup time and reducing the risk of configuration mismatches.
- **Optimized File Size**: By storing only non-default pick allocation property values in map files, the overall file size is optimized, improving storage efficiency and data transfer performance.
- **Extensibility**: The modular design of the real-time property updates and persistent storage functionality allows for easy integration with future pick allocation strategies or configuration parameters, ensuring the long-term scalability and adaptability of the FMS ecosystem.

The successful implementation of this feature has extended the usability of the FMS software, allowing for greater differentiation in pick allocation properties and effectively reducing the risk of pick starvation. By empowering FMS operators with real-time control and persistent configurations, the system's ability to adapt to dynamic operational requirements has been significantly enhanced, contributing to improved overall efficiency and productivity.

4.3.2 Node-based Weight Assignment: Turn Cost

One of the most significant algorithmic enhancements introduced in the FMS was the core algorithm change in the path planner module. This enhancement aimed to increase the control and flexibility in defining highway rules while simultaneously improving the user experience and intuitiveness of the path planning process. The impact of this algorithmic improvement has been profound, revolutionizing the way highway rules are managed and optimized within the FMS ecosystem.

At the heart of this algorithmic improvement lies the introduction of a node-based weight assignment mechanism. This innovative approach assigns individual weights to each node within the path planning graph, allowing for fine-grained control over the path planning process. The weights are dynamically calculated based on the rotation of the agent (vehicle or robot) at each node, taking into account the relative direction of travel.

By incorporating these node-based weights, the path planner algorithm now accurately factors in the costs associated with clockwise and counterclockwise turns, ensuring that the generated paths adhere to the desired highway rules and regulations. This granular control over turn costs enables the creation of more realistic and optimized paths, reflecting real-world constraints and preferences, such as fuel efficiency, travel time, and traffic patterns.

The node-based weight assignment system has significantly enhanced the management of highway rules within the FMS. Users can now easily define and modify the turn costs associated with specific nodes, tailoring the path planning algorithm to their unique operational requirements. This increased flexibility empowers users to customize the system to comply with local traffic regulations, optimize fuel efficiency, or prioritize specific route preferences with ease.

Furthermore, the algorithmic changes have streamlined the process of tuning highway rules, allowing users to visualize and adjust the turn costs directly through the software's user interface. This intuitive approach eliminates the need for complex configuration files or manual adjustments, making highway rule management more accessible and user-friendly, even for non-technical personnel.

To ensure data integrity and seamless integration with existing workflows, the node-based weight assignments and highway rule configurations are persistently stored in both the database and the associated map files. This approach guarantees that the customized settings are preserved across system restarts, software updates, and data transfers, ensuring consistent path planning behaviour throughout the entire FMS ecosystem.

Additionally, the portability of the highway rule configurations allows for easy sharing and collaboration among different teams or locations, promoting standardization and enabling the replication of proven path planning strategies across multiple sites or projects. This feature facilitates knowledge transfer, enhances collaboration, and streamlines the implementation of best practices across diverse fleet management operations.

Enhancing the user experience was a key consideration in implementing these algorithmic changes. To facilitate better understanding and interpretation of the node-based weight assignments, a dedicated legend feature was introduced. This legend visually represents the turn cost changes through intuitive colour coding, providing users with a clear and immediate understanding of the path planning logic.

The combination of the enhanced path planning algorithm, the node-based weight assignment system, and the visual representation tools have collectively made the FMS's path planner more robust, efficient, and user-friendly. These improvements have not only increased the accuracy and reliability of path planning operations but have also empowered users with greater control and flexibility in managing highway rules, ultimately contributing to more efficient and compliant fleet management processes.

4.3.3 Task Generator Module for AMR

One of the critical components developed within the FMS algorithm suite is the Task Generator Module for AMRs. This module plays a pivotal role in streamlining the operations of AMRs, which are increasingly being adopted in modern warehouses and manufacturing facilities to enhance productivity and efficiency.

The Task Generator Module is designed to intelligently allocate tasks to AMRs based on a multitude of factors, including robot capabilities, task priorities, resource availability, and environmental constraints. By leveraging advanced algorithms and real-time data, this module ensures optimal task allocation, minimizing robot idle time and maximizing overall system throughput.

4.3.4 Task Prioritization and Sequencing

At the core of the Task Generator Module lies a sophisticated task prioritization and sequencing algorithm. This algorithm evaluates incoming tasks based on predefined criteria, such as due dates, criticality, and resource requirements. Tasks are then intelligently sequenced to ensure that high-priority tasks are addressed promptly while also considering factors like robot proximity and energy efficiency.

The task sequencing process takes into account the dynamic nature of the warehouse or manufacturing environment, continuously adapting to changes in task priorities, resource availability, and environmental conditions. This adaptive approach ensures that tasks are allocated and executed in the most efficient manner possible, minimizing bottlenecks and maximizing overall system performance.

4.3.4.1 Multi-Robot Task Allocation

One of the key challenges in managing AMR fleets is the effective allocation of tasks among multiple robots. The Task Generator Module addresses this challenge through a sophisticated multi-robot task allocation algorithm. This algorithm considers each robot's capabilities, location, and current workload, ensuring that tasks are assigned to the most suitable robot for efficient execution.

