A systematic study on advanced intelligent techniques in automated guided vehicles control for Industry 5.0 perspective

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ABSTRACT

Automated guided vehicles (AGVs) play a crucial role in streamlining operations within manufacturing plants, warehouses, and distribution centers. As the industrial landscape transitions from Industry 4.0 to Industry 5.0, there is an increasing demand for more advanced, intelligent control systems to support the evolving complexity of these environments. This paper presents a systematic study of the advanced intelligent techniques driving the autonomous behavior of AGVs, with a focus on their application in Industry 5.0. The review categorizes intelligent techniques—such as machine learning, soft computing, game theory, and other intelligent algorithms—used for enhancing AGV functionalities including path planning, task scheduling, and energy-efficient operation. Emphasis is placed on how these approaches enable adaptability and smarter decision-making in dynamic industrial settings. The study concludes with key insights and outlines future research directions to further enhance AGV performance in the context of Industry 5.0.

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1. INTRODUCTION

Industrial automation is progressing rapidly, driven by the integration of soft computing techniques into hardware control systems. To enhance productivity, automation is being implemented across all departments within modern manufacturing environments. Automated guided vehicles (AGVs), widely used for material handling and intra-facility transportation, are now being controlled through increasingly sophisticated methods. In the context of AGVs, key areas of technological advancement include scheduling, path planning, and energy-efficient optimization. This literature review is structured around these core categories to provide a comprehensive analysis of the current state and future directions of AGV control techniques. A comprehensive review of existing literature on AGV automation and optimization has been conducted to identify the various methodologies employed in this domain and to inform future research directions. The introduction of artificial intelligence (AI), internet of things (IoT), robotics, and big data in the mechanical manufacturing systems brings up the idea of Industry 5.0. Algorithms that are intelligent and learning based are discussed in this literature review to give the idea about the future of Industry 5.0 scenario in the future.

AGV scheduling is the process of optimizing the movement of the AGVs for different tasks by optimizing the travel time, collision avoidance, optimal resource utilization, and maximizing throughput. Scheduling, path planning and energy efficient operation of AGV are few operations that are to be optimized for smooth industrial operation. Simulation plays a crucial role in optimizing decision-making and operations in smart production systems while aiding companies in assessing risks, costs, and implementation challenges toward Industry 4.0. Despite progress in this field, systematic studies on simulation-based research in Industry 4.0 remain limited. This study investigates the intersection of simulation and Industry 4.0, proposing a conceptual framework and systematically reviewing literature. This study investigates the intersection of simulation and Industry 4.0, proposing a conceptual framework and systematically reviewing literature. Hybrid simulation and digital twin emerge as key methodologies for modeling and analyzing Industry 4.0 systems [1]. This study analyzes the evolution of autonomous driving simulators, categorizing them by task applicability and evaluating their validity, accessibility, and maintenance. It highlights critical issues in open-source simulators and explores solutions to enhance their credibility [2].

Research by Stepanyants and Romanov [3] examines the need for an integrated simulation environment for connected and automated vehicles (CAVs), focusing on cooperative driving automation. It reviews existing vehicular simulation tools, signal propagation, and cooperative perception models, highlighting integration challenges. The paper surveys current simulation approaches and proposes an open-source architecture to achieve full domain coverage. The literature [4] presents an environment simulator for assessing AGVs in industrial settings, enabling hazard evaluation while reducing costs and verification efforts. It reviews proven simulation solutions based on industry requirements, leading to the development of an evaluation environment using the Gazebo simulator.

While simulators provide insights into the expected operational behavior of AGVs, it is essential to analyze the underlying algorithms used for automation to understand how their real-time performance can be enhanced. Accordingly, the following sections discuss algorithms applicable to AGV environments with a focus on performance optimization.

The contribution of this review paper is attempting to give the reader the idea of different algorithms of AGV path planning, scheduling and energy efficient AGV operation. New algorithms, performance, and their gaps are discussed for further research ideas in this area.

The methodology incorporated in this review paper is based on the progressive nature of the algorithms used in the scheduling, path planning and energy efficient operations of the AGV. The search for the algorithms on all these methods is stipulated to the past 25 years of publication in reputed journals. The key words included for search were based on the new algorithms either the machine learning algorithms or the optimization algorithms used in the field of the AGV scheduling and other related topics. The aim of the review is to know possibilities of improvement in the AGV scheduling algorithms by understanding the objectives of each implementation and finding the scope for further research in multi-objective approach. The papers that were not involving algorithms that are related to machine learning and optimization algorithms were avoided, not to lose the focus on the topics considered. Only reputed journals were considered to avoid bias in the research papers.

