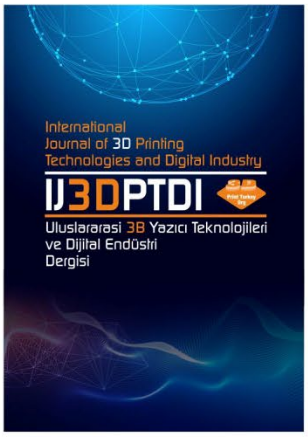

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Yazarlar (Authors): Neslihan DEMIR, Pinar DEMIRCIOGLU, Ismail BOGREKCI

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ADVANCING INDUSTRY 4.0 WITH ROS: A CASE STUDY ON AUTONOMOUS MOBILE ROBOT TECHNOLOGICAL ADVANCEMENTS

Neslihan DEMIR [a,b], Pinar DEMIRCIOGLU [a,c], Ismail BOGREKCI [a*]

[a]Aydın Adnan Menderes University, Faculty of Engineering, Mechanical Engineering Department,TURKEY
[b] PhD Student of YOK 100-2000 on Robotic Technologies, TURKEY
[c] Institute of Materials Science, TUM School of Engineering and Design, Technical University of Munich, Germany

[*] *Corresponding Author: ibogrekci@adu.edu.tr*

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ABSTRACT

In the world of Industry 4.0, Autonomous Mobile Robots (AMRs) are now vital parts of modern industrial automation. This study examines how the Robot Operating System (ROS) plays a crucial role in advancing technology for AMRs. By looking at real-life examples, it shows how ROS helps in creating and using AMRs, changing how industrial processes work. The study demonstrates how ROS is being integrated into AMR design and operation, leading to improved autonomy, flexibility, and productivity in industrial settings. This study discusses how ROS-powered AMRs have transformed various tasks like material handling, warehouse logistics, and autonomous navigation, leading to increased productivity and cost-efficiency. It also explores the challenges and opportunities brought about by ROS in the Industry 4.0 era, including sensor fusion, machine learning, and human-robot teamwork. Furthermore, ROS not only influences the design and operation of AMR, but also enables smooth integration with advanced technologies such as sensor fusion and machine learning. This opens up opportunities for improved flexibility and teamwork between humans and robots in the ever-evolving environment of Industry 4.0. The importance of ROS in connecting traditional manufacturing practices with the changing demands of the fourth industrial revolution is emphasized.

Keywords: Autonomous mobile robots, Obstacle avoidance, Artificial intelligence, Robot Operating System, Industry 4.0.

1. INTRODUCTION

In the current era of technological advancement, establishing optimal manufacturing systems alone is insufficient to ensure the sustainability of companies. Therefore, the integration of Industry 4.0 (I4.0) applications into manufacturing systems is imperative. Industry 4.0 is serving a bridge for coordinating initiative technological systems such as cyber physical systems, internet of things, artificial intelligence, digital twin, blockchain etc. Cyber-physical systems (CPS), one of these systems, are characterized as systems where computational elements interact closely with the physical environment and its ongoing operations. These systems both provide and utilize data-accessing and data-processing services concurrently. CPS include industrial robots produced with today's technology in production [1]. Numerous international companies have adopted these technologies by bringing together under the Industry 4.0 applications. However, it is evident that these new technological applications are far from cost-effective for small and medium-sized local companies. As a result, the survival of small and medium-sized companiess appears increasingly challenging in the coming years.

Recent years have witnessed the integration of new technological applications into businesses, both large and small. Particularly, CPS into manufacturing process have led to more efficient outcomes and the achievement of cost related objective in specific applications. Before CPS technologies, robotic applications were one level higher than automation technologies, nevetheless still relied on human involvement. Industrial robotic applications along with CPS have reduced dependence on human factor and enabled the creation of optimized processes in manufacturing systems. In this context, Industry 4.0 has been influential to develop the integration of physical and virtual environment with industrial robotic applications. In recent years, Robot Operating System (ROS) has emerged as a framework for combining these two divergent environments in robotic applications.

Given that most businesses in manufacturing industry of Türkiye are of medium and small scale, the cost-effectiveness of such applications is a critical necessity in the years ahead. Meeting this need has become increasingly important, particularly with the growing emphasis on academic research and diverse perspectives on various aspects of manufacturing systems.

It is often observed that in Türkiye, the adaptation of robotic applications along with CPS to the manufacturing sector largely relies on foreign academic and commercial initiatives. Unfortunately, the existing applications in our country are dependent on solutions sourced from abroad. The motivation behind this study is to stimulate the need for new approaches, applications, and research to eliminate this dependency and enable our country to become a technology creator and producer, thus minimizing external reliance.

2. LITERATURE REVIEW

This study aims to unveil an application that minimizes human intervention as much as possible, utilizing the concepts of robotics along with CPS and ROS to facilitate the transfer of required materials such as raw materials, semi-finished products, parts, tools, equipment, and more between operation centers and warehouses within a manufacturing facility. In pursuit of this objective, existing academic and commercial research on mobile autonomous robot applications has been reviewed.

In a competitive market, the use of innovative technologies is crucial for a company's survival. One common form of these technologies is robotics, as highlighted in the World Robotics 2020 Industrial Robots report by the International Federation of Robotics (IFR). The report states that by 2020, there were 2.7 million industrial robots globally, marking a 12% rise in sales from the year before (IFR, 2020). These results highlight the importance for companies to utilize robotics and other innovative technologies in order to stay competitive and successful in a constantly changing environment.

Research indicates a high demand for robotics applications in the manufacturing industry, but it is essential to acknowledge that the innovation levels of these applications vary significantly. Rapid technological advancements necessitate the categorization of robotics applications. Lottermoser et al. (2017) classified industrial robots into three generations based on mobile industrial robots as a starting point. When considering this classification, it is crucial to recognize that not all encountered industrial robot applications are at the same technological level. According to Lottermoser et al. (2017), the three generations of industrial robots are as follows [2]:

- First-generation industrial robots can automatically perform a series of movements at specified intervals.
- Second-generation industrial robots use sensors for their environment and movements. They also have a control mechanism that allows for partial or full dependence on human factors during applications, with flexibility beyond rigidity.
- Third-generation industrial robots are capable of operating entirely autonomously, making decisions and functioning independently when facing challenges during applications.

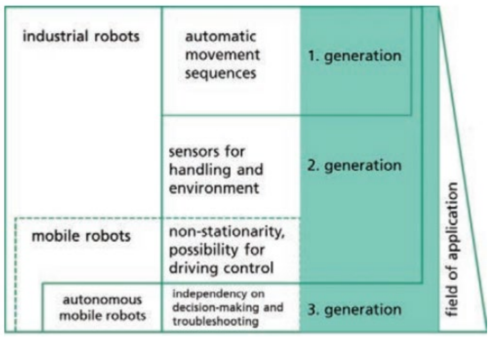


Figure 1. The developmental phases of industrial robots.

It's important to note that this generational classification provides a framework for understanding the progression of industrial robot capabilities. However, in practice, there may be variations and overlaps between generations, and the classification may not always perfectly align with specific robot models or applications. As technology continues to evolve, the lines between these generations may blur further, leading to even more capable industrial robots in the future.

In the classification of Lottermoser et al., third generation industrial robots are referred to as Industrial Mobile Robots (IMRs). According to ANSI R15.08, there are three types of IMRs, listed in Table 1.

Table 1. Types of IMRs according to ANSI

Types	Features
Type A	AGV or AMR
Type B	AGV or AMR + active or passive attachments such as conveyor, roller table etc.
Type C	AGV or AMR + Robotic Manipulator

Robotic Industries Association (RIA) takes into account Automated Guided Vechile (AGV) and Autonomous Mobile Robot (AMR) in all types of IMRs. But it also defined that AGV is capable of following exact guide paths, whether physical or virtual, such as lines, bands or magnets and AMR is capable of generating dynamically paths based on the current environment and determining the most efficient trajectory between the current location and target destination. Unlike AGVs, AMRs do not rely on fixed paths and can adapt to changes in their surroundings [3]. The difference between AGVs and AMRs shows how robotic systems are improving to work independently in changing industrial settings, making manufacturing processes more efficient and adaptable.

AGVs are common, but they follow predefined paths on the ground and do not require extensive support. In contrast, autonomous industrial mobile robots, powered by AI algorithms, handle tasks like positioning, mapping, path planning, and navigation. This autonomy minimizes human intervention and enhances manufacturing processes' flexibility and efficiency. Therefore, based on these characteristics, one could assert that the autonomous mobile robot discussed in the research represents the third generation of industrial mobile robots as AMR. Essentially, it is an independent robot operating with ROS, equipped with decision-making and problem-solving capabilities that do not rely on human intervention.

Until the last decade, AGVs were predominantly favored for industrial applications over IMRs. Zhang et al. (2018) developed a cyber-physical system-based model for dynamic shop floor material handling with AGVs and base stations [4]. However, AMRs have acquired significant attention in academic studies over the past decade. Santoro (2021) developed a sensory system capable of autonomous movement in industrial environments, facilitating interaction between human operators and autonomous mobile robots (AMRs). The AMR featured four mecanum-wheeled mobility, enabling omnidirectional movement, and incorporated algorithms aimed at reducing computational costs while fusing and filtering sensor data [5].

The literature contains various approaches, perspectives, and studies related to mobile robots. Researchers collaborate across disciplines to undertake the complicated challenges of autonomous robot development. Particularly, due to the interdisciplinary nature of the field of robotics, there are relatively few comprehensive studies on the creation of mobile robots as a whole. In addition to the literature, there is also a significant global market for commercial applications. The leading companies in the global autonomous mobile robot market are listed in Table 2.

These visionary companies stand at the forerunner of shaping the future of automation and robotics. With a firm commitment to this technology, research, and development, they have guided in a diverse array of autonomous mobile robot solutions across numerous industries, spanning manufacturing, logistics, healthcare, and beyond. These enterprises not only pursue excellence in product design and functionality but also employ significant influence in propelling the field forward through their contributions to academic research (Table 3) and technological innovation.

Table 2. The leading companies operating in the autonomous mobile robot market.

Company	Website	Country
KUKA	www.kuka.com	Germany
ONWARD ROBOTICS	https://onwardrobotics.com/	USA
Locus	www.locusrobotics.com	USA
6river Systems	www.6river.com	USA
ZEBRA Robotics	www.zebra.com/us/en.html	USA
inVia Robotics	www.inviarobotics.com	USA
Clearpath Robotics	www.clearpathrobotics.com	Canada
Magazino	www.magazino.eu	Germany
Grey Orange	www.greyorange.com	USA
DAHIEN Robotics	www.daihen-robot.com/en/	Japan
Geek+ Technologies	www.geekplus.com/en/	China
Syrius Technology	https://siriustech.io/	China
Mobile Industrial Robotics	www.mobile-industrial-robots.com	Denmark
Amazon Robotics	www.amazonrobotics.com/#/	USA
Astro Technologies	www.astrotechnology.com/	USA
Conveyco Technologies	www.conveyco.com/	USA
Vecna Robotics	www.vecnarobotics.com/	USA
Atheon	https://aethon.com/	USA
Bluebotics	www.bluebotics.com/products/	Switzerland
Hi-Tech Robotic Systemz	www.hitechroboticsystemz.com/	India
Symbotic (prev CasePick Systems)	www.symbotic.com/solutions/	USA
Rovenso	www.rovenso.com/	Switzerland
Pal Robotics	pal-robotics.com/	Spain
Accerion	https://accerion.tech/	Netherlands
Robotnik	www.robotnik.eu	Spain
IncubedIT GmbH	www.incubedit.com/	Austria
Botsync	www.botsync.sg/	Singapore
CtrlWorks Pte Ltd	www.ctrlworks.com/	Singapore
Autonomous Logistics Technologies	www.alogtech.com/	USA
Robocv	robocv.com/	Russia
Oxbotica	www.oxbotica.com/	United Kingdom
Milvus Robotics	milvusrobotics.com/	Türkiye
Lars Robot	www.larsrobot.com/	Türkiye
Etnamatica	www.etnamatica.com/index.php	Italy
Follow Inspiration S.A.	http://followinspiration.pt/	Portugal

As the demand for autonomous mobile robots continues its relentless climb across global markets, these industry leaders remain indispensable drivers of progress, reshaping our perception and utilization of robotics in the modern world.

Industrial mobile robots hold an undeniable appeal for a numerous of researchers, engineers, and global industry giants, owing to their adaptable and impactful nature. Simultaneously, they offer a fertile ground for interdisciplinary exploration, spanning mechanical, electronic, computer, and software engineering domains.

The versatility and potential of industrial mobile robots make them a significant focus of research and development efforts. These robots attract attention from various disciplines, from mechanical and electronical engineering to computer science and software development. The interdisciplinary nature of industrial mobile robots fosters innovation and collaboration on a global scale. As these technologies progress, they have the potential to transform how automation and robotics are approached in different industries, leading to increased efficiency and productivity levels.

Table 3. Academic Studies on Autonomous Mobile Robots.

Author(s)	Year	Study Title and Description
Marroquin, A., Garcia, G., Fabregas, E., Aranda-Escolastico, A., Farias, G. [6]	2023	**Title:** Mobile Robot Navigation Based on Embedded Computer Vision **Description:** The previous level of technology allowed for the creation of solutions using tools such as mobile robots and programmable electronic systems. A new design was introduced that combined the Khepera IV mobile robot with an NVIDIA Jetson Xavier NX board. This configuration ran a navigation control algorithm that relied on computer vision and included a model for detecting objects. The Khepera IV then had additional features like guided driving, which included tracking trajectories for safe navigation and identifying traffic signs to make informed decisions. A robotic platform was built to test the system in real-time and compare it to a digital model of the Khepera IV in the CoppeliaSim simulator. The findings from the navigation control study showed a noticeable improvement compared to previous efforts, particularly in terms of how fast a vehicle could navigate and how accurately it could detect traffic signs. The analysis of navigation control showed that the system was successful around 93% of the time. The design also allowed for the experimentation with new control strategies or algorithms based on Python, which could lead to further enhancements in the future.
Hercik, R., Byrtus, R., Jaros, R., Koziorek, J. [7]	2022	**Title:** Implementation of Autonomous Mobile Robot in SmartFactory **Description:** This research explored the integration of Autonomous Mobile Robots (AMRs) within the production line context at the Technical University of Ostrava. AMRs were strategically deployed to collaborate with the production line, facilitating the collection and delivery of manufactured items as required. The study elaborated on the procedural steps involved in initializing the AMR, including the creation of a virtual map, establishment of a robust communication network, and programming of the robot's functionalities. Emphasizing precision and attention to detail, the primary objective of the experiment was to evaluate the mobility and communication capabilities of the mobile robot. The research underscored the paramount importance of accuracy in its operations, with a focus on achieving precise movements within ±3 mm tolerance. The culmination of this study was the development of a self-driving robot capable of reliably executing tasks with exceptional accuracy, thereby enhancing production efficiency in smart factory environments.
Jang, K., Kim, S., Park, J. [8]	2021	**Title:** Reactive Self-Collision Avoidance for a Differentially Driven Mobile Manipulator **Description:** The research focused on developing a self-collision avoidance algorithm designed for a differentially driven mobile manipulator. The main goal was to address the issue of self-collision arising when a manipulator interacts with a mobile robot. The aim was to create an algorithm enabling the manipulator to move smoothly without risking collisions with itself, while maintaining its intended motion profile. The primary objective of the study was to enable the robot to navigate autonomously in a safe and efficient manner, adjusting its actions to avoid obstacles. By creating and testing a self-collision avoidance algorithm, the research made a valuable contribution to robotics advancement, particularly in the domain of mobile manipulators with differential drive systems.
Luo, R. C., Lee, S. L., Wen, Y. C., Hsu, C. H. [9]	2020	**Title:** Modular ROS Based Autonomous Mobile Industrial Robot System for Automated Intelligent Manufacturing Applications **Description:** The purpose of this study was to create a modular ROS system that focused on an IMR system, specifically designed for use in intelligent manufacturing applications. This involved using a finite state machine to seamlessly integrate and control different modular features within the mobile manipulator, improving its mobility and manipulation abilities. For mobility, the robot utilized SLAM technology to map out its surroundings and pinpoint its location. Furthermore, navigation and collision avoidance strategies were developed to enable it to move freely throughout indoor environments. To enable manipulation, we utilized an RGB-D camera mounted on the end

		effector for an eye-in-hand system. This system leveraged learning-based object detection and shape-based grasping pose estimation to enhance flexible manipulation capabilities. Our robotics lab at National Taiwan University had developed an IMR with a meticulously designed mechanism and a fully modular ROS environment. The experiments included setting up an intelligent industrial scenario where materials were collected and products were transported from one location to another. Through our ROS-based architecture managing the data/command flow between functions, we successfully demonstrated the system and validated its stability.
Ramasubramanian, A.K., Papakostas, N. [10]	2020	**Title:** Operator - mobile robot collaboration for synchronized part movement **Description:** The study introduced a new method that allowed an operator and a mobile robot to collaborate in loading, unloading, and transporting parts. Emphasizing the integration of tasks performed by the operator and the mobile robot, the study focused on implementing a practical control strategy. The success of this approach relied on seamless coordination between the human operator and the robot system. To achieve this, researchers developed a control strategy capable of aligning tasks initiated by the operator with the actions of the mobile robot. The study operated on the premise that the robotic arm and gripper possessed the necessary capabilities to handle the specified load. Consequently, the proposed method proved suitable for scenarios involving heavy or elongated parts, where combining human and robot capabilities could enhance efficiency and productivity. By introducing a flexible control strategy for operator-robot teamwork, the study laid the groundwork for enhanced collaboration between human workers and automated mobile devices across various industrial settings. The findings indicated that this approach could effectively be applied in situations where leveraging the distinct advantages of both human and robotic skills could significantly improve the manipulation of heavier and larger components.
Pääkkönen, R. [11]	2020	**Title:** Cloud-based Remote Control of Autonomous Mobile Robots in Industrial Environments **Description:** The master's thesis discussed the utilization of cloud technology to control mobile robots in industrial settings. The research investigated how cloud computing could enable rapid responses and simulate an industrial environment. In a laboratory setting, a robot was constructed on a cloud user's virtual machine, and tests were conducted. The findings demonstrated that utilizing cloud-based digital twinning proved to be an effective method for virtualizing autonomous robots in industrial environments. The described technology facilitated immediate response times and the development of intricate models for industrial scenarios. The study's results underscored the advantages of cloud-based remote control and digital twinning in revolutionizing the simulation, management, and optimization of industrial settings for enhanced efficiency and productivity.
Aiello, A. [12]	2020	**Title:** Robotic arm pick-and-place tasks: Implementation and comparison of approaches with and without machine learning (deep reinforcement learning) techniques **Description:** The research combined two different methods to complete tasks. The traditional approach used advanced technology but did not include modern AI techniques. The alternative approach tackled the same issue with machine learning. In the traditional method, tools like MoveIt, Gazebo, and RViz in the ROS framework were used. The second method utilized deep reinforcement learning to solve the problem with machine learning techniques. The research aimed to offer valuable insights into the benefits and possible improvements of incorporating machine learning methods, particularly deep reinforcement learning (RL), into practical robotic applications.
Bergani, H.A.F. [13]	2019	**Title:** Design & construction of mobile robot with a manipulator arm for multipurpose application **Description:** The study presented the design and development of a versatile, wheeled mobile robot suitable for multipurpose applications. The hardware system encompassed a carefully selected robot platform, components,

		microcontroller, electronics, sensors, and electrical control circuits to support comprehensive sensing functions. Furthermore, a methodology was planned for positioning a limited number of sensors on the robot chassis, optimizing its suitability for autonomous navigation. The research also included the development of a program that enabled the robot to perform specific tasks such as line following and obstacle avoidance, enhancing its capabilities for diverse applications.
Oltean, S.E. [14]	2019	**Title:** Mobile Robot Platform with Arduino Uno and Raspberry Pi for Autonomous Navigation **Description:** The research introduced an affordable mobile robot setup with a stable four-wheel design, utilizing the connections of Raspberry Pi and Arduino Uno. This robot was capable of mapping, navigating, avoiding obstacles, and following lines. Moreover, it included a robotic arm with one degree of freedom for lifting and moving loads. By combining Raspberry Pi and Arduino Uno, the robot could efficiently carry out autonomous navigation tasks, making it suitable for diverse applications in different settings. This platform was a user-friendly and cost-effective option that allowed researchers and developers to delve into mobile robot technologies. It served as a reliable base for creating a variety of applications in this rapidly growing field.
Sichkar, D.P., Bezumnov, N., Voronov, V.I., Voronova, L.I., Dankovtsev, V.I. [15]	2019	**Title:** Moving Elements of Mobile Robots Stabilization Modelling **Description:** The study tackled the issue of keeping mobile robots stable as they carried heavy loads. To address this challenge effectively, a simulation process was created. This simulation focused on determining the exact balance points for different parts of the robot, using an open artificial intelligence system. A key factor in the success of the study was the incorporation of machine learning technology. Machine learning algorithms were used to analyze and improve the sensor architecture for load transportation. The TensorFlow library, along with the tflearn extension, was utilized for detection and data processing tasks in the machine learning-based approach. The study also included real-world applicability, moving beyond theoretical simulations. Network training was conducted in an open artificial intelligence environment using the Gym library. This practical aspect ensured that the research findings could be implemented in actual mobile robot systems.
Bostelman, R. [16]	2018	**Title:** Performance Measurement of Mobile Manipulator **Description:** The study focused on creating models and defining research areas to measure the performance of a mobile manipulator used in a specific manufacturing application. The research explored applications that were unable to measure the performance of mobile manipulators at the time. It delved into uncharted territories to discover new and innovative ways to assess mobile manipulator performance. Through thorough investigation and analysis, the study aimed to enhance understanding and improve the evaluation of these adaptable robotics systems.
Lee, H.Y., Murray, C.C. [17]	2018	**Title:** Robotics in order picking: evaluating warehouse layouts for pick, place, and transport vehicle routing system **Description:** The research examined how two different types of mobile robots were used to fulfill orders at a loading depot. One robot, called a picker, gathered items from shelves, while the other, a transporter, carried the items to the packaging station based on a list of what needed to be picked. To expedite the delivery process to the packaging station, a strategy was created that considered the challenges of routing vehicles for loading, unloading, and transporting items. A sophisticated mathematical model was created to tackle three main issues. Next, the study looked into how the mix of robots in the fleet could be changed to improve performance. Then, it studied how the layout of the warehouse affected the system's performance when using mobile robots. The research showed that having more paths crossing the aisles led to lower system performance, centrally located packaging stations improved system performance, and the distance between packaging stations and loading positions played a key role in identifying fleet changes enhancing system efficiency.

Urrea, C., Yau, A. [18]	2016	**Title:** Design, Construction and Programming of a Mobile Robot Controlled by Artificial Vision **Description:** The study discussed creating a mobile robot that used computer vision to recognize objects of various colors. The robot received advanced artificial intelligence through a program on a laptop. Emphasis was placed on the robot's mechanical durability for practical use. The robot was upgraded with a fake vision camera and a distance sensor so it could move around by itself and gather important information about its surroundings. The main aim of the study was to increase the robot's vision range to 180 degrees. With this wider scope, the robot could now be more precise in its movements and tasks. This new ability made it more adaptable and useful in various fields like industrial automation and advanced robotics research.
Eliot, E. [19]	2013	**Title:** Design, Analysis and Fabrication of An Articulated Mobile Manipulator **Description:** The research aimed to investigate a versatile mobile robot manipulator designed for complex loading and placement tasks in dynamic environments. The manipulator system included a 5-axis articulated arm for loading and placement applications, adaptable to various task variations. Key drive and power components were strategically placed at the lower section for optimal load distribution and efficient handling. With a state-of-the-art suspension system, the mobile platform was designed for maximum stability and weight-bearing capabilities, efficiently distributing weight across the wheels for optimal performance.

3. ANALYSIS OF KEY PARAMETERS IN AUTONOMOUS MOBILE ROBOTICS

When examining critical factors related to self-propelled moving robots, the point is to measure and internalize a number of things pivotal for their efficient working and efficacy. While navigating a robot or making it make decisions as well as controlling it among many other chores, one must take into consideration the above aspects for the robot to work properly. They are presented in tabular form (Table 4).

Table 4. Analysis of Key Parameters in Autonomous Mobile Robotics [20].

Parameter	Description	Importance Level
Sensors	Types, Fusion	High
Localization	Methods, Accuracy	High
Mapping	Algorithms, Resolution	High
Path Planning	Algorithm, Efficiency	High
Control	Architecture, Feedback	High
ROS	Software framework	High
Obstacle Avoidance	Obstacle Detection, Safety	High
Environment	Indoor/Outdoor, Terrain	High
Payload, Capacity	Weight, Handling	Medium
Diagnostics and Telemetry	Error Reporting, Monitoring	Medium
Power Management	Battery Life, Charging	Medium
Communication	Connectivity, Protocols	Medium
Machine Vision	Object Recognition	High
Decision-Making	AI, Behavioral	High
Human-Robot Interaction (HRI)	Interface, Safety	Medium
Maintenance and Reliability	Requirements, Reliability	Medium
Cost and Scalability	Analysis, Scalability	Medium
Regulatory and Ethical Considerations	Compliance, Ethics	Medium

3. CASE STUDY: APPLICATIONS WITH ROS

ROS serves as middleware that abstracts the hardware layer, manages devices at the hardware level, codes commonly used functions, facilitates communication between operations, and executes packages for robotic systems. It functions as a framework that handles both physical components and communication networks for data management in robotic applications. Given these attributes, leveraging applications for CPSs with the ROS middleware proves to be beneficial.

In the ROS environment, various practical applications tailored to real-world scenarios of mobile transportation robots are achievable through the utilization of Gazebo and Rviz interfaces. ROS packages specifically designed for each pertinent task can be effectively employed. Gazebo serves as the platform for three-dimensional simulation, while Rviz facilitates three-dimensional visualization.

This research investigates the development of the ProdigiMover [21], an autonomous mobile transportation robot, within the domain of scientific research projects conducted at Adnan Menderes University. Specifically, the study explores its design and implementation within ROS framework, alongside its autonomous navigation capabilities evaluated within the simulated Gazebo environment, employing a range of methodological approaches in Figure 2. We aim to confirm the efficiency of our methods and provide valuable insights to the autonomous robotics field through thorough testing and analysis in the simulated Gazebo environment.

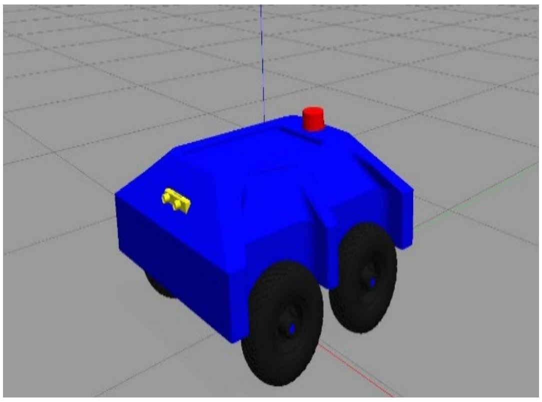


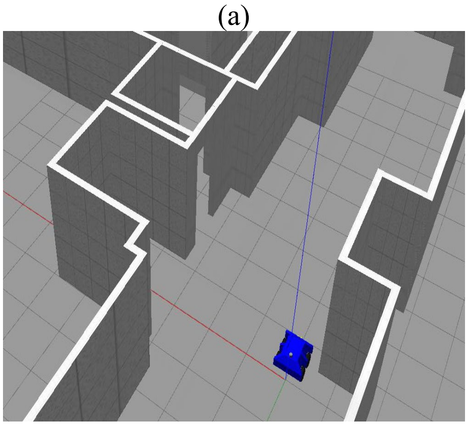
Figure 2. The ProdigiMover: Navigating the Empty World of Gazebo.

The key point is to compose a robotic system (physical system) together with communication network (ROS). There are three types of communication in ROS, messages (publisher and subscriber), services (server-client) and actions. In this application, publisher and subscriber was selected for communication. The publisher node sent out messages without specifying or having knowledge of the subscriber. The subscriber, in turn, selected the relevant message from the published messages. The ROS master initialized and facilitated communication between nodes, managing and executing information about the nodes.

The mobile transportation robot's execution of its intended tasks primarily unfolds within the Gazebo environment. This is attributed to the comprehensive description of its links and joints encapsulated within the description package, allowing for the instantiation of a fully embodied mobile robot within the simulation realm.

Within this ROS-enabled simulation package, worlds have been meticulously crafted, each with its unique characteristics and nomenclature. Worlds are illustrated in Figure 3 for simulating a workhouse and warehouse. Simulation package enables to execute algorithms of mapping, localization and path planning, which enable autonomous mobility and obstacle avoidance in unknown environment. This simulation environment plays a key role in validating the effectiveness and robustness of the implemented algorithms, ensuring the ProdigiMover's readiness for real-world deployment in various practical scenarios.

(a)



(b)

Figure 3. The ProdigiMover's Endeavors in Gazebo's Workhouse (a) and Warehouse (b) Environments.

Simultenous Mapping and Localization (SLAM) algorithms constructed firstly laser-based gmapping for mapping of creating existing world. Thus created map could be utilized for localization and path planning algorithms, presented in Figure 4. The 'Workhouse' simulation environment constitutes a purposeful construct characterized by a linear track featuring distinct start and end points. This configuration has been thoughtfully designed to facilitate a spectrum of experimental tasks centered around path planning and SLAM algorithms. On a created map, global and local maps were included and so global and local plans could be generated by using path planning algorithms. This integrated approach ensures the coordination between mapping, localization, and path planning processes, enhancing the ProdigiMover's autonomy and adaptability in navigating complex environments.

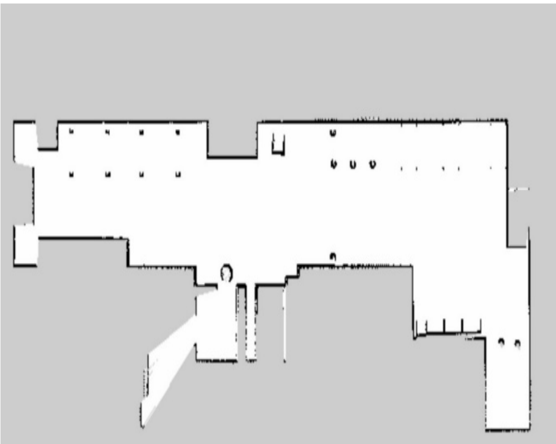


Figure 4. Created map of workhouse world by SLAM gmapping.

Localization was fulfilled with Adaptive Monte Carlo Localization (AMCL) algorithm. This algorithm allowed to estimate mobile robot position and orientation by utilizing odometry data. In this technique, particles represented potential position and direction of mobile robot. Each translocation induced distribution and probabilistically weighting of these particles.

Path planning process also performed simultaneously with AMCL. In ROS environment, move base package was utilized to carry out path planning algorithms. Global and local plans were created by path planning algorithms. It was illustrated in Figure 5.

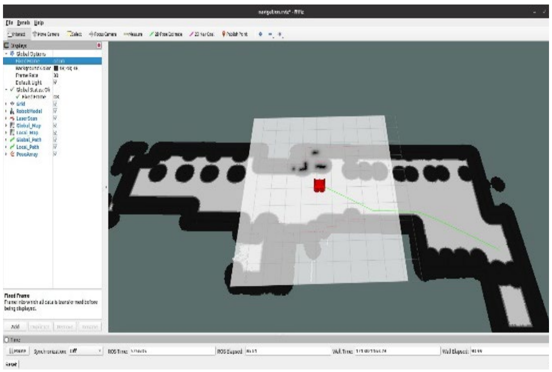


Figure 5. Autonomous movement through path planning algorithms in Rviz.

4. ADVANCING INDUSTRY 4.0: KEY CONSIDERATIONS IN ENHANCED CONNECTIVITY, AI INTEGRATION, CUSTOMIZATION

The autonomous navigation and control of mobile robots represent a foremost and complicated challenge within the field of robotics. For any autonomous vehicle, the essential prerequisites revolve around proficient obstacle detection and precise line-following capabilities. The foundation of successful autonomous navigation systems is highlighted by these fundamental features, and they are thought indispensable for ensuring the safe and efficient movement of robotic objects in various environments. In this academic discourse, the details of these core requirements are explored, with their significance, associated challenges, and the technological advancements that drive progress in this crucial area of research and development within robotics being clarified.

In the context of Industry 4.0, significant advancements in autonomous mobile robots have been witnessed, exemplified by their increasing integration into various sectors. Here are more examples of these advancements, presented in passive sentences:

- Enhanced Connectivity and Communication: Autonomous mobile robots are being equipped with advanced sensors and communication modules, allowing them to be seamlessly integrated into industrial networks and controlled remotely. Data exchange and real-time coordination are enabled, facilitating efficient decision-making in complex manufacturing environments.

- AI and Machine Learning Integration: Autonomous robots are being equipped with AI and machine learning capabilities, enabling them to autonomously learn and adapt to their surroundings. This includes the ability to recognize and respond to changes in the production line, optimizing tasks such as quality control, defect detection, and predictive maintenance.

- Customization and Flexibility: The trend of customization and flexibility in manufacturing is supported by autonomous robots that are easily reprogrammable and adaptable to varying production requirements. They can be quickly redeployed for different tasks, allowing for responsive manufacturing processes.

- Collaborative Robotics: Collaborative robots, designed to work alongside human operators, are increasingly being utilized in scenarios where safety is vital. They are equipped with features such as sensors and collision avoidance systems, ensuring safe and efficient collaboration between robots and human workers.

- Autonomous Material Handling: In logistics and warehousing, the integration of autonomous mobile robots for material handling has become prevalent. These robots are guided by real-time data to select optimal routes, transport goods, and autonomously adapt to changing warehouse layouts, streamlining the entire supply chain.

- Aerial Robots and Drones: The application of aerial robots and drones is expanding across industries. Equipped with advanced sensors, cameras, and autonomous navigation capabilities, they are used for tasks such as aerial inspections, monitoring, and data collection in agriculture, construction, and environmental monitoring.

- Energy Efficiency and Sustainability: Autonomous robots are being designed with a focus on energy efficiency and sustainability. Energy-saving features, such as regenerative braking and intelligent power management systems, are incorporated to minimize their environmental footprint while optimizing operational costs.

- Cybersecurity Measures: Ensuring the cybersecurity of autonomous mobile robots is paramount. Robust security protocols and regular software updates are implemented to safeguard these robots from potential cyber threats, preserving data integrity and operational safety.

- Predictive Maintenance Strategies: Autonomous robots are equipped with diagnostic sensors that continuously monitor their performance. By analyzing this data, predictive maintenance schedules can be generated, allowing proactive servicing to reduce unplanned downtime and enhance system reliability.

These examples illustrate the pervasive impact of autonomous mobile robots in Industry 4.0, with passive sentences highlighting their integration, adaptability, and safety measures, all contributing to the transformation of industrial processes and logistics.

5. CONCLUSION

In conclusion, this case study has offered important lessons regarding the using of ROS in propelling Industry 4.0 forward, focusing on the fundamental technological advancements associated with self-governing mobile robots. It shows how important ROS is in driving technological growth in this area through careful consideration of practical applications and demonstrations in driving forward progress and shaping the future of robotics.

The design and operation of AMRs have been demonstrated through integration with ROS, showing how enhanced autonomy, adaptability, as well efficiency can be realized in industry settings. The areas are sensors, mapping, path planning, control and human-robot interaction all of which serve to show how robots keep changing by using ROS and as a result are more competent and adaptable.

Moreover, ROS has been investigated for its role in connecting old-school manufacturing operations with the constantly changing requirements of Industry 4.0. The great attention is paid to the integration of sensor data, machine learning and communication systems through ROS for sound decision making processes as far as high precision machine vision systems are concerned.

In addition, we have underscored the crucial role played by ROS in guaranteeing the safety, dependability and expansibility of self-driving mobile robots so that they can be successfully used in industry. Furthermore ethical issues related to them which are very essential need to be considered. Promoting a future where robotics raises productivity while prioritizing humanity and societal values.

This case study essentially confirmed that ROS is more than just a framework – it is the one thing that changes everything in achieving Industry 4.0. In recent times, autonomous mobile robots have increasingly become part and parcel of contemporary industrial processes, something that places ROS at the center of their development and operation. It is a fact that through technological innovation such as the one demonstrated in this study, new limits in autonomous robotics possibilities within the industry 4.0 space are being continuously discovered.

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