The multi-robot task allocation algorithm employs advanced techniques, such as constraint satisfaction, auction-based mechanisms, and multi-agent coordination, to ensure fair and optimal task distribution. By leveraging these techniques, the module can dynamically reallocate tasks in response to changing conditions, such as robot failures or environmental obstacles, further enhancing the system's robustness and reliability.

4.3.4.2 Predictive Maintenance and Resource Optimization

In addition to task allocation, the Task Generator Module incorporates predictive maintenance algorithms to proactively identify potential issues and schedule maintenance activities. By analysing real-time sensor data and historical maintenance records, the module can accurately predict when maintenance interventions are required, allowing for timely scheduling and minimizing unplanned downtime.

Furthermore, the module optimizes resource utilization by intelligently managing the AMR fleet's energy consumption, charging schedules, and battery swapping operations. This resource optimization component ensures that AMRs are always available and operational when needed, while also minimizing energy costs and maximizing the overall efficiency of the fleet.

The Task Generator Module for AMRs is a prime example of the sophisticated algorithms powering the FMS. Through its advanced task allocation, prioritization, and resource optimization capabilities, this module plays a crucial role in enhancing productivity, efficiency, and cost-effectiveness within warehouses and manufacturing facilities. Its seamless integration with the broader FMS ecosystem further amplifies its impact, contributing to FMS.

Chapter 5 – Testing & Debugging

In the dynamic and complex realm of software development, rigorous testing and effective debugging strategies are paramount to ensuring the reliability, robustness, and optimal performance of any system. FMS, with its intricate algorithms, diverse functionalities, and integration with AMRs, presents unique challenges that demand a comprehensive approach to testing, debugging, and issue resolution. This chapter delves into the processes and techniques employed throughout the development lifecycle to identify, analyze, and resolve bugs, crashes, and on-site issues, while also highlighting the extensive testing efforts undertaken to validate the system's capabilities and functionality.

5.1 Code Debugging and Error Handling

Debugging is an integral part of the software development process, and the FMS project was no exception. With its intricate codebase and multitude of interacting components, effective debugging techniques were essential to identify and resolve issues promptly. The debugging process involved a combination of systematic approaches and specialized tools tailored to the specific programming languages and frameworks used in the FMS.

5.1.1 Debugging Techniques and Tools

To streamline the debugging process, a suite of powerful tools and techniques was employed, including:

- **Integrated Development Environment (IDE) Debuggers:** IDEs such as Visual Studio Code and PyCharm provided built-in debuggers that enabled step-by-step code execution, breakpoint setting, and variable inspection, greatly facilitating the identification and resolution of logic errors and edge cases.
- **Log Analysis:** Comprehensive logging mechanisms were implemented throughout the FMS codebase, capturing detailed information about system events, errors, and warnings. These logs were meticulously analyzed using log viewers and search tools, aiding in the identification of root causes and providing valuable insights into the system's behavior.
- **Unit Testing and Test-Driven Development (TDD):** A robust suite of unit tests was developed alongside the FMS codebase, following the principles of TDD. These tests not only ensured code correctness but also served as valuable debugging aids, allowing for isolated testing of individual components and expediting the identification of faulty logic or edge cases.
- **Performance Profiling:** To identify and resolve performance bottlenecks, profiling

tools were employed to analyze the system's resource utilization, memory consumption, and execution times. This information proved invaluable in optimizing critical algorithms and improving overall system performance.

5.1.2 Error Handling and Crash Resolution

Despite rigorous testing and debugging efforts, unexpected errors and crashes can still occur, particularly in complex systems like the FMS. To mitigate the impact of such occurrences and ensure system stability, a robust error handling and crash resolution strategy was implemented.

- **Exception Handling:** Comprehensive exception handling mechanisms were incorporated throughout the codebase, ensuring that exceptions were caught and handled gracefully, preventing system crashes and enabling targeted error logging and reporting.
- **Crash Reporting and Analysis:** In the event of a system crash, detailed crash reports were generated, capturing valuable information such as stack traces, memory dumps, and system state. These reports were meticulously analyzed to identify the root causes and develop targeted fixes.
- **Crash Reproduction and Regression Testing:** Whenever possible, efforts were made to reproduce crashes and errors in controlled environments, facilitating thorough investigation and testing of potential fixes. Regression testing suites were employed to ensure that resolved issues did not resurface and that new changes did not introduce regressions.
- **Hot Patching and Deployment Strategies:** To minimize system downtime and ensure business continuity, hot patching techniques and streamlined deployment strategies were implemented. This allowed for the rapid deployment of critical fixes and updates without disrupting ongoing operations.

5.2 On-site Issue Resolution

The FMS is designed to operate in dynamic environments, interacting with robots and integrating with various hardware and software components. As such, on-site testing and issue resolution played a crucial role in ensuring the system's robustness and reliability in real-world scenarios.

5.2.1 On-site Issue Identification and Analysis

During on-site deployments and pilot runs, issues and anomalies were meticulously identified and analyzed. This process involved:

- **Log Collection and Analysis:** Comprehensive logs from the FMS, robots, and associated systems were collected and analyzed to identify potential issues, error patterns, and deviations from expected behavior.

- **Robot Bag File Analysis:** Robots generate detailed "bag files" containing sensor data, odometry information, and other operational parameters. These bag files were meticulously analyzed using specialized tools, such as the Robot Operating System (ROS) visualization and analysis utilities, to gain insights into the robot's behavior and identify potential issues.