2. SCHEDULING ALGORITHMS OF AUTOMATED GUIDED VEHICLES

Article [5] investigates how scheduling rules impact the performance of flexible manufacturing systems (FMSs), focusing on mean flowtime as a performance criterion. Machine and AGV scheduling rules are evaluated through simulation under varying conditions, including changes in processing time distributions, breakdown rates, and AGV priority schemes. The findings highlight the sensitivity of scheduling rules to these factors, offering insights into their application in both standalone and complex scheduling systems. A comprehensive bibliography is also included for further reference.

This paper [6] addresses the dispatching problem for AGVs by developing a multi-attribute dispatching rule using additive weighting. The rule considers three attributes: the remaining space in a workstation's outgoing buffer, the distance between an idle AGV and a workstation with a waiting job, and the remaining space in the destination workstation's input buffer. A neural network dynamically adjusts attribute weights based on the system's current state. Simulations in a job shop environment demonstrate that the adaptive multi-attribute rule outperforms fixed-weight and single-attribute rules, achieving a better balance across performance measures.

This study highlights the limitations of traditional real-time scheduling (RTS) methods using multiple dispatching rules (MDRs), which, while improving production performance, fail to adapt to dynamic shop floor changes. To overcome this, a reinforcement learning (RL)-based RTS approach is proposed, integrating an offline learning module and a Q-learning-based RL module. This adaptive method incrementally updates the RTS knowledge base and optimizes scheduling decisions over time. Results show the RL-based approach outperforms previous MDR strategies, machine learning-based single dispatching rule (SDR) methods, and heuristic dispatching rules across various performance criteria, enhancing responsiveness and efficiency in dynamic manufacturing environments [7].

This study focuses on scheduling AGVs to ensure efficient and uniform material distribution from a truck dock to machining units in an automotive manufacturing plant. By analyzing this simpler material distribution problem, the researchers assessed the number of AGVs needed to meet machining unit demands. They proposed and evaluated innovative dispatch rules through simulations, measuring efficiency and uniformity for both single and multiple AGV scenarios. For multiple AGVs, the concept of zoning with comparable demand and minimal overlap was introduced, supported by deadlock avoidance protocols. Simulation results highlight the effectiveness of the proposed approach and its implications for material handling efficiency [8].

This paper addresses the challenges of RTS for AGVs in dynamic and complex flexible shop floors. It proposes an adaptive deep reinforcement learning (DRL)-based approach using mixed dispatching rules to minimize make span and delay ratio. The problem is modeled as a Markov decision process (MDP), detailing state and action representations, reward functions, and optimal policies. A novel deep Q-network (DQN) is developed to select suitable dispatching rules and AGVs based on the system's state. A case study on a real-world shop floor demonstrates the approach's feasibility and effectiveness [9].

This paper introduces a novel approach for scheduling resource-constrained FMSs, addressing machine loading/unloading, operation scheduling, machine assignment, and AGV scheduling. It incorporates AGV energy efficiency, modeled as a linear function of load and distance, to enhance environmental sustainability. Due to the problem's NP-hard nature, a modified multi-objective particle swarm optimization (MMOPSO) algorithm is proposed and compared with the classic MOPSO using five performance metrics. Results evaluated via a multi-criterion decision-making (MCDM) approach demonstrate MMOPSO's superior performance [10]. This study addresses the multi-automated guided vehicle scheduling problem with unloading safety detection (MAGVSUSD) in matrix manufacturing workshops, aiming to minimize travel, penalty, and AGV usage costs. A mixed-integer linear programming model and a population-based iterated greedy (PIG) algorithm are proposed, integrating hyper-heuristics, a two-stage destruction strategy, and adaptive local search. Experimental results confirm the algorithm's superiority over existing approaches [11]. This study addresses the flexible flow-shop scheduling problem with dynamic transport waiting times (FFSPDW) in smart manufacturing. A waiting time calculation approach is proposed to evaluate make span under different buffer capacities. Additionally, a memetic algorithm integrated with this approach is developed and validated through variance analysis. Experimental results confirm its efficiency in providing high-quality solutions with short computation time, making it suitable for industrial applications [12]. The Table 1 mention the few important scheduling algorithms and their key outcomes.

