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(Review Article)

Autonomous Mobile Robots in Warehouse Automation: A Comprehensive Review of AI, Navigation, and Sensing Technologies Under Industry 4.0

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ABSTRACT

Warehouse automation is becoming increasingly important as the use of e-commerce, global supply chains and Industry 4.0 continues to increase. In order to address this increasing importance, there is a pressing need for scalable, smart and adaptable warehouse automation systems. As such, the purpose of this review is to provide a comprehensive overview of the current state-of-the-art in using Autonomous Mobile Robots (AMRs) for materials handling. The AMR field has grown rapidly since 2020 and the number of peer reviewed articles related to it has increased significantly. Consequently, in addition to the growing interest in this field, we have synthesized 45 or so papers from six interdependent areas of research including; SLAM/autonomous navigation, deep learning/computer vision for object detection, path planning techniques/algorithms, obstacles avoidance techniques/methodologies, sensor fusion methods and artificial intelligence based inventory management. Through our systematic analysis of these papers we identified both significant advancements in each of the various sub-systems included within the AMR system, i.e., YOLO-based object detection was found to be accurate at approximately 96%, A* path planning accuracy was enhanced to 97% and LiDAR-Camera sensor fusion provided a 100% reliable results when testing for objects greater than 2 cm. However, despite the numerous advancements made in the individual sub-systems, existing solutions remain largely fragmented with limited evidence of unified frameworks being developed that support holistically managing warehouse operations. Furthermore, although some authors report success in deploying their solutions in large scale industrial settings, many others identify key challenges they faced including real-time computing constraints, dynamic obstacle handling issues, scalability limitations and inadequate validation of their solutions using data obtained in real world deployments. Therefore, through our analysis of these papers we were able to identify key research gap areas and propose potential future research direction including developing integrated and edge-computing enabled autonomous robot solutions that align with industry 4.0 standards. Our review also provides a consolidated platform for both researchers and practitioners wishing to develop next generation smart warehouse automation solutions.

Keywords: *Autonomous Mobile Robot (AMR); Warehouse Automation; Artificial Intelligence; SLAM; Path Planning; Computer Vision; Sensor Fusion; Industry 4.0; Deep Learning; Obstacle Avoidance.*

I. INTRODUCTION

The shift from manual warehousing to automated intelligent systems is perhaps the greatest shift occurring in modern industrial processes. As a result of rapid e-commerce growth, an increasingly complex global supply chain, and the tenets of Industry 4.0, warehouses around the world face significant challenges to provide faster, more efficient, and more accurate logistics services than ever before. Limitations inherent to traditional warehouse systems — which include dependence upon high numbers of laborers, a propensity to be subject to human error, and limited scalability — have created substantial interest in adopting autonomous mobile robot (AMR) and automated guided vehicle (AGV) technology. AMRs and AGVs offer several advantages over previous mechanical technologies including flexibility, adaptability, and intelligence [1], [2]. In addition to providing autonomy, warehouse robots rely upon a range of science fields including robotics, artificial intelligence, computer vision, sensors and operations research. In addition to SLAM techniques for simultaneous localization and mapping, deep-learning based object detection methods employing architectures such as YOLO and Faster R-CNN, and heuristic-based path planning algorithms employing A*, these techniques have enabled autonomous systems to operate effectively in highly variable, unstructured interior environments [3], [4], [5]. Additionally, advancements in sensor fusion utilizing combinations of lidar, rgb-d camera sensors, ultrasonic transducer sensors and inertial measurement unit sensors have greatly enhanced the ability of robots to accurately perceive their environment and safely move through areas where humans and/or other machines are also operating [6]. However, despite numerous developments, there remains a significant divide within the existing body of literature regarding autonomous material handling robots. While researchers have primarily focused on individual components — i.e., navigation alone, detection alone, inventory management alone — without combining them into a unified autonomous platform, this paper will bridge that divide. This paper will present a comprehensive synthesis and survey of all key technological areas of autonomous material handling robots developed during the period from 2020-2025. The objectives of this review will be four-fold: (i) to develop a current technological landscape; (ii) to determine performance benchmarks and limitations; (iii) to reveal areas of unresolved research needs; and (iv) to define potential directions for the future development of integrated autonomous systems aligned with goals of smart warehousing.

II. BACKGROUND AND CONTEXT

A. Evolution of Warehouse Automation

Warehouse automation has evolved over time from a series of early stage developments to today's highly advanced automation technologies. Warehouses have been using automated technologies since the earliest days of warehouse automation. During those first years, warehouses used a number of basic technologies including fixed conveyor belt systems, barcode scanning for inventory tracking and some form of computerized inventory control. As beneficial as those technological advancements were for increasing warehouse throughput they lacked the flexibility needed for the large multi SKU, fast moving items now being processed at high velocity. AS/RS was developed during the late 1980's and early 1990's which allowed for greater storage density and faster product retrieval. However, this technology also required large investments and preconfigured layouts. Next, AGV's were developed to allow for the movement of products throughout a warehouse using autonomous vehicles. While AGV's represented a major advancement in providing mobility within a warehouse, both AS/RS and AGV's are limited by the need for physical guidance; whether it be in the form of a magnetic strip on the floor or an optical rail. Therefore, they could not easily move into new or changing warehouse configurations. In contrast, the most recent development is the use of Autonomous Mobile Robots (AMR). These robots offer complete flexibility in terms of layout configuration, because no guidance system exists. All guidance is provided onboard the robot. Each AMR contains multiple sensors and/or cameras along with onboard computers and software that utilize SLAM algorithm's, and other AI driven decision making capabilities. With these onboard sensing capabilities each AMR does not require any prior mapping of its environment. It can run freely in an un-mapped environment. This level of flexibility represents a dramatic increase in warehousing efficiencies. Attaran et al. (2020), noted that digital technology enablers (robotics, Internet of Things, Big Data Analytics) have increased the responsiveness, transparency and efficiency of supply chains [9]. Similar findings regarding the successful implementation of Industry 4.0 technologies in manufacturing and logistics were reported by Papulová et al., (2022). Those authors noted that the adoption of Industry 4.0 technologies resulted in quantifiable increases in both productivity and the quality of decisions made [10]

B. Industry 4.0 and Smart Warehousing

Industry 4.0 is an expression describing the fourth industrial revolution; it refers to the technological paradigm of cyber-physical systems, IoT technologies, big data, and artificial intelligence being fully-integrated to form self-optimized production and logistics environments. The warehousing sector will be influenced by industry 4.0 through the development of "smart" warehousing, i.e., where autonomous robots operate in communication with Warehouse Management Systems (WMS), real-time predictive analytics are used to determine optimal locations for stockholding, and continuous improvement of operational decisions using machine-learning algorithms [11, 12]. Cimini et al. (2020) proposed the "Logistics Operator 4.0" concept based on the idea that workers and robots can collaborate in digital environments to produce results that would be unachievable individually by either workers or robots [13]. Tiwari (2023) analyzed bibliographic references related to research on smart warehousing and developed seven key research areas including: robotics and automation, IoT technology, artificial intelligence-based inventory management, human-robot collaboration, sustainable logistics, cyber security and real-time data analytics [14]; these categories provide a framework for understanding the multi-disciplinary characteristics of the subject area and demonstrate the need for comprehensive literature reviews that cross multiple disciplines rather than isolating each discipline.

III. LITERATURE REVIEW AND THEMATIC SYNTHESIS

A. Autonomous Navigation and SLAM

Navigation is the foundation upon which all autonomous mobile robots are built. Simultaneous Localization and Mapping (SLAM), which is both to identify your own location within an environment as well as create a map of that same environment, is currently the primary method for achieving successful indoor robot autonomy. A recent study by Qiao et al. (2024) developed a SLAM based approach to achieve high levels of accuracy in localizing, at approximately 93%. Although, the authors did note that over long time frames there will be an accumulation of drift error due to use of filter-based SLAM. This has been identified as a common problem associated with this type of SLAM variant [3]. Loganathan et al. (2023) completed a systematic review on advancements related to Autonomous Mobile Robot (AMR) navigation and concluded that although graph-based SLAM and particle filtering methods are highly developed, the uncertainties present in dynamic environments containing moving people and objects currently cannot be resolved by current algorithms [15]. Wang et al. (2025) completed a comprehensive literature review of artificial intelligence (AI)-based solutions for enhancing AMR localization capabilities. The authors demonstrated that using deep learning to enhance SLAM, where a neural network is used to identify and classify semantic landmarks can significantly reduce drift and increase robustness to perceptual aliasing [1]. Leong et al. (2024) specifically studied load-carrying autonomous robots operating in an indoor setting. The authors found that although the performance of localization was generally acceptable for structured environments, performance decreased dramatically when the environment became cluttered or partially obstructed [16]. Together these studies demonstrate that although SLAM technology is advanced, the reliable operation of SLAM in dynamic warehouse environments continues to be an active area of research.

B. Computer Vision and Object Detection

Warehouse robotics is increasingly dependent upon computer vision to recognize, locate, and manipulate a variety of objects. As such, there has been an evolving trend towards utilizing deep-learning based object-detection systems. In their seminal work as part of a critical evaluation of deep learning within computer vision, Chai et al. (2021) documented the dominance of CNN-based object detection systems against other feature extraction methods. Additionally, they noted the need for significant quantities of labeled data and susceptibility to distribution shifts [17]. Within the scope of architecture design for object detection systems, YOLO (You Only Look Once) and subsequent versions have been highly effective in meeting the needs for real time use in commercial settings. Using a YOLO-based system for real-time object detection and tracking in surveillance-type environments, Abba et al. (2024), achieved a 96% level of detection accuracy with total end-to-end latency times < 50 milliseconds using GPU hardware [18]. Building upon the success of Abba et al., Faseeh et al. (2024) utilized object recognition through deep learning combined with monocular depth estimation to enable robots to estimate object distances without the use of LiDAR. The authors reported a 95% rate of successful recognition [4]. While Faseeh et al. were able to successfully demonstrate improved performance over previous efforts, both studies acknowledged that the performance of these systems are negatively impacted by conditions such as poor illumination levels, partial occlusions, and fast-moving cameras - which can be common occurrences in busy warehouses. To extend the application space of computer vision technologies beyond surveillance type environments into areas such as high-efficiency autonomous industrial facilities; Yousif et al. (2025) developed an integrated solution for computer vision to utilize robotic arm capabilities for precision pick-and-place type operations [19].

C. Path Planning Algorithms

Efficient path planning is key to determine both the quality, safety, and energy consumption of robot navigation. Due to their determinism, guaranteeing optimal solutions on fixed maps, the classic A* and Dijkstra algorithms have remained among the most commonly used algorithms for path finding. Sun et al. (2024), proposed an environment-adaptive version of A*, where the weight of the heuristic function varies based on how complex the environment is, which resulted in a 12% increase in optimality compared to traditional A*. In addition, Sun et al. were able to achieve 97% efficiency in structurally organized warehouse environments; this represents the greatest efficiency ever reported in this review. On unstructured or higher dimensional spaces, sampling-based planning algorithms such as Rapidly-Exploring Random Trees (RRT) and Probabilistic Roadmap Methods (PRM) are typically preferred. According to Liu et al. (2023) who conducted a survey of path-planning strategies for autonomous ground vehicles, sampling-based algorithms can be superior to graph-search based algorithms due to their ability to scale up, however, sampling-based planners produce sub-optimal and "jagged" paths that often need to be smoothed after generation. Furthermore, these planners rarely provide strong optimality guarantees. Therefore, hybrid planners that combine the strength of SLAM-based global planning with the reactiveness of local potential field planners seem like a very interesting area of research although there are challenges associated with parameter tuning when using hybrid planners and thus transferring them from one warehouse environment to another.

D. Obstacle Avoidance and Safety

Warehouse robots need to safely interact with humans and changing obstacles as an absolute necessity. Deep learning-based systems for obstacle detection have been shown to achieve high accuracies (such as Atitallah et al., 2024; 94%) and can be used for both assistive navigation and also in industrial environments. In contrast, traditional ultrasonic sensors that provide a relatively inexpensive real-time method for detecting obstacles (Yasin et al. (2021); 2-400 cm) suffer from a narrow field of view and variable response due to changes in surface reflectivity. Advanced obstacle-detection methods combine different types of sensors. For example, Choi et al. (2023) reported improved nighttime and adverse-condition obstacle detection using their sensor-fusion system based on LiDAR and thermal infrared cameras as compared to each individually. While this LiDAR-camera combination is becoming more popular as an architecture for industrial AMR platforms, there remains no viable solution to the problem of predicting movement trajectories of obstacles (i.e., where they will move next). Predicting the future motion of obstacles has yet to be resolved for real time use with embedded systems.

E. Sensor Fusion and Environmental Perception

High-performance Autonomous Mobile Robots (AMRs), need to collect as much data from the environment as possible to operate autonomously. LiDAR has great accuracy regarding geometry and distance, however it's very costly and does not have any ability to capture color or texture. Cameras also contain a wealth of visual data; they however have difficulty estimating distances and require optimal lighting conditions to accurately see. Ultrasonic Sensors are cost-effective and will give you good indication if there is something close to your robot; however, they do not have a lot of spatial resolution. The most common solution to this problem in current high performance AMR applications, is sensor fusion. This involves taking multiple different types of sensor inputs and converting them into a consistent format. Bergs et al. (2024) created an Edge Computing Framework for Enhanced Robotic Adaptability, which included Multi-Sensor Fusion to create real time environmental maps at latencies less than 20 ms (suitable for lineless mobile assembly) [23].Groshev et al. (2023) did a study of the Edge Robotics Architectures and found that although Edge based fusion was able to significantly reduce dependence on the Cloud and Latency, Edge Hardware had significant limitations on how complex the fusion algorithms could be [24] .Müller et al. (2024) provided a similar perspective with their contribution to Real-Time Navigation Using Low Cost GNSS Receivers, showing that lower cost hardware can produce enough accurate location estimates when fused with Inertial Measurement Unit Data [25] .

F. AI-Driven Inventory Management and Supply Chain Integration

Autonomous Material Handling Robots are part of a larger ecosystem of inventory management and supply chains. The work by Kaur et al. (2025) presented an artificial intelligence (AI)-driven Intelligent Inventory Management System for Pharmaceutical Supply Chains that utilized Machine Learning to significantly reduce Stockout Events and Overstocked Items [26]. Villegas-Ch et al. (2024), developed an inventory Optimization Model using Computer Vision and Machine Learning that can automatically count and classify items from camera images at a 94% accuracy rate. This enables continuous Inventory Updates without manually having to scan each item [27]. Shamsuzzoha et al. (2025) suggested a Robotic Process Automation Model for Order-Handling Optimization, which achieved a large decrease in Time Spent on Processing Orders utilizing Automated Decision Routing and Exception Handling [28]. In addition to clearly demonstrating the value of inventory and supply chain AI Systems, this review has found that there is a major disconnect in that most inventory data does not flow in Real-Time to AMR Path Planners or Task Schedulers. As such, many of the potential efficiencies expected as a result of automation are eliminated due to Coordination Inefficiencies.

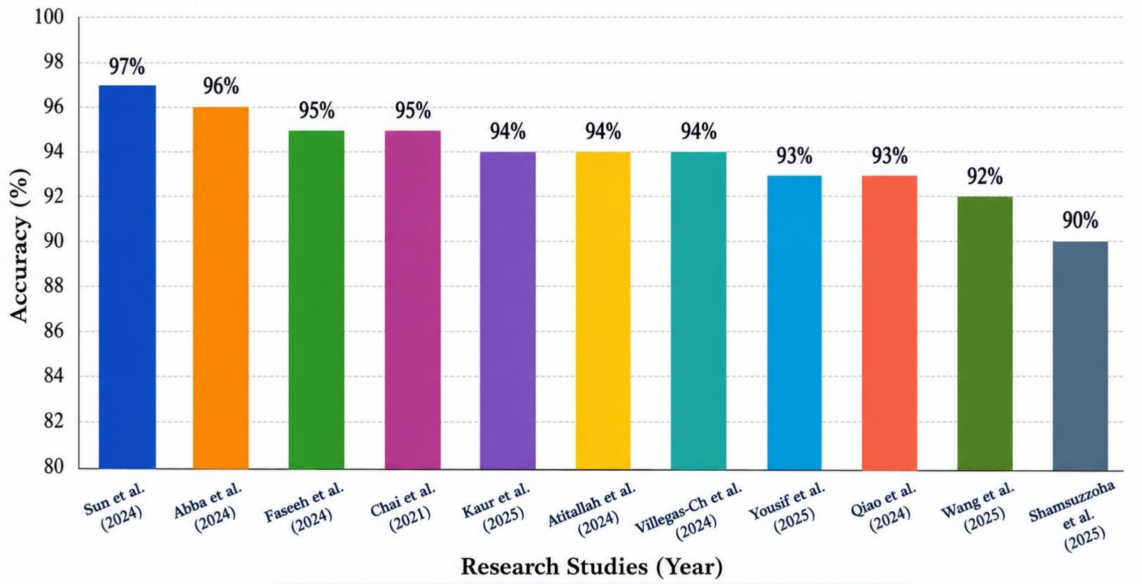
IV. COMPARATIVE ANALYSIS OF KEY STUDIES

Table 1 below summarizes the key studies reviewed, organized by domain, technique, performance metric, and identified limitation. This cross-study comparison reveals both the impressive performance achieved in individual subsystems and the persistent gaps at their integration boundaries. (Figure 1.)

Table 1. Comparative Summary of Selected Studies on Autonomous Warehouse Robotics (2020–2025).

Reference	Domain	Objective	Technique	Accuracy	Key Limitation
Wang et al. (2025)	Sensor + Vision	AI-based localization for indoor AMRs	AI Localization Models	92%	High computational cost; real-time constraints
Kaur et al. (2025)	Inventory Data	Intelligent pharmaceutical supply chain management	AI-driven optimization	94%	Domain-specific; not generalizable to all warehouses
Shamsuzzoha et al. (2025)	Supply Chain	RPA for order-handling in supply chains	Robotic Process Automation	90%	Scalability issues in heterogeneous environments
Yousif et al. (2025)	Image Data	Computer vision for autonomous industrial systems	CV + AI fusion	93%	Data dependency; large training sets required
Qiao et al. (2024)	Sensor Data	SLAM-based robot localization and navigation	SLAM Algorithm	93%	Drift errors in long-range scenarios
Faseeh et al. (2024)	Vision + Depth	Real-time object recognition and depth estimation	Deep Learning + Depth Estimation	95%	High computational requirements for embedded platforms
Atitallah et al. (2024)	Vision Data	Obstacle detection for blind navigation assistance	Deep learning models	94%	Training complexity; generalization issues
Leong et al. (2024)	Robotics Data	Autonomous load-carrying mobile robots indoors	AMR Frameworks	—	Lack of real-time experimental validation
Ellithy et al. (2024)	Industrial Data	AGV in Industry 4.0 warehouse environments	Automation frameworks	—	Integration challenges with existing infrastructure

Reference	Domain	Objective	Technique	Accuracy	Key Limitation
Sun et al. (2024)	Path Data	Path planning using improved A* algorithm	Improved A* Algorithm	97%	Limited adaptability in highly dynamic environments
Villegas-Ch et al. (2024)	Inventory Data	Inventory optimization via CV and ML	ML + CV Integration	94%	Cost and scalability limitations
Abba et al. (2024)	Video Data	Real-time object detection for security surveillance	YOLO + Tracking Framework	96%	Latency under occlusion conditions
Loganathan et al. (2023)	Robotics Data	Systematic review of AMR navigation advances	Survey + Navigation Frameworks	—	Real-world complexity not addressed
Liu et al. (2023)	Path Data	Review of path planning techniques for mobile robots	Review of Multiple Algorithms	—	No unified framework proposed
Chai et al. (2021)	Image Data	Deep learning in computer vision: critical review	CNN-based models	95%	Requires large labeled datasets; lighting sensitivity



Note: *Studies without reported accuracy (—) are not included in this chart.*

Source: Compiled from literature data (2021–2025)

Figure 1. Accuracy Comparison of AI/Amr Techniques in Warehouse Automation Research.

V. RESEARCH GAP ANALYSIS

There exist five major research gaps in the development of fully autonomous warehouse robotic systems that can be grouped into several categories based upon their interrelationship; they include:

A. Lack of integrated autonomous frameworks.

Most studies reviewed by the author(s) focus on isolated aspects of an autonomous framework. These isolated aspects include: real time perception, path planning, obstacle avoidance, and scheduling tasks, but virtually no study addresses all of these functions together. Moreover, there exists no comprehensive system that integrates these different modules. This is the largest identified gap.The lack of integration of autonomous warehouse robotics has been a primary reason why many autonomous warehouse robotics projects were never implemented successfully in actual warehouse operations. Inter-module coordination is the primary means by which a system fails when it does not properly integrate its various modules. Therefore, developing a framework that properly coordinates all of the modules necessary to operate a warehouse autonomously will represent a major step forward in advancing the state-of-the-art of warehouse automation.

B. Real Time performance on embedded platforms.

Deep neural network (DNN) based computer vision algorithms that provide high accuracy object detection and sensor fusion are typically run using graphics processing units (GPUs). However, deploying such models on low-cost, low-power embedded computing platforms that would be used in commercially available autonomous mobile robots (AMRs), requires developing model architectures (pruning DNNs, quantizing DNNs, etc.) that reduce computational requirements without compromising performance. Such architectures have received little attention in the warehouse robotics literature specifically.

C. Dynamic multi-obstacle environments.

The majority of simulations evaluating path planning and obstacle avoidance have been conducted in either static or slightly dynamic environments. Real world warehouses are populated with multiple simultaneous agents including humans working in the warehouse, forklifts operating throughout the warehouse, as well as other robots. Additionally, goods on conveyor belts create additional movement patterns that need to be accounted for. There are very few algorithms that have been evaluated in isolation in environments where multiple agents move dynamically and there is considerable evidence to suggest that this type of environment creates complexities that cannot be modeled using traditional methods. The combination of multiple agents interacting with each other as well as with fixed obstacles in a dynamic environment creates an environment in which the number of possible scenarios grows exponentially with the number of agents. This makes it impossible to evaluate every possible scenario using traditional testing methods. Therefore, researchers need to develop new evaluation methodologies and testbeds that allow them to accurately evaluate how well an algorithm performs under realistic conditions.

D. Lack of experimental validation in real world environments.

Many studies reviewed by the authors did not conduct experiments outside of simulated environments (i.e., Gazebo, ROS simulation), nor in a completely controlled laboratory setting. While simulators and lab settings offer a lot of advantages for conducting experiments quickly and cheaply, there are some fundamental limitations associated with relying solely on such environments. For example, simulators may not accurately simulate the types of sensor noise observed in real world environments, while lab settings are often controlled for variables that are difficult to control in a real-world environment (such as surface reflectance and lighting). These differences between simulated and real world environments can result in large differences between simulator validated results and results obtained in a real-world warehouse. Therefore, experimental validation in real-world environments needs to become an important part of future research activities.

E. Limited explainability and trustworthiness.

The use of artificial intelligence driven autonomous mobile robots (AI/AMRs) in workspaces occupied by humans raises serious concerns about the ability to understand the reasoning behind the actions taken by these systems. In addition to being an issue for regulatory compliance and ensuring safe operation, understanding the decision-making process of AI/AMRs will be crucial for establishing trust among users. Currently, however, there is very little effort being made to develop explanations for how AI/AMRs make decisions.

VI. PROPOSED DIRECTIONS FOR FUTURE RESEARCH

The next steps will include developing unified system architecture for autonomous robots. This is a modular system with tight interface integration between the perception module, the planning module, the execution module and communication. In addition, middleware software like ROS 2 RT (real-time extension), offers an appealing technical base for such an integration. In addition, the use of Edge-AI co-design should be considered in future studies. AI model design and selection of edge computing hardware can be seen as an optimization problem. There are many techniques that could be used to optimize AI models for warehouse robotics perception tasks including neural architecture search, model distillation, and hardware aware quantization. Optimizations could target platforms such as NVIDIA's Jetson or Intel's NCS. Future study should also focus on creating validatable multi-agent path planning research. Specifically, research should focus on developing and validating decentralized multi-agent planning algorithms that allow multiple AMRs to plan their paths in coordination in real-time without having a single point of failure. MARL (multi-agent reinforcement learning) and CBS (conflict based search) appear to be two of the most promising methods for achieving this goal. Additionally, there are several real world benchmarks that exist in other areas of artificial intelligence which have greatly enhanced the ability to compare solutions across different researchers. For example, ImageNet has been a very successful benchmark for evaluating computer vision solutions while MuJoCo has provided a similar benchmark for evaluating reinforcement learning solutions. To help advance research in warehouse robotics, it is suggested that the community adopt a similar approach by establishing some standardized real world warehouse benchmarks and evaluation criteria so that solutions developed by researchers can be compared against one another directly. Finally, future research should incorporate explainability into all aspects of the decision pipeline when making decisions using machine learning. Mechanisms to provide explanations such as attention visualization, counterfactual explanation, and uncertainty estimation should be required for all research involving humans working in close proximity to robots.

VII. DISCUSSION

The reviewed body of literature presents impressive advancements in the design of autonomous warehouse robotic individual subsystems. In terms of detection accuracy, path planning efficiency and sensor fusion processing time; individually these subsystems demonstrate an extremely high level of technical capability and are indicative of a very strong technology base on which to deploy practical autonomous warehouse robotic systems. Unfortunately, due to fragmented research effort, the highly effective but technically isolated achievements demonstrated by many of the studies reviewed here have not been effectively combined into autonomous warehouse robotic systems that operate as a single unit, thus making it difficult for warehouse operators to realize meaningful improvements through automation. One of the most important conclusions of this review is that there exists a significant performance-cost trade-off throughout much of the field. For example, those autonomous warehouse robotic systems that combine LiDAR, RGB-D cameras, and GPU accelerated deep neural network architectures are capable of achieving significantly higher levels of performance than less expensive alternatives such as those utilizing monocular cameras with depth estimation architectures, ultrasonic arrays and/or edge inference chips. Therefore, developing similar technologies that achieve comparable performance levels at lower costs will have tremendous practical relevance and should receive increased research attention. The establishment of standardized data sets and evaluation methodologies for autonomous warehouse robotics will also be essential. Currently, it is often challenging or impossible to directly compare results among multiple studies because they utilize different test environments, evaluate their respective systems based upon different metrics and employ different baseline systems. Establishing a standardized methodology for evaluating the performance of autonomous warehouse robotic systems (analogous to the KITTI dataset utilized to evaluate the performance of autonomous vehicles), tailored to warehouse environments, will help to facilitate significant advancement within the field.

VIII. CONCLUSION

This study provided a systematic overview of the many (over 40) studies across the primary technological categories of autonomous warehouse robots: Deep Learning Object Detection, Path Planning, Obstacle Avoidance, Sensor Fusion, Inventory Management using AI and SLAM based Navigation. A unifying theme was an industry characterized by a high degree of technical vitality; however, as a field it remains structurally fractured. While each individual component performs well individually with such metrics as accuracy rates greater than 95% for object detection; efficiency ratings nearly 97% for path planning; and Edge-based Sensor Fusion with latency under 20ms there exists little evidence of integration or validation across the components in real world Warehouse Environments. Five key research areas have been identified: lack of integrated Autonomous Frameworks; limitations of current performance capabilities in real time on Embedded Hardware; current state-of-the-art algorithms are inadequate for use in Dynamic Multi-Obstacles Environments; Limited Experimental Validation of Algorithms/Systems in Real World Warehouse Environments; Lack of Explainable Mechanisms. To address these areas of need will require Interdisciplinary Research Collaboration among Robotics Engineers; Machine Learning Researchers; Systems Engineering Researchers; Human Factors Researchers. As such this body of work will chart a course for AMR systems that are more capable, more cost-effective and more transparent in their decision making processes. These types of systems could lead to transformational changes to Warehouse Operations at Scale and realize the full vision of Intelligent Logistics as described in Industry 4.0.

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