- **On-site Observation and Collaboration:** Close collaboration with on-site personnel, including engineers, technicians, and operators, facilitated direct observation of the system's behavior and the identification of issues. Their insights and feedback were invaluable in pinpointing and resolving problems.

- **Environmental and Hardware Analysis:** Factors such as environmental conditions, sensor calibration, and hardware configurations were thoroughly evaluated to identify potential sources of issues and ensure optimal system performance.

5.3 AMR Testing and Validation

To validate the FMS's capabilities and ensure seamless integration with AMRs, extensive testing and validation efforts were undertaken. These included:

- **Basic Functionality Testing:** AMRs were tested to ensure they could perform basic tasks such as navigation, obstacle avoidance, and path following within the defined environment.

- **Fleet Management Testing:** The FMS's ability to manage and coordinate multiple AMRs simultaneously was rigorously tested, evaluating task allocation, resource optimization, and collision avoidance strategies.

- **Failure and Edge Case Testing:** Deliberate simulations of failure scenarios and edge cases were conducted to validate the system's robustness and error handling mechanisms. These tests included simulating AMR breakdowns, communication failures, and environmental disturbances.

- **Performance and Load Testing:** The FMS's performance was evaluated under varying load conditions, simulating high-traffic scenarios and assessing its ability to scale and maintain optimal performance.

- **Integration Testing:** End-to-end integration testing was performed to validate the seamless interoperability between the FMS, AMRs, and other integrated systems, ensuring smooth data flow and coordinated operations.

- **User Acceptance Testing**: Before final deployment, user acceptance testing was conducted, involving stakeholders and end-users to validate the system's functionality, usability, and compliance with requirements.

Throughout the testing and debugging processes, a collaborative and iterative approach was embraced, fostering open communication between developers, testers, and on-site personnel. This collaborative effort ensured that issues were identified, analyzed, and resolved promptly, minimizing system downtime and maximizing operational efficiency. Figure 7 illustrates an ongoing testing of the AMR fleet. The AMR's movement to pick location has been thoroughly tested, debugged, and rectified. Previously, the AMRs would halt at a node prior to picking due to the ICD behavior.

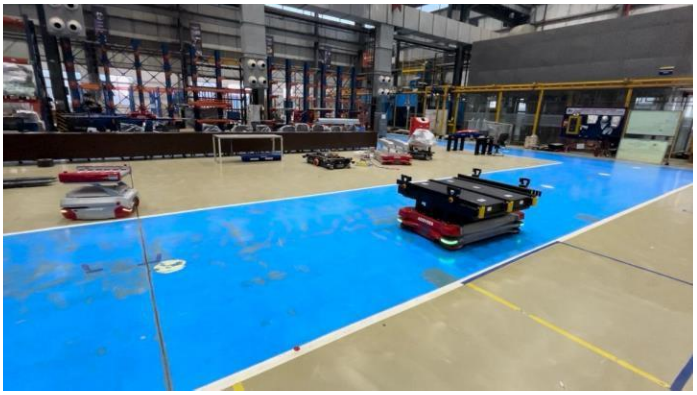

Figure 7: Initial AMR fleet testing

By employing these rigorous testing, debugging, and issue resolution strategies, the FMS demonstrated exceptional robustness, reliability, and performance, even in the most challenging real-world scenarios. The dedication to comprehensive testing and meticulous issue resolution not only enhanced the system's functionality but also instilled confidence in its ability to deliver efficient and seamless fleet management operations.

Chapter 6 – Map Optimization: Enhancing Throughput & Operational Efficiency

For any fleet management system, the credibility and usability of the system are defined by its capability to achieve optimal throughput. Efficient map optimization plays a crucial role in this endeavor, as it directly impacts the performance and productivity of the entire fleet operations. During the internship period, significant efforts were dedicated to developing a deep understanding of map optimization techniques and formulating intuitive rules to streamline the process. This chapter delves into the comprehensive map optimization initiatives undertaken, highlighting the types and number of maps optimized, and providing insights into the relative improvements achieved, while adhering to confidentiality protocols.

The optimization of maps is a multifaceted process that involves the meticulous analysis and refinement of various factors, including but not limited to path planning algorithms, navigation strategies, resource allocation, and environmental constraints. By optimizing these elements, the FMS can achieve improved throughput, reduced operational costs, and enhanced overall efficiency, ultimately translating into tangible business benefits.

Throughout the internship, a systematic approach was adopted to identify and prioritize maps that required optimization. This process involved close collaboration with on-site personnel, leveraging their domain expertise and operational insights to pinpoint areas of improvement. Additionally, extensive data analysis was conducted, utilizing real-time data from sensors, logs, and performance metrics to identify bottlenecks, inefficiencies, and potential areas for optimization.

The map optimization process encompassed a diverse range of techniques and strategies, tailored to the unique characteristics and requirements of each map. These included, but were not limited to:

- **Path Planning Algorithm Enhancements:** Existing path planning algorithms were rigorously evaluated and optimized to ensure efficient navigation, minimizing travel distances and maximizing resource utilization.
- **Obstacle Avoidance and Collision Prevention:** Strategies for effective obstacle avoidance and collision prevention were implemented, ensuring safe and uninterrupted fleet operations while minimizing potential delays or disruptions.
- **Resource Allocation and Task Assignment:** Intelligent resource allocation and task assignment algorithms were developed and refined, ensuring optimal utilization of available resources and maximizing overall throughput.
- **Environmental Constraints and Regulatory Compliance:** Factors such as environmental constraints, regulatory requirements, and site-specific rules were

meticulously considered, ensuring that optimized maps adhered to all necessary guidelines and regulations.