Table 1. Scheduling review

Category	Key focus	Main contribution	Key outcome
FMS and scheduling rules	Impact of scheduling rules on FMS performance	Evaluates machine and AGV scheduling rules under varying conditions (processing time, breakdown, and priority scheme)	Insights into rule sensitivity and application in dynamic environments [5]
AGV dispatching and optimization	AGV dispatching with multi-attribute rule	Neural network adjusts weights dynamically for optimal AGV scheduling	Outperforms fixed-weight and single-attribute dispatching rules in job shop environments [6]
RTS and reinforcement learning	Adaptive RTS for shop floors	Q-learning-based RTS integrates offline learning and dynamic optimization	Outperforms MDR and heuristic methods improving scheduling efficiency [7]
AGV Scheduling for material handling	AGV allocation in automotive manufacturing	Evaluates AGV demand and proposes zoning-based scheduling with deadlock avoidance	Efficient AGV for material transport [8]
DRL for AGV scheduling energy-efficient scheduling in FMS	- Real-time AGV scheduling in flexible shop floors - AGV scheduling with energy efficiency considerations	- DRL selects optimal AGV dispatch rules dynamically - MMOPSO for scheduling	Reduced make span and delay ratio in complex shop environments [9]
Multi-AGV scheduling and cost minimization	AGV scheduling with safety detection	Mixed-integer linear programming and iterated greedy algorithm for cost optimization	Superior performance in resource-constrained FMS [10]
Flow-shop scheduling transport waiting time	Scheduling under dynamic transport conditions	Memetic algorithm with waiting time optimization	High-quality scheduling solutions with fast computation [12]

3. SOFTCOMPUTING AND INTELLIGENT TECHNIQUES IN AGV APPLICATION

This study addresses the challenge of real-time production scheduling in cloud manufacturing (CM) with AGVs, focusing on distributed real-time scheduling (DRTS) for dynamic and customized orders. A cloud–edge collaboration framework is proposed, where edge devices handle distributed actors and the cloud hosts a centralized learner. The problem is modeled as a semi-MDP, integrating processing service sequencing and logistics assignment. A distributed dueling deep Q network (D3QN) algorithm is developed to minimize job tardiness and flow-time. Experimental results highlight D3QN's superiority over state-of-the-art methods, showcasing its potential for efficient real-time decision-making in CM [13].

The job shop scheduling problem (JSSP) has been extensively studied, with various approaches proposed to improve scheduling decisions in dynamic production environments. Technological advancements, especially in Industry 4.0, have significantly enhanced production efficiency. In the context of Industry 5.0, there is a focus on human factors, sustainability, and resilience. The flexible shop floor scheduling problem (FJSSP) now addresses challenges such as coordinating machines with alternative routes and diverse operators. Recent research highlights that worker well-being and skills impact scheduling performance. As industries contribute significantly to global energy consumption and greenhouse gas emissions, sustainability has become a key consideration in scheduling. This paper introduces the sustainable flexible scheduling problem (SFJSSP), which prioritizes human and energy efficiency in scheduling. It reviews recent literature on flexible job shop scheduling with human and environmental factors, analyzes emerging trends, and outlines future research directions to advance towards scheduling 5.0, proposing a new model that incorporates these factors [14].

To address the hybrid flow-shop scheduling problem in sand casting enterprises with complex, multivariate, and multistage production, an improved cuckoo algorithm was developed. A single-layer coding rule, based on casting category numbers, was designed to represent the "single-batch" coupling relationship, with a corresponding decoding mechanism for both the batch and single-piece processing stages. The algorithm incorporated new crossover and mutation operations to enhance search capabilities, replacing the original flight strategies. A strategy to separate superior and inferior populations was used to speed up evolution. Finally, orthogonal experiments optimized algorithm parameters, and simulations confirmed the effectiveness of the scheduling model and the improved algorithm [15]. Use of multi agent DRL method called as coupling deep Q network(C-DQN) on multiple AGVs in the automated container terminals is discussed in the literature [16]. The solution of the article tunes the scheduling conflicts that occurs in the cooperative gaming algorithms, thus increasing the scheduling efficiency.

As global trade expands, ports and terminals are becoming more crucial, with AGVs serving as key carriers for loading and unloading operations. A multi-AGV dynamic scheduling problem aimed at improving terminal efficiency amid the complexities and uncertainties of port operations. The scheduling process is modeled as a MDP with mixed decision rules. A novel adaptive learning algorithm, based on a DQN, is developed to generate optimal policies. The algorithm is trained using data from simulations of an automated terminal in Shanghai, China. Simulation results show that, compared to traditional methods like genetic algorithms and rule-based scheduling, the proposed approach offers superior performance in terms of effectiveness and efficiency [17]. As manufacturing systems become more flexible and intelligent, AGV scheduling has gained significant attention. However, research on dynamic AGV scheduling with energy efficiency, particularly battery replacement, is limited. A novel approach using DRL to address dynamic scheduling and battery replacement in production logistics systems is adopted in the article. The bi-objective optimization of AGV scheduling and battery management is modeled as a MDP for data-driven decision-making. A new dueling deep double Q-network algorithm is developed to minimize tardiness and energy consumption. Experiments and case studies show that the proposed method outperforms existing approaches in terms of efficiency and environmental impact. It can significantly enhance customer satisfaction and reduce production costs, especially in Industry 4.0 environments [18].

A hydraulic cylinder parts manufacturing shop scheduling problem (HCPMS), which combines parallel batch processing with flexible job shop scheduling. A multi-objective scheduling model is developed, optimizing make span, total energy consumption, and total machine workload. To solve the problem, an improved multi-objective migrating birds' optimization (IMOMBO) algorithm is proposed. A double-layer coding rule is introduced, considering single-piece and batch processing, with a corresponding decoding rule based on whether quenching and tempering are required. A multi-population co-evolution mechanism enhances solution diversity, and six neighborhood structures are used for local searches to improve solution quality. The effectiveness of the IMOMBO algorithm is demonstrated through comparative experiments and a practical case, showing its superiority over four other algorithms [19].

Reinforcement learning methods have been used to solve production scheduling problems with flexible processing constraints, but challenges like delayed rewards arise due to dynamic job arrivals and transportation constraints. The flow time of operations can only be determined after processing, and job sequencing is often neglected in single-agent scheduling methods. Additionally, the lack of information sharing between agents requires manually designed reward functions, reducing policy accuracy. An attempt is made to use multi-agent scheduling framework that enables collaboration between agents handling machines and jobs, addressing dynamic flexible job-shop scheduling problems (DFJSP) with transportation time constraints. A partial observation MDP is formulated, and a reward-sharing mechanism is introduced to resolve delayed rewards and improve policy learning. An improved multi-agent dueling double deep Q network (DDQN) algorithm is developed for long-term training. Results show that the proposed method outperforms state-of-the-art methods in reducing weighted flow time in both trained and unseen scenarios. A case study demonstrates its efficiency and adaptability in handling complex scheduling problems with job insertion, transportation constraints, and flexible processing routes [20]. To address the issues of low efficiency, poor path planning quality, and limited search completeness in narrow passage environments associated with rapidly-exploring random tree (RRT), the study proposes the grid-based variable probability rapidly-exploring random tree (GVP-RRT) algorithm. The algorithm preprocesses the map through gridization to extract path region features, and then uses random growth with variable probability density, guided by grid, probability, and feature-based strategies, to enhance growth in narrow passages. This improves the algorithm's completeness. Additionally, path re-optimization based on the triangle inequality principle is applied. Simulation results show that GVP-RRT improves planning success rates by 11.5–69.5%, reduces average planning time by over 50%, and produces shorter average planning path lengths compared to other algorithms [21].

Achieving mass personalization in DFJSP poses significant challenges in performance and adaptability, especially in variable contexts. A novel scheduling strategy based on heterogeneous multi-agent reinforcement learning (MARL), enabling centralized optimization and decentralized decision-making through collaboration between job and machine agents is incorporated. Historical experiences support data-driven learning. DFJSP with transportation time is modeled as heterogeneous multi-agent partial observation MDP, with a reward-shaping mechanism to minimize weighted tardiness. A dueling double DQN algorithm incorporates this mechanism to find optimal strategies for machine allocation and job sequencing, addressing sparse rewards and speeding up learning. Numerical experiments show that the proposed method outperforms state-of-the-art baselines in reducing weighted tardiness and demonstrates strong adaptability to new scenarios, highlighting the benefits of a heterogeneous MARL approach for dynamic and flexible scheduling challenges [22]. Talebpour *et al.* [23] explore how vehicle-to-vehicle (V2V) communication enhances traffic awareness and driving safety by enabling real-time data exchange among connected vehicles. Given the complexities of lane-changing—a key factor in congestion and collisions—the study introduces a game-theoretical model that integrates shared information to predict lane-switching behavior. Using the method of simulated moments, the model is calibrated against NGSIM data and validated for predictive accuracy. While limitations exist, results indicate that this approach offers a more realistic representation of lane-changing compared to traditional gap-acceptance models. A simulation framework based on fictitious play further supports these findings. This study explores a decentralized traffic control system for CAVs, leveraging V2V communication and onboard controllers for scalable and fault-resistant trajectory optimization. Focusing on highway merging—one of the major bottlenecks—the research introduces a dynamic game-theoretic approach that enables individual vehicles to make optimal decisions in conflicting situations. To address computational challenges, a zero-suppressed binary decision diagram (ZDD) is used for efficient solution enumeration. Numerical experiments validate the method, showing that it outperforms static game-based and individual decision models by facilitating smoother merging, even in constrained traffic conditions [24].

Roundabouts improve traffic safety by reducing vehicle conflicts, but entry and exit restrictions can raise collision risks. This study introduces a coordinated lane-change strategy to assist vehicles in mandatory lane shifts within roundabouts. It defines a driver's aggressiveness based on acceleration patterns and employs a cost function with model predictive control (MPC) for motion regulation. The Stackelberg game is used to model interactions between lane-changing and surrounding vehicles, optimizing lane-change timing. Simulations confirm that the approach enhances vehicle speed and driving stability, improving overall traffic flow [25]. Mandatory lane merging can disrupt traffic flow and reduce roadway efficiency. This study applies a Stackelberg game-theoretic model to analyze driver behavior, where a merging vehicle's aggressiveness influences its decision to merge immediately, accelerate, or decelerate before switching lanes. The interaction between merging and mainline vehicles is examined, showing that varying levels of aggressiveness impact both traffic stability and road capacity. The findings suggest that this model can be useful for traffic flow analysis and autonomous driving applications [26].

This study introduces a game-theoretic model to manage lane-changing conflicts in automated vehicles. When a vehicle attempts to switch lanes with a closely following vehicle in the target lane, a conflict arises as the following vehicle must slow down to create space. Existing models lack a clear resolution for such scenarios, potentially leading to inefficient traffic flow or safety risks. The proposed approach evaluates the payoffs of both vehicles under different strategies and determines optimal actions based on benefit equilibrium. Simulations reveal that lane-changing is more likely when the following vehicle is within 40 meters, while it is avoided when the gap exceeds 41 meters, ensuring smoother and safer traffic interactions [27].

This study introduces a decision-making and lateral control framework for cooperative obstacle avoidance in guided vehicle platoons across various scenarios. A centralized strategy determines optimal overtaking maneuvers, while a distributed lateral controller with a safe corridor planner ensures smooth trajectory tracking. Using an interactive behavior model, game theory optimizes overtaking timing and mode while minimizing disruptions to surrounding vehicles. A linear time-varying model predictive control (LTV-MPC) approach reduces computational load, enhanced by an iterative control logic for improved accuracy. Hardware-in-the-loop simulations confirm the framework's effectiveness in handling both static and moving obstacles [28].

This study explores vehicle group intelligence (VGI) as a key area in intelligent transportation systems through bibliometric analysis. Examining 2,821 publications from SCIE and SSCI databases, the research identifies major knowledge bases and research trends using document co-citation and keyword co-occurrence techniques. Key areas include vehicle platoon stability, wireless communication, cooperative driving in merging zones, and adaptive cruise control effects on traffic flow. The study also highlights emerging trends in vehicle platooning, cooperative merging, safety control, stability analysis, and communication. Additionally, it outlines future research directions in control architectures, platoon applications, cooperative strategies, and communication security, offering valuable insights for researchers in the VGI field [29]. A novel distributed formation control and coordination scheme for multi-lane heterogeneous vehicle platoons with a bi-level framework consisting of formation and dynamic control layers. The proposed distributed formation control scheme is relative position based and aims to achieve a desired geometric formation and common group velocity in the presence of bounded sensor noise in the inter-agent relative position measurements. This suits a platooning application well as the control needs to be more conservative to prioritize robustness over achieving an optimal configuration. This paper assumed a static formation and group velocity, but it would be beneficial to investigate dynamic adjustments based on desired platoon movements [30].

Wang *et al.* [31] introduce an iterative learning-based approach for optimizing the coordination of CAVs at on-ramps. A decentralized learning-based iterative optimization (DLIO) method is used to pre-train merging trajectories while ensuring safety and convergence. To adapt these trajectories to real-time traffic, a decision tree models possible vehicle passing sequences, and a heuristic Monte-Carlo tree search (HMCTS) algorithm determines the optimal merging order. A two-stage velocity planning method further refines vehicle flow. Simulations in SUMO show that the approach enables smooth merging without queuing, improving traffic efficiency and multi-vehicle coordination compared to baseline models. A study reviews key advancements in motion planning and control for automated vehicles, essential for ensuring safety and comfort. The planning module generates driving paths, while the control module executes vehicle movement. Various methods are analyzed, highlighting their strengths and weaknesses. The study predicts future research will focus on integrating diverse algorithms for improved performance, developing more accurate vehicle models, and enhancing the adaptability of planning and control systems within human-vehicle-road environments [32].

Falcone *et al.* [33] present an MPC approach for active front steering in autonomous vehicles, optimizing trajectory tracking on slippery roads at high speeds. Two MPC strategies are proposed: one using a nonlinear vehicle model and another employing successive online linearization for reduced computational complexity. The performance and computational demands of both approaches are analyzed. Simulations and experiments, conducted at speeds up to 21 m/s on icy roads, demonstrate the effectiveness of the proposed control method in maintaining stability and trajectory adherence. Ren *et al.* [34] propose a hybrid-intelligent real-time optimal control approach using deep neural networks (DNNs) to enhance the autonomy of AGV navigation. The motion planning problem is formulated as a nonlinear optimal control problem (OCP), solved offline using a direct method with smooth transformations. Optimal state-action pairs from generated trajectories are used to train DNNs, which then provide real-time feedback control. By shifting complex computations offline, the approach avoids repeated planning while ensuring robust and efficient AGV navigation, as demonstrated through numerical experiments.

Proposed study examines the coordinated scheduling of AGVs and yard cranes (YCs) in a U-shaped container terminal to enhance operational efficiency. A hybrid AGV speed optimization strategy is proposed, balancing energy consumption and task urgency. A mixed-integer time-energy scheduling model minimizes both maximum completion time and energy use. To optimize task configurations and AGV speed, a novel inverse learning-based slime-mold genetic algorithm (LSMAGA) is introduced. Experimental results demonstrate improved convergence speed and efficiency, reducing maximum completion time by up to 15.51% compared to other strategies while maintaining energy efficiency [35].

Wang *et al.* [36] introduce a DRL-based optimization method to improve navigation channel traffic and reduce delays in dry bulk export terminals (DBETs). The proposed channel traffic scheduling (CTS) approach models the problem as an MDP, incorporating real-world constraints such as tidal windows and dynamic traffic modes. To handle large state-action spaces, a hierarchical DRL framework enables layered decision-making. A proximal policy optimization method trains DRL agents to generate efficient scheduling plans, minimizing ship mooring, unberthing, and de-ballasting delays. Numerical experiments validate the approach, demonstrating faster convergence and high-quality industrial-scale scheduling solutions. This paper reviews recent advancements in AGV navigation techniques, evaluating their relevance and effectiveness in modern industrial and transportation systems. The study explores whether classical navigation methods remain applicable, the optimization potential of heuristic techniques, and the impact of AI on AGV performance. By analyzing five years of academic research, the paper identifies key navigation strategies and highlights the most widely adopted approaches for further investigation [37].

This paper explores recent advancements in AGV obstacle avoidance techniques, addressing challenges in dynamic and complex environments. By analyzing scholarly research from the past five years, it examines the relevance of traditional obstacle avoidance methods, the latest sensor technologies for environmental perception, and the role of AI in enhancing AGV decision-making and autonomy. The study provides insights into both fundamental and emerging approaches, offering valuable guidance for researchers and engineers in the field [38]. Table 2 is the summary of the above survey.

Table 2. Intelligent techniques review

Category	Key focus	Main contribution	Key outcome
Hybrid flow-shop and job scheduling	Hybrid flow-shop scheduling, flexible job-shop scheduling (FJSSP), dynamic scheduling	Improved cuckoo search, MARL	Enhanced scheduling efficiency, adaptability to job insertion and transportation constraints [15], [20], [22]
AGV scheduling and battery management	Energy-efficient AGV scheduling, real-time AGV coordination	Deep reinforcement learning (DDQN), bi-objective optimization (energy and scheduling)	Reduced tardiness, energy consumption, improved AGV efficiency in Industry 4.0 [16], [18]
Port and terminal optimization	Multi-AGV scheduling for ports and container terminals	DQN-based scheduling, LSMAGA optimization for AGV and crane coordination	Increased port efficiency, reduced completion time and energy use [17], [35]
Path planning and obstacle avoidance	RRT-based navigation in narrow passages, vehicle obstacle avoidance	Grid-based variable probability RRT (GVP-RRT), DRL	Improved path planning success rates, faster AGV movement in complex environments [21], [38]
Traffic flow and lane management	Game-theoretic models for lane-changing, V2V communication for merging	Predictive lane-switching behavior, Stackelberg game and reinforcement learning	Improved traffic flow, lane-change coordination, reduced congestion [23], [24], [26], [27], [31]
Autonomous vehicles and platooning	Heavy vehicle formation control, platoon coordination	Finite-state machine, trajectory planning, and lateral control	Improved obstacle avoidance, smoother vehicle coordination and traffic efficiency [30]
Automated navigation and AI optimization	AI-driven AGV control, motion planning	Deep learning-based real-time control, neural network optimization	Enhanced AGV navigation, better decision-making under uncertainty [34], [37]
Dry bulk export and traffic scheduling	DBETs channel traffic optimization	Hierarchical DRL, Markov modeling, and scheduling optimization	Minimized traffic delays, optimized mooring and unberthing [36]

4. PATH PLANNING IMPLEMENTATIONS IN AUTOMATED GUIDED VEHICLE

Luo [39] addresses the challenges in AGV path planning by improving the traditional A* algorithm, which often suffers from path roughness and slow computation. The proposed approach incorporates a dynamic weighting factor to refine the evaluation function for better path optimization and employs an 8-neighborhood search strategy to enhance search efficiency. Experimental results validate the effectiveness of these modifications, showing notable improvements in both planning speed and path smoothness.

Research paper proposes an environmental weight A* algorithm to enhance AGV path planning by dynamically adjusting weights based on obstacle density, reducing search time and improving stability. To optimize conflict resolution, a local multi-direction method is introduced, integrating directional travel rules with the path-finding algorithm to prevent opposite-direction conflicts and unnecessary detours. Additionally, a dynamic priority method based on traffic prediction assigns AGV priorities at conflict nodes, improving efficiency in localized congestion. Experimental results confirm that the proposed approach offers faster and more stable path searches [40]. AGVs, as high-end automated logistics equipment, are widely used in warehouses and workshops, relying on route sign identification for navigation. To enhance tracking accuracy, this paper applies a PSO algorithm to fine-tune AGV controller parameters, minimizing tracking deviation. A kinematic model of the AGV is analyzed, and a PID controller optimized by PSO is developed. Simulations in MATLAB compare system performance before and after optimization, demonstrating that the optimized PID controller significantly improves AGV tracking accuracy and control performance [41].

Luo *et al.* [42] introduces the A* guiding deep Q-network (AG-DQN) algorithm for optimizing AGV pathfinding in robotic mobile fulfillment systems (RMFS). RMFS environments pose challenges such as dynamic scenes, narrow spaces, and high decision-making demands. The AG-DQN algorithm integrates the A* algorithm with deep reinforcement learning like DRL, accelerating training while reducing decision-making time. It enables AGVs to efficiently complete tasks using only system layout information. Tested on various RMFS layouts, AG-DQN outperformed standard DQN and A*, reducing decision-making time by 49.92% in small-scale and 71.51% in large-scale models. This approach enhances AGV efficiency in warehouse automation.

The research introduces an innovative path planning approach that integrates the RRT algorithm with the DDQN to enhance the learning efficiency and convergence speed of DRL. By leveraging RRT to guide DDQN training, the proposed method effectively improves performance in complex and high-dimensional task environments. Experimental results demonstrate that this approach significantly enhances DDQN’s capability, offering a novel perspective on combining classical path planning algorithms with modern deep learning techniques for intelligent navigation and decision-making [43]. A study introduces an edge computing approach leveraging vehicle intelligence to optimize AGV scheduling by balancing efficiency, collision avoidance, and energy use. A multi-objective model is developed, incorporating electric capacity constraints, and solved using an artificial plant community algorithm. Designed for real-time deployment on embedded platforms, the method improves AGV coordination and energy efficiency. Benchmark tests confirm its effectiveness in collision-free scheduling and optimized logistics operations [44].

Yang *et al.* [45] examine order processing in KIVA robot-assisted warehouses, where robots deliver racks to workstations for efficient item retrieval. To optimize order and rack scheduling, an integrated mixed-integer programming model is proposed, aiming to minimize rack visits while balancing workloads. A simulated annealing framework, leveraging problem-specific heuristics, is developed to solve the model effectively. Computational experiments demonstrate superior performance compared to rule-based methods and existing algorithms, with insights provided for warehouse management.

The article reviews energy efficiency in manufacturing systems, driven by the depletion of fossil fuels, rising energy costs, and regulatory pressures. It examines research from the past decade, highlighting technologies and strategies to improve energy efficiency, with a focus on management and control strategies. The study emphasizes energy reduction and resource optimization within discrete manufacturing, aligning with Industry 4.0 advancements. This review offers valuable insights for academia and industry to identify trends, address challenges, and guide future research on sustainable manufacturing practices [46]. This study proposes an improved A* algorithm, EBS-A*, enhancing path planning for mobile robots through expansion distance, bidirectional search, and smoothing. These modifications improve reliability, efficiency, and path robustness. Simulation and ROS-based experiments show a 278% efficiency gain, a 91.89% reduction in critical nodes, and the elimination of right-angle turns compared to traditional A* [47]. This study proposes an improved A* algorithm to enhance operational efficiency and reduce path length. Experimental results show a 9.11% reduction in planning time and a 9.29% shorter path compared to the standard A*, demonstrating significant performance gains [48]. This study addresses key challenges in parking management, including vehicle overstaying, 3iDAR sensor integration, cold weather simulation, and penalty optimization. It also explores improving parking decisions by incorporating driver preferences [49]. This published article proposes a multi-swarm co-evolution (MCO) algorithm for autonomous underwater vehicle (AUV) path planning in a 3D marine environment. By balancing exploration and exploitation, integrating shared dynamic optimal particles, and using a cross-integration mutation strategy, MCO enhances robustness and search efficiency. Experimental comparisons confirm its superiority over existing swarm intelligence algorithms [50]. A minimum time velocity profile in the path using velocity, jerk, and acceleration as the constraint is obtained by applying two reference paths [51]. The jerk limited velocity planning is implemented for the path planning. Receding horizon control techniques is used on the fleets of automated vehicles in the real-world scenario, to coordinate them for logistics operations [52]. Dynamic obstacles are very important in a path planning implementation, thus addressing this challenge becomes unavoidable. Dynamic obstacle environments are created to check the validity of hybrid A*-diffusion planner (HADP) algorithm in [53]. It is a learning-based path planning algorithm. Table 3 summarizes the literature survey.

Table 3. Advanced path planning techniques review

Category	Key focus	Main contribution	Key outcome
AGV path planning	A* algorithm improvements	Dynamic weighting, environmental factors, conflict resolution	Faster, smoother, and more stable paths
AGV control and scheduling	Tracking and energy optimization	PSO-based PID control, edge computing for scheduling	Improved accuracy, collision-free and energy-efficient AGV operations
Warehouse automation	Mixed-integer programming with heuristics	Optimized order fulfillment and workload balance	
Deep learning in navigation KIVA robot scheduling	A"-guided DQN, RRT-DDQN hybrid approach	Faster decision-making and improved learning efficiency	
Autonomous vehicles and platooning	Heavy vehicle formation control, platoon coordination	Finite-state machine, trajectory planning, and lateral control	
Autonomous underwater vehicles	3D marine path planning	Multi-swarm co-evolution for robust search	Superior search efficiency and robustness

Although scheduling, path planning, and energy efficient AGV process is taken up as separate topics in the review process all three have inter-related parameters. To go forward in the research on AGVs a multiparameter tuning algorithms that would balance all the three topics moderately has to be brought in for an overall performance improvement in the AGV domain.

Few of the literature gives the direction so as to which parameters need to be concentrated for further improvements in the AGV domain. Table 4 gives us the idea about the scope of improvement in the path planning and scheduling performance in the AGV environment. The table suggests the concepts on which the scope for improvement in the further research can be carried out. Planning time, decision making time reduction in critical nodes, path length search robustness, and efficiency are few important parameters that can be observed for further research. Few of the limitations considered from the articles discussed above are given in Table 5.

Table 4. Probable parameters for research scope

Algorithm/method	Performance metric	Numerical improvement	Reference
GVP-RRT	Planning success rate	↑ 11.5%–69.5% improvement	[21]
	Planning time	↓ Over 50% reduction	[21]
	Path length	↓ Shorter average path	[21]
*AG-DQN (A-guided DQN) **	Decision-making time (small-scale RMFS)	↓ 49.92% reduction	[42]
	Decision-making time (large-scale RMFS)	↓ 71.51% reduction	[42]
EBS-A*	Planning efficiency	↑ 278% improvement	[47]
	Reduction in critical nodes	↓ 91.89% fewer nodes	[47]
	Path smoothness (right-angle turns)	Completely eliminated	[47]
Improved A*	Planning time	↓ 9.11% reduction	[48]
	Path length	↓ 9.29% reduction	[48]
MCO for AUV path planning	Search robustness and efficiency	Improved (no specific % given)	[50]
Energy efficiency review	Energy and resource optimization in manufacturing	Conceptual and strategic improvements; no numerical data	[46]
Parking management system	Overstaying, sensor integration, and penalty optimization	Addressed qualitatively; no numerical data	[49]

Table 5. Limitations of articles

Paper/algorithm	Limitations
GVP-RRT [21]	– The reported improvements (e.g., success rate and planning time) are based on simulations, which may not capture the full complexity of real-world robot motion planning. – Performance in high-dimensional configuration spaces or real-time dynamic environments is not discussed. – The grid-based approach may introduce discretization errors or inefficiencies in complex continuous spaces.
AG-DQN [42]	– Though AG-DQN reduces decision-making time, it is data- and training-intensive due to its reinforcement learning component. – Performance depends on the quality of A* guidance and may not generalize well to unseen or highly dynamic RMFS layouts. – No discussion of how it handles collisions, delays, or multi-agent conflicts in practical warehouse systems.
EBS-A* [47]	– The 278% efficiency gain is impressive, but results are likely from idealized or controlled environments. – May not handle non-grid maps or environments with irregular geometries effectively. – No real-world deployment details or robustness under sensor uncertainty or noise.
Improved A* [48]	– Improvements in planning time and path length are incremental (≈9%), which may not be significant in large-scale or mission-critical applications. – The algorithm still inherits the inherent limitations of deterministic search (e.g., sub-optimal paths in unknown terrains).
Parking management system [49]	– Real-world variability like driver behaviour, network outages, and environmental interference are not deeply addressed. – No integration details with existing city-level smart infrastructure.
MCO for AUV path planning [50]	– The algorithm is tested only in simulated marine environments; real underwater conditions (e.g., currents, noise) can degrade performance. – Computational complexity of multi-swarm co-evolution may limit real-time application on resource-constrained AUVs. – No direct comparison with hybrid or deep learning-based methods for marine path planning.

The suggestion from the Table 5 is that the simulations thus developed in the previous implementations should have an experimental validity so that there is a real time backup for the claims in the path planning and scheduling implementations for AