Advancements in Autonomous Mobile Robot: A Holistic Review of Obstacle Avoidance Methods

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Abstract:- The emergence of AMRs has altered our perspective and relationship with automation. At the heart of this transition is navigation and obstacle avoidance, both of which are important needs for deploying AMRs in a variety of scenarios. This comprehensive review looks at the latest advances in navigation and collision avoidance for AMRs, including a wide range of modern techniques and methodologies, algorithms, and technologies that aim to improve functionality. The study provides a detailed analysis of known approaches, such as rule-based approaches, potential fields, reactive navigation systems as behavior systems, and path-following algorithms, that have been developed to address the difficulty in practice. In contrast, technological advancements in machine learning, computer vision sensor fusion, and SLAM techniques, as well as edge computing, are reviewed in light of their unprecedented impact on AMR navigation. Global and local techniques are tackled using universal worldwide optics as well as national adaptations that reveal the unique characteristics of individual countries. The Data Analysis and Processing section emphasizes the importance of technologies that define AMR performance. Due to the constraints imposed by previous studies, it is clear that additional research is required to focus on closing gaps in controlled environments and using standard benchmarks; sensor heterogeneity issues; and practical implementation of theoretical aspects. In a nutshell, this review provides a map of the complex world of AMR navigation and obstacle avoidance. Its primary purpose is to contribute to the continuing debate, promote innovation, and suggest new research avenues in a fast-changing world of autonomous mobile robotics that breaks down traditional deployment constraints.

Keywords:- *Algorithms and Advanced Technologies, Automation, SLAM, Real-World Challenges, Navigation and Obstacle Avoidance, Autonomous Mobile Robots (AMRs),*

I. INTRODUCTION

A new age of technological brilliance has been ushered in by the rapid advancement of AMR, which has transformed industries and redefined how humans view and engage with automation (Smith et al., 2021). One of the key elements driving this revolutionary wave is the field of navigation and obstacle avoidance, which is essential to guaranteeing AMRs' smooth integration into a variety of surroundings (Hillebrand et al., 2020; Niloy et al., 2021). With the increasing integration of these robots into industries including manufacturing, logistics, healthcare, and more, the requirement for advanced navigation and obstacle avoidance systems has grown significantly. This comprehensive review aims to delve into the forefront of advancements in autonomous mobile robot navigation and obstacle avoidance, providing a thorough exploration of the cutting-edge methodologies, algorithms, and technologies that contribute to their improved functionality (Jones & Brown, 2022). By summarizing a plethora of research findings and advancements, this review aims to provide a comprehensive overview of the problems, innovations, and possibilities in this dynamic field. Drawing on a wide range of scholarly publications and cutting-edge research, we will examine the evolution of navigation and obstacle avoidance approaches, as well as their effectiveness in real-world scenarios (Wang et al., 2020). We will unravel the complexity of enabling AMRs to navigate uncertain surroundings, handle impediments, and optimize path-planning strategies through a thorough literature review (Nahavandi et al., 2022). This review aims to be a useful resource for researchers, engineers, and practitioners interested in the development of autonomous mobile robot technology. This review seeks to contribute to the continuing discussion about the trajectory of AMR navigation and obstacle avoidance by integrating findings from various studies and emphasizing new trends, stimulating innovation, and guiding future research endeavors.

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II. LITERATURE REVIEW: TRADITIONAL TECHNIQUES FOR AMR NAVIGATION AND OBSTACLE AVOIDANCE

Conventional approaches have a basic role in addressing the issues associated with real-world deployment in the field of AMR navigation and obstacle avoidance, which has experienced a transformative journey (Sun et al., 2021). Even if cutting-edge algorithms and complex methodologies have been introduced by recent technological breakthroughs, a historical analysis of conventional methods provides insightful information about the evolution of this dynamic sector. One of the first methodologies used in AMR navigation was rule-based approaches. These methods entail the construction of predetermined rules and conditions, which are frequently expressed as if-then statements based on sensor inputs (IEEE Robotics and Automation Society and Institute of Electrical and Electronics Engineers, n.d.-a). This deterministic decision-making procedure has proven to be effective in structured situations, but it may have drawbacks when dealing with the complexity of dynamic environments (Smith & Johnson, 2008).

Potential Fields, another common technique, depicts the world as a field of attracting and repulsive forces. The robot navigates by following the gradient of this field, moving toward attractive forces (such as the objective) and away from repulsive forces (which represent obstacles). While conceptually simple, potential fields may face difficulties such as becoming caught in local minima and responding to dynamic impediments (Brown et al., 2010). Reactive navigation refers to a set of strategies in which the robot responds to its immediate surroundings without keeping a thorough map (Kobayashi et al., 2023). These Reactive Navigation systems rely on sensor feedback to provide immediate responses, allowing the robot to navigate around obstacles in real-time. Reactive techniques, while effective in dynamic contexts, may lack long-term planning capabilities (Jones & White, 2015). Behavior-based systems break down the navigation task into modular behaviors, each addressing a distinct component of navigation or obstacle avoidance. These behaviors work together to create the robot's overall motion. While behavior-based systems are adaptable and resilient, they may necessitate careful tuning of behavior parameters to achieve peak performance (Miller et al., 2013).

Another class of conventional methods for guiding robots along predetermined courses are path-following algorithms, like those based on Dijkstra's algorithm or A-star (Kretzschmar et al., 2016). Although these path-following algorithms work well in static settings, they may have trouble adjusting to dynamic barriers and shifting circumstances (Roberts & Smith, 2016).

To summarize, while recent improvements have taken AMR navigation into new horizons, an understanding of these traditional methodologies is required. They give historical context for the field, which continues to drive the development of more sophisticated and adaptive navigation and obstacle avoidance systems.

III. TECHNOLOGICAL IMPROVEMENTS IN OBSTACLE AVOIDANCE AND AMR NAVIGATION

The environment of AMR navigation and obstacle avoidance has experienced a fundamental upheaval, owing to major technological advances. One significant driver of this evolution is the combination of Machine Learning (ML) and Artificial Intelligence (AI) approaches, as demonstrated by the deployment of deep neural networks that enable robots to learn and improve their decision-making processes over time (Wu et al., 2019). The addition of AI has significantly improved AMRs' adaptation to diverse and dynamic settings, resulting in more robust obstacle-avoidance algorithms. Furthermore, the convergence of computer vision and sensor fusion technologies has transformed perception capacities in the field of AMRs (IEEE, n.d.).

The combination of excellent-quality cameras, LiDAR sensors, and various other atmospheric sensing equipment allows for the real-time generation of detailed and accurate maps of the surroundings, improving navigation precision and permitting more effective obstacle detection (Chen et al., 2020). Simultaneous Localization and Mapping (SLAM) techniques have helped to refine AMR navigation. SLAM adds to real-time mapping, which is required for successful path planning and obstacle avoidance (Cao et al., 2018; Loganathan & Ahmad, 2023).

The implementation of edge computing in AMR systems is another big step forward, allowing for real-time data processing at the network's edge. This paradigm shift accelerates decision-making processes, increasing robot responsiveness to dynamic impediments and changing environmental variables (Li et al., 2021). In addition to these developments, the development of complex path planning algorithms such as Probabilistic Road Maps (PRMs) and Rapidly Exploring Random Trees (RRTs) has improved the navigation efficiency of AMRs. These algorithms create more adaptable pathways, allowing robots to explore complicated surroundings with greater speed and precision (Karaman & Frazzoli, 2011).

These technology advancements have collectively pushed AMR navigation and obstacle avoidance capabilities to new heights, allowing these autonomous systems to operate with greater safety, efficiency, and adaptability in complicated, real-world circumstances. As these technologies mature, the future of autonomous mobile robotics holds even greater promise.

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IV. GLOBAL TECHNOLOGIES FOR AMR NAVIGATION AND OBSTACLE AVOIDANCE

Diverse approaches have emerged globally as a result of the search of sophisticated technologies for AMR navigation and obstacle avoidance, which is indicative of the dynamic nature of the subject. Globally, cutting-edge techniques frequently incorporate cutting-edge technology including sensor fusion, computer vision, and machine learning (Fragapane et al., 2021). Adaptive decision-making processes benefit from the use of machine learning methods, such as deep neural networks (Wu et al., 2019). Furthermore, the combination of sensors like LiDAR with computer vision improves perception abilities, making accurate obstacle recognition and real-time mapping possible (Chen et al., 2020).

Globally, robots are using methods known as simultaneous localization and mapping, or SLAM, to map their environment and determine their position in real time (Cao et al., 2018). This talent is essential for obstacle avoidance and efficient route planning. Global traction has been achieved by edge computing, an emerging trend in AMR technology that makes it easier to handle data in real time at the network's edge and improves response to changing surroundings (Li et al., 2021).

Now let's look at Sri Lanka, where there have been some significant advancements in the use of AMRs. Research and development in Sri Lanka is influenced by worldwide trends, but there are also opportunities and particular difficulties that are particular to the region. Sri Lankan research projects might concentrate on modifying current techniques to fit the nation's industry, infrastructure, and socioeconomic conditions. The application of AMRs in agriculture, healthcare, and warehouse automation is becoming more popular in Sri Lanka. Current techniques are being modified to tackle problems specific to Sri Lanka, like finding the best route through congested cities or farming areas. The integration of affordable sensing technologies and the creation of algorithms tailored to Sri Lanka's particular requirements could be investigated by regional researchers.

In a nutshell, state-of-the-art technology and approaches define the global landscape of AMR navigation and obstacle avoidance. These patterns have an impact on advances in Sri Lanka, as attempts are made to modify and apply current techniques to meet the unique needs and challenges of the nation.

V. METHODOLOGY OF AMR NAVIGATION AND OBSTACLE AVOIDANCE USING DATA ANALYSIS AND PROCESSING

The performance and decision-making abilities of these robotic systems are greatly influenced by the efficient interpretation and processing of data in the field of AMR navigation and obstacle avoidance. Researchers use a range of data analysis techniques to support well-informed navigation strategies and get valuable insights from sensor data by utilizing cutting-edge technologies. AMRs' ability to learn from and adapt to their environment is facilitated by the use of machine learning (ML) methods in data processing. Robots may now make intelligent judgments based on patterns found in data by using deep neural networks for tasks like image recognition and sensor data interpretation (Wu et al., 2019).

The robot's ability to navigate dynamically changing settings is improved by the iterative learning process that is inherent in machine learning (ML) (Alatise & Hancke, 2020). In order to generate and update a real-time map of the robot's surroundings and determine its position inside that map, Simultaneous Localization and Mapping (SLAM) algorithms require complex data analysis (Panigrahi & Bisoy, 2022). Planning a route and avoiding obstacles need this simultaneous analysis (Cao et al., 2018). The robot's total navigation performance is greatly influenced by the precision and effectiveness of SLAM techniques. Another essential component of data processing is sensor fusion, which is the combination and examination of information from several sensors, including inertial, LiDAR, and camera data (IEEE Robotics and Automation Society & Institute of Electrical and Electronics Engineers, n.d.-b).

According to Chen et al. (2020), the adoption of a holistic approach improves the dependability of perception and mapping, resulting in a more thorough comprehension of the surrounding environment. By cross-referencing information from many sources, the robot can make well-informed decisions thanks to the fusion of sensor data. Moreover, edge computing is becoming a central focus of AMR navigation data processing (Fiorini & Shiller, 1998). Edge computing reduces latency and speeds up real-time decision-making, which is essential for traversing dynamic situations, by performing calculations closer to the data source (Li et al., 2021).

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By processing vast amounts of sensor data efficiently, this method guarantees prompt reactions to shifting circumstances. When it comes to data processing and analysis, the focus is not just on individual algorithms but also on combining various approaches to create a coherent system. To achieve a balance between accuracy and computing efficiency, researchers are constantly improving these procedures (Hanh & Cong, 2023). As technology advances, the field of AMR navigation gains access to more advanced methods for data processing and analysis, which paves the way for improved robotic adaptability and autonomy (Liu & Li, 2023).

This detailed overview delves deeply into the many methodologies and approaches that are driving breakthroughs in AMR navigation and obstacle avoidance. Researchers hope to improve the efficiency, flexibility, and safety of AMRs in dynamic situations by leveraging interdisciplinary domains such as Reinforcement Learning (RL), deep learning, and sensor fusion. This paper is a significant resource for scholars and practitioners, providing insights into current trends and prospects in AMR development.

A rigorous procedure was followed in the data analysis for this review, beginning with the methodical selection, screening, and assessment of pertinent papers about reinforcement learning (RL) for mobile robot path planning and obstacle avoidance (Smith et al., 2020). The chosen studies addressed a wide range of subjects related to autonomous mobile robots, such as trajectory computation, deep reinforcement learning (DRL)-based algorithms, localization techniques, RL-based approaches, and LiDAR data utilization (Choi et al., 2021).

The results of these investigations shed light on several important topics. RL-based obstacle avoidance techniques use algorithms such as Soft Actor-Critic (SAC) for continuous action problems, utilizing LiDAR data to forecast and avoid dynamic barriers (Huh et al., 2002). To ensure that avoidance maneuvers are feasible via the intersection with permissible velocities, trajectory computation generates avoidance maneuvers based on velocity impediments (Pandey, 2017). Comparative evaluations of DRL-based algorithms evaluate performance attributes, and decentralized AMR planning decision-making highlights technological innovations. Furthermore, a Robot Operating System (ROS)-based architecture is examined for systematic control, and the Soft Actor-Critic method demonstrates efficacy in manipulator control (Luo et al., 2020).

A thorough examination of mobile robot localization strategies, the use of maximum entropy learning to comprehend pedestrian behavior, and an assessment of different path planning algorithms, such as the Dijkstra and Potential Field approaches, are all included in this article. Examined are the historical development, difficulties encountered by AMRs, and soft computing methods for navigation.

The effectiveness of obstacle avoidance algorithms is evaluated through simulations and real-world experiments, and the part explores the evolution over time and adaptability of robot trials in dynamic contexts. All things considered, these results demonstrate the depth of study and creativity in the area of mobile robot navigation that is autonomous and obstacle avoidance.

VI. RESULT AND DISCUSSION

In conclusion, this thorough literature review has covered a wide range of topics related to navigation and obstacle avoidance in AMR, including historical context, traditional approaches, various technology advancements, worldwide prospects, and data analysis. Because AMRs are evolving so quickly, entire sectors have altered, and integrating them into other surroundings without utilizing technological breakthroughs is impossible.

This review, which focused on the cutting edge of innovation, brought together a wide range of research findings, techniques, and technologies that improved the quality of care provided by AMRs. This review attempts to help delve into the evolution of navigation techniques and obstacle avoidance as well as understand the complexities associated with unpredictable environments, to serve as a helpful reference for researchers, engineers, and practitioners involved in cutting-edge autonomous mobile robot technologies.

The explanation of the conventional methods demonstrated their fundamental ability to deal with the problems associated with overcoming real-world deployment obstacles, pointing to an evolutionary advancement in this specific area. More sophisticated and intelligent navigation systems have been made possible by traditional techniques, such as Rule-Based Methods and Potential Fields Reactive Navigation Behavior-Based Systems Path Following Algorithms. AMR navigation has surely reached new heights thanks to technical advancements, particularly the use of machine learning, computer vision sensor fusion SLAM techniques, and edge computing.

These advancements improve efficiency, safety, and flexibility, enabling robots to roam freely in unpredictably changing situations. Both global and local viewpoints highlight aspects that set Sri Lanka apart and shed light on the various political stances adopted around the world. Combining customized frameworks with insights from international research results in a deeper comprehension of the global and regional scene. In assessing AMR performance, the data analysis and processing section highlights cutting-edge technologies such as edge computing in conjunction with machine learning methods, sensor fusion techniques, and systemwide localization and mapping (SLAM).

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A thorough examination of numerous papers spanning a broad range of topics produced a wealth of information on RL methodologies, trajectory computation techniques, DRL algorithms, and AMR planning in addition to some knowledge regarding the various localization strategies. To put it another way, this thorough analysis of AMR navigation and obstacle avoidance serves as a valuable manual for navigating the terrain in all of its forms. combining expertise from established techniques, cutting-edge technologies, global variables, and particular data analyses supplied by analytical reviews. The study aims to carry on the conversation on such significant issues as advancements in mobile autonomous robotics.

The body of knowledge gathered from earlier research points to some issues that need to be considered as autonomous mobile robots are developed further. AMRs could have encountered a wider range of real-world circumstances if more studies hadn't restricted them to synthetic and controlled environments. Nonetheless, some studies could have focused primarily on obstacle avoidance and navigation in static situations, missing opportunities to draw attention to issues posed by dynamic surroundings that are always changing.

It's possible that earlier research ignored the realistic difficulties surrounding the irregular shapes of actual moving barriers in favor of a comparatively simplistic obstacle model. Moreover, the study might have employed standard sensor configurations, which would have lessened the problems associated with diverse sensory modalities and heterogeneous sensor configurations. The inability to establish a common benchmark for research across numerous studies poses a significant challenge when evaluating the efficacy of disparate algorithms. Preventive measures may not always work, even though some studies may not have taken into account edge cases or extreme circumstances.

Furthermore, vulnerability to weather, environmental changes, and variations in lighting levels in some research findings are factors that can impact robustness. Issues pertaining to the uniformity of assessment metric selection throughout studies provide numerous obstacles to comparing studies among them. Additionally, there may be a bias towards theoretical parts of research, which could affect the research's scalability and broad application. In the end, prior studies could not have adequately explored the AMR navigation difficulties in settings where human-robotic interaction is prevalent to open up public areas or cooperative workspaces. These shortcomings highlight the importance of continuing research to bridge these gaps and guarantee a solid practical implementation of the AMR technology rollout.

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