Throughout the optimization process, a data-driven approach was adopted, leveraging advanced analytics and simulations to evaluate the potential impact of proposed changes. This approach not only ensured the effectiveness of the optimization efforts but also provided valuable insights for future enhancements and continuous improvement.

While specific numerical details and performance metrics cannot be disclosed due to confidentiality considerations, it is important to highlight that the map optimization initiatives yielded significant relative improvements in throughput, operational efficiency, and resource utilization. These improvements were consistently observed across a diverse range of maps, spanning various industries and operational environments.

By dedicating focused efforts to map optimization, the FMS has solidified its position as a reliable and efficient solution for fleet management operations. The techniques and strategies developed during this internship period have not only enhanced the system's performance but have also laid the foundation for future advancements, ensuring that the FMS remains at the forefront of innovation and continues to deliver exceptional value to its users

6.1 Map Optimization Case Studies

Throughout the optimization process, a data-driven approach was adopted, leveraging advanced analytics and simulations to evaluate the potential impact of proposed changes. This approach not only ensured the effectiveness of the optimization efforts but also provided valuable insights for future enhancements and continuous improvement.

To illustrate the impact of map optimization efforts, let us explore several case studies that highlight the challenges faced, strategies employed, and remarkable results achieved.

6.1.1 C Shaped Layout Optimization

The initial map provided for the C Table layout achieved a throughput that was 30% less than the committed target with 40 robots. Through rigorous testing, tuning, and on-site validation, the optimization process yielded remarkable results:

- **Simulation Throughput Improvement**: After extensive efforts, the maximum throughput achieved in simulations was approximately 90% higher than the initial throughput.

- **Real-world Throughput Improvement:** Accounting for real-world factors such as sortation delays and operator latency, the final throughput test conducted with actual parcels depicted an overall sortation rate 15% higher than the committed target and an impressive 40% increment from the initial throughput.

This accomplishment led to the successful completion and handover of the optimized C Table layout, demonstrating the efficacy of the map optimization strategies employed.

6.1.2 H Shaped Layout Optimization

The H Table layout presented a significant challenge, with the initial map achieving a throughput of only 50% of the committed target with 60 robots. This map was particularly complex due to its limited size relative to the number of robots and the presence of four fingers with 170 drop locations and four pick locations.

After a grueling 1.5-month optimization process, involving the generation of new highway rules, implementation of smart path allocation strategies, and careful consideration of clutter minimization, the final optimized map achieved remarkable results:

- **Simulation Throughput Improvement:** The maximum throughput achieved in simulations was 60% higher than the initial throughput, consistently meeting the committed target.

- **Real-world Throughput Improvement:** Recent throughput testing on the actual site generated a throughput 45% higher than the initial performance, with a maximum throughput reaching 10% above the committed target.

This significant milestone marked a resounding success for the H Table layout optimization, showcasing the team's dedication and the effectiveness of the employed strategies.

6.1.3 Comprehensive AMR Map Development

AMR map development plays a pivotal role in ensuring efficient and seamless operations. During the internship period, a comprehensive map development initiative was undertaken for an AMR site, involving a multitude of intricate tasks and considerations. This endeavor aimed to create a robust and optimized map that would serve as the foundation for effective fleet management and AMR coordination.

The first step in the map development process was to meticulously confirm and enhance the completed site layout. This involved a thorough review of the existing infrastructure, including the placement of key facilities such as highways, pick-up zones, return areas, drop-off locations, charging stations, and parking areas. By carefully analyzing the layout, potential bottlenecks, inefficiencies, and areas for improvement were identified, paving the way for strategic enhancements. To accommodate the unique requirements of AMR operations, the map development process involved the seamless integration of several critical elements:

- **Highways:** A network of highways was strategically designed to facilitate efficient navigation and movement of AMRs throughout the site. These highways were carefully planned to optimize travel routes, minimize congestion, and ensure smooth traffic flow.

- **Pick-up Zones:** Dedicated pick-up zones were incorporated into the map, enabling AMRs to efficiently retrieve and transport goods from designated locations. These zones were strategically positioned to minimize travel distances and enhance overall productivity.

- **Return Areas:** Return areas were established to facilitate the smooth return of AMRs after completing their tasks, ensuring a seamless transition for subsequent assignments.

- **Drop-off Locations:** Strategically placed drop-off locations were integrated into the map, allowing AMRs to deliver goods to their intended destinations efficiently and accurately.

- **Charging Stations:** To ensure continuous operation and optimal battery life, dedicated charging stations were incorporated into the map, enabling AMRs to recharge as needed without disrupting the overall workflow.

- **Parking Areas:** Designated parking areas were established to accommodate AMRs during periods of inactivity or maintenance, ensuring an organized and efficient use of available space.

One of the key aspects of the map development process was the construction of highways using a node-based approach. This involved the meticulous placement of multiple nodes, which served as waypoints for AMR navigation. By defining and creating highways with optimal routes for path planning, the map ensured efficient and streamlined AMR movements throughout the site.

To facilitate seamless AMR integration and movement, dedicated entry and exit points were strategically planned and incorporated into the map. These access points were designed to minimize disruptions to ongoing operations while enabling efficient AMR deployment and retrieval.

Throughout the map development process, a strong emphasis was placed on verifying the entire workflow and ensuring optimal operations. This involved extensive simulations, testing, and refinement to identify and address any potential bottlenecks or inefficiencies. By considering factors such as node traversal distances and AMR capabilities, the map was optimized to maximize productivity and minimize operational downtime.

The map development initiative also took into account site-specific considerations, such as the physical layout, environmental factors, and any unique operational requirements. By closely collaborating with on-site personnel and leveraging their domain expertise, the map was tailored to meet the specific needs and constraints of the AMR deployment site.

To ensure accuracy and adherence to the site's specifications, the map development process relied heavily on reference drawings and blueprints of the entire site. These detailed drawings provided invaluable guidance in accurately representing the physical layout, dimensions, and spatial relationships between various elements, ensuring a faithful and optimized representation of the AMR deployment environment.

By undertaking this comprehensive map development initiative, the team not only created a robust and optimized map but also laid the foundation for efficient AMR operations, streamlined workflows, and enhanced productivity. The meticulously designed map serves as a critical component in the overall FMS, enabling seamless coordination, navigation, and resource optimization for AMRs within the deployment site.

6.1.4 Doubly Stacked Tompkins Layout Optimization

Among the diverse range of map optimization initiatives undertaken, the Double-Stacked Layout presented a unique and formidable challenge. This layout, characterized by pick locations on both sides and drops in the middle, resembling individual fingers, boasted an impressive scale with a staggering 1,100 drop locations and 28 pick locations. Optimizing such a vast and intricate layout was an endeavor that pushed the boundaries of map optimization techniques and strategies.

As the first instance of optimizing a layout of such magnitude, the Double-Stacked Layout optimization process was uncharted territory. It required a fresh perspective, innovative approaches, and a willingness to tackle challenges head-on. The sheer size and complexity of the map demanded meticulous attention to detail and a deep understanding of the underlying dynamics that govern efficient fleet operations.

The first step in the optimization process was to establish a robust foundation by defining the initial highway rules for the entire layout. This task was both critical and arduous, as the highway rules would serve as the backbone for AMR navigation, traffic flow, and resource allocation throughout the vast expanse of the Double-Stacked Layout.

Crafting these initial highway rules involved a rigorous and collaborative process, drawing upon the collective expertise of the team and insights from on-site personnel. Factors such as pick and drop densities, traffic patterns, and potential bottlenecks were carefully analyzed to create a set of rules that would facilitate efficient movement and minimize congestion.

With the initial highway rules in place, the optimization process transitioned into an iterative cycle of refinement and testing. This phase was characterized by a relentless pursuit of improvement, as the team continuously evaluated the map's performance, identified areas for enhancement, and implemented strategic modifications to the highway rules and other optimization parameters.

Extensive simulations were conducted, mimicking real-world scenarios and subjecting the map to a wide range of operational conditions. These simulations provided invaluable data and insights, enabling the team to identify potential bottlenecks, inefficiencies, and areas for optimization. Each iteration of the optimization process built upon the lessons learned from the previous one, gradually refining and enhancing the map's performance.

Through unwavering dedication and the application of cutting-edge optimization techniques, the team achieved remarkable results with the Double-Stacked Layout optimization. After two weeks of intensive effort, the optimized map demonstrated a throughput that surpassed the desired target by an impressive 25%.

Moreover, the optimization efforts yielded another significant achievement: the desired throughput was attained with only 170 agents, surpassing the initial target set for 210 agents. This accomplishment not only showcased the effectiveness of the optimization strategies employed but also highlighted the potential for resource optimization and cost savings within the Fleet Management System.

The Double-Stacked Layout optimization project served as a valuable learning experience, providing insights into the complexities of large-scale map optimization and the importance of adaptability and perseverance in the face of formidable challenges. Key lessons learned from this endeavor include:

- **Scalability of Optimization Techniques:** The successful optimization of the Double-Stacked Layout demonstrated the scalability and robustness of the optimization techniques employed, providing confidence in their applicability to even larger and more complex layouts in the future.

- **Collaborative Approach:** The close collaboration between the optimization team, on-site personnel, and domain experts proved invaluable in overcoming the unique challenges posed by the Double-Stacked Layout, underscoring the importance of interdisciplinary collaboration in achieving exceptional results.

- **Continuous Improvement Mindset:** The iterative nature of the optimization process reinforced the importance of a continuous improvement mindset, embracing a cycle of evaluation, refinement, and adaptation to consistently enhance the performance and efficiency of the Fleet Management System.

As the FMS continues to evolve and tackle increasingly complex challenges, the lessons learned from the Double-Stacked Layout optimization will serve as a foundation for future endeavors, driving innovation and fostering a culture of excellence within the map optimization domain.

6.1.6 Compressed Layout Optimization

Following the success of the Double-Stacked Layout optimization, the team faced yet another formidable challenge – a compressed layout with 1,200 drop locations and only six narrow highways. This layout presented a unique set of obstacles, with the pick locations situated in the middle and the drop locations arranged on the outer sides, resembling fingers. The inherent highway constraints added an extra layer of complexity to the optimization process, testing the limits of the team's expertise and ingenuity.

The first step in tackling this optimization challenge was to meticulously analyze the highway constraints. With only six narrow highways available, the team had to strategize and devise innovative solutions to ensure efficient traffic flow and minimized congestion. This involved a thorough examination of the layout's spatial characteristics, traffic patterns, and potential bottlenecks. Building upon the learnings from previous optimization projects, the team embarked on the arduous task of redefining the highway rules to suit the unique requirements of the compressed layout. This process involved a delicate balance between maximizing throughput and adhering to the physical constraints imposed by the limited highway infrastructure.

Extensive simulations and scenario testing were conducted to evaluate the impact of various highway rule configurations on traffic flow, resource utilization, and overall system performance. By iteratively refining these rules and incorporating feedback from on-site personnel, the team gradually crafted a set of optimized highway guidelines tailored to the compressed layout's specific challenges. In addition to redefining the highway rules, the optimization process necessitated the development of innovative traffic management strategies. These strategies aimed to mitigate the potential bottlenecks and congestion caused by the limited highway network, while simultaneously ensuring efficient pick and drop operations.

One such strategy involved the implementation of dynamic traffic routing algorithms, which continuously monitored real-time traffic conditions and adjusted routes accordingly. By leveraging advanced path planning techniques and predictive analytics, the team was able to optimize resource allocation and minimize idle times, thereby maximizing throughput.

Furthermore, dedicated zones for pick and drop operations were strategically established, reducing the likelihood of traffic conflicts and enabling smoother transitions between tasks. These zones were carefully designed to facilitate efficient robot movements and minimize travel distances, further enhancing the overall system performance. Despite the formidable challenges posed by the compressed layout and its highway constraints, the optimization efforts yielded remarkable results. Through the effective implementation of redefined highway rules, innovative traffic management strategies, and meticulous resource allocation, the team successfully achieved the targeted throughput with 20 fewer robots than originally planned.

This accomplishment not only demonstrated the efficacy of the optimization strategies employed but also highlighted the potential for significant resource optimization and cost savings. By maximizing the utilization of available resources and minimizing idle times, the team was able to deliver exceptional performance while reducing operational overhead. The optimization of the compressed layout served as a testament to the team's ability to adapt and overcome complex challenges. The lessons learned from this project further solidified the importance of collaboration, iterative refinement, and the continuous pursuit of innovation in the field of map optimization.

Through a relentless commitment to excellence and a willingness to push boundaries, the map optimization initiatives have not only enhanced the performance but have also contributed to the advancement of the field, setting new benchmarks for efficiency, productivity, and resource optimization in fleet management operations.

6.1.7 Optimizing Unique Rectangular Configurations

Among the diverse range of layouts optimized during the internship period, the rectangle layout stood out as a unique and challenging configuration. This rectangular-shaped layout featured pick and drop locations along its boundaries, presenting a distinct set of obstacles that required innovative approaches and meticulous optimization strategies.

One of the primary challenges posed by the rectangle layout was the inherent criss-crossing of robot paths. With pick and drop locations situated along the perimeter, robots were required to navigate through intersecting routes, increasing the likelihood of congestion and potential collisions. This intricate path intersection pattern demanded a comprehensive understanding of traffic flow dynamics and the development of effective strategies to mitigate potential bottlenecks.

A key objective of the rectangle layout optimization process was to minimize clutter formation, which could significantly impact throughput and overall system efficiency. Clutter formation occurs when robots congregate in specific areas, leading to congestion, interference, and potential deadlocks, ultimately hindering smooth operations.

To address this challenge, the optimization team employed advanced simulations and path planning algorithms to analyze robot movements and identify potential clutter hotspots. By strategically adjusting highway rules, implementing dynamic traffic routing, and optimizing resource allocation, the team aimed to distribute robot traffic evenly across the layout, minimizing the likelihood of clutter formation.

One of the innovative approaches employed during the rectangle layout optimization process was the utilization of newly developed turn cost techniques. These techniques involved the assignment of weights or costs to specific turns or maneuvers within the layout, influencing the path planning algorithms and encouraging more efficient and streamlined robot movements.

By carefully calibrating these turn costs and incorporating them into the optimization process, the team was able to guide robot towards more optimal routes, reducing unnecessary turns and minimizing the potential for congestion and clutter formation.

Despite the unique challenges posed by the rectangle layout, the optimization efforts yielded remarkable results. With only 60 robots at their disposal, the team successfully achieved 90% of the expected throughput from simulations, a remarkable feat considering the layout's complexity and potential for congestion.

This achievement not only showcased the team's ability to adapt to unique configurations but also highlighted the effectiveness of the optimization strategies employed. By meticulously minimizing clutter formation, leveraging innovative turn cost techniques, and optimizing resource allocation, the team was able to extract maximum performance from a limited number of robots, demonstrating the system's scalability and potential for cost-effective deployments.

The optimization of the rectangle layout served as a valuable learning experience, reinforcing the importance of continuous refinement and adaptability in the field of map optimization. As the Fleet Management System continues to encounter unique layouts and configurations, the lessons learned from the rectangle project will prove invaluable.

6.1.8 Competitor Layout Optimizations

In the highly competitive landscape of fleet management solutions, the optimization team faced a formidable challenge – to surpass the throughput achieved by Libao, a prominent competitor, on their renowned Tompkins layout. This endeavor was undertaken not only to demonstrate the superiority of the Fleet Management System but also to push the boundaries of map optimization and resource utilization.

The first step in tackling this challenge was to meticulously construct the Tompkins layout from scratch within the Fleet Management System. This process involved a thorough understanding of the layout's specifications, dimensions, and spatial constraints, ensuring an accurate representation of the physical environment. By starting from the ground up, the team had the opportunity to incorporate lessons learned from previous optimization projects and leverage innovative techniques and strategies from the outset, rather than being constrained by existing configurations.

Once the Tompkins layout was accurately replicated within the system, the team embarked on the crucial task of defining optimized highway rules. These rules would serve as the foundation for efficient AMR navigation, traffic flow, and resource allocation throughout the layout. Drawing upon their extensive experience in map optimization, the team carefully analyzed the layout's characteristics, potential bottlenecks, and traffic patterns. Through rigorous simulations and iterative refinement, they crafted a set of highway rules tailored to the Tompkins layout, ensuring optimal traffic flow and minimizing congestion.

To validate the effectiveness of the optimized highway rules and identify areas for further improvement, the team conducted intense testing and continuous refinement cycles. These cycles involved simulating a wide range of operational scenarios, stress-testing the system under various load conditions, and meticulously analyzing performance metrics. SBy leveraging advanced analytics and data-driven insights, the team was able to identify potential bottlenecks, inefficiencies, and opportunities for optimization. Each iteration of the testing and refinement process built upon the lessons learned from the previous cycle, gradually fine-tuning the system's performance and pushing the boundaries of throughput optimization.

Through their unwavering dedication and the application of cutting-edge optimization techniques, the team achieved a remarkable feat – surpassing the throughput achieved by Libao on the

Tompkins layout, while utilizing fewer resources. Specifically, the optimization efforts yielded the following impressive results:

- **550 mm Grid Size:** On a grid size of 550 mm, the optimized Tompkins layout achieved a 20% increase in throughput compared to Libao's performance.

- **650 mm Grid Size:** Even on the larger 650 mm grid size, the optimized layout demonstrated a 10% throughput increase over Libao's performance.

Remarkably, these superior throughput levels were achieved with 20 fewer robots than initially planned, highlighting the team's ability to optimize resource utilization and minimize operational costs without sacrificing performance. This accomplishment served as a testament to my ability to mentor the new two interns on developing and optimizing the layout. As well as to adapt to diverse layout configurations, leverage innovative optimization techniques, and continuously push the boundaries of what is achievable in the realm of fleet management.

As the industry continues to evolve and competitors strive to match the team's achievements, the lessons learned from this optimization project will serve as a foundation for future innovations. The team's expertise in building layouts from scratch, defining optimized highway rules, and conducting rigorous testing and refinement cycles will continue to drive the development of more advanced optimization strategies, ensuring the FMS's continued dominance in the market.

Through a relentless pursuit of excellence and a commitment to continuous innovation, the map optimization initiatives have not only demonstrated the system's capabilities but have also contributed to the advancement of the field, setting new benchmarks for throughput optimization and resource utilization in fleet management operations.

6.2 Continuous Pursuit of Excellence

While the map optimization initiatives yielded significant improvements in throughput, operational efficiency, and resource utilization, the pursuit of excellence is an ongoing endeavor. The techniques and strategies developed during this internship period have laid a solid foundation for future advancements, ensuring that the FMS remains at the forefront of innovation and continues to deliver exceptional value to its users.

Through a combination of data-driven insights, collaborations with domain experts, and the application of cutting-edge optimization algorithms, the map optimization process will continue to evolve, adapting to new challenges and embracing emerging technologies to further enhance the FMS's capabilities and solidify its position as a reliable and efficient solution for fleet management operations.

Chapter 8 – Conclusion

Throughout the course of my internship at Addverb Technologies Pvt. Ltd. as a Mobile Robotics Intern, I had the privilege of contributing to the development, enhancement, and optimization of the Fleet Management System. This comprehensive project encompassed a wide range of activities, from software development and algorithm optimization to map construction and on-site issue resolution. The experience not only allowed me to actively participate in the advancement of this remarkable system but also provided invaluable insights into the intricacies of fleet management operations and the challenges faced in real-world deployments.

The internship journey began with a deep dive into the FMS codebase, where I gained a thorough understanding of its modular architecture, client-server model, and various components responsible for task allocation, path planning, simulation execution, and robot communication. This foundational knowledge served as a springboard for my subsequent contributions, which ranged from bug fixes and performance optimizations to the development of new features and functionalities.

One of the notable achievements during this period was the implementation of a multi-edge incorporation algorithm, which addressed a significant limitation in the system's map generation and editing capabilities. By enabling the concurrent addition of multiple edges, this feature significantly expedited the map creation process, resulting in substantial time savings and increased productivity for map developers.

Furthermore, I played a pivotal role in enhancing various modules within the FMS, including the replayer, map exportation, multi-selection, traffic light switching, path visualization, and log extraction functionalities. These enhancements not only resolved critical issues but also introduced new capabilities, streamlined workflows, and improved the overall user experience for FMS operators.

Recognizing the importance of efficient data management, I developed a comprehensive database utility that seamlessly integrated with MongoDB, enabling the extraction and serialization of data collections as JSON files. This utility empowered developers and analysts with the ability to initiate collection extraction through a user-friendly RESTful API, facilitating data analysis, reporting, and decision-making processes within the FMS ecosystem.

Concurrent with software development efforts, I actively contributed to the optimization of numerous maps across diverse layouts and configurations. These optimization initiatives involved the meticulous analysis and refinement of various factors, including path planning algorithms, navigation strategies, resource allocation, and environmental constraints. By leveraging advanced analytics, simulations, and cutting-edge optimization techniques, remarkable improvements in throughput, operational efficiency, and resource utilization were achieved.

Throughout the map optimization process, I adopted a data-driven approach, collaborating closely with on-site personnel and domain experts to identify potential areas for enhancement. The optimization strategies employed were tailored to the unique characteristics and requirements of each map, ensuring adherence to operational constraints and regulatory guidelines.

While specific numerical details and performance metrics cannot be disclosed due to confidentiality considerations, it is important to highlight that the map optimization initiatives consistently yielded significant relative improvements across a diverse range of maps, spanning various industries and operational environments. These improvements not only enhanced the FMS's performance but also laid the foundation for future advancements, solidifying its position as a reliable and efficient solution for fleet management operations.

During the internship period, I had the opportunity to mentor two new interns, guiding them in understanding the intricacies of the FMS and imparting knowledge on highway optimization techniques. This mentorship experience not only facilitated knowledge transfer but also fostered a collaborative learning environment, where we collectively tackled complex challenges and shared insights.

One of the notable achievements in this regard was the successful optimization of the renowned Tompkins layout, where our team surpassed the throughput achieved by Libao, a prominent competitor, while utilizing fewer resources. This accomplishment served as a testament to our ability to adapt to diverse layout configurations, leverage innovative optimization techniques, and continuously push the boundaries of what is achievable in the realm of fleet management.

8.1 Main Findings:

- The implementation of the multi-edge incorporation algorithm significantly streamlined the map generation and editing process, resulting in substantial time savings and increased productivity for map developers.
- Enhancements to various FMS modules, such as the replayer, map exportation, multi-selection, traffic light switching, path visualization, and log extraction, resolved critical issues and introduced new capabilities, improving overall system performance and user experience.
- The development of a comprehensive database utility facilitated efficient data extraction, serialization, and analysis, empowering developers and analysts with valuable insights for decision-making processes.
- Map optimization initiatives consistently yielded significant relative improvements in throughput, operational efficiency, and resource utilization across a diverse range of layouts and configurations.

- The successful optimization of the renowned Tompkins layout surpassed the throughput achieved by a prominent competitor while utilizing fewer resources, demonstrating the team's ability to adapt, innovate, and push the boundaries of fleet management.
- The mentorship of two new interns fostered a collaborative learning environment, facilitated knowledge transfer, and contributed to the collective understanding of highway optimization techniques.

8.2 Recommendations for Further Work

- **Advanced Path Planning Algorithms:** Explore and implement advanced path planning algorithms, such as dynamic replanning and multi-agent path planning, to further optimize AMR routing and handle dynamic obstacles or changing environmental conditions.

- **Machine Learning for Traffic Management:** Leverage machine learning techniques to analyze historical traffic patterns and clutter data, enabling the system to proactively adjust traffic light switching and path planning strategies for improved efficiency and throughput.

- **Integration with Building Information Modeling (BIM):** Develop seamless integration with BIM systems to facilitate automated map generation and updates based on architectural models, reducing the manual effort required for map creation and maintenance.

- **Augmented Reality for Map Visualization:** Investigate the potential of augmented reality (AR) technologies for enhancing map visualization and interaction, enabling intuitive map editing, path planning, and simulation analysis within a mixed-reality environment.

- **Distributed Fleet Management:** Explore the implementation of distributed fleet management architectures to enable scalability and improve responsiveness in large-scale deployments with multiple AMR fleets operating across different facilities or geographic locations.

8.3 Mentoring Experience

In addition to my technical contributions, I had the opportunity to mentor two new interns during my internship tenure. I guided them through the intricacies of the FMS codebase, introduced them to map optimization techniques, and provided hands-on training in developing new features and enhancing existing functionality.

Mentoring these interns was a rewarding experience that allowed me to share my knowledge and expertise while also honing my leadership and communication skills. I witnessed their growth and development as they successfully contributed to various aspects of the FMS, solidifying my belief in the importance of knowledge transfer and nurturing future talents.

As the industry continues to evolve and embrace emerging technologies, it is crucial for the FMS to remain at the forefront of innovation. By continuously refining its capabilities, adapting to new operational requirements, and integrating advanced techniques, the FMS will not only solidify its position as a market leader but also pave the way for a more efficient, sustainable, and seamless future in fleet management operations.

The journey undertaken during this internship has laid a strong foundation for continued growth and excellence. With the collective efforts of dedicated professionals, unwavering commitment to innovation, and a relentless pursuit of optimization, the FMS is well-positioned to redefine the boundaries of what is achievable in the realm of fleet management, driving efficiency, productivity, and operational excellence to unprecedented heights. As I embark on the next chapter of my professional journey, I carry with me the invaluable lessons and experiences gained during this internship. I am confident that the skills and knowledge acquired will serve as a strong foundation for tackling future challenges and driving innovation in the rapidly evolving field of robotics and automation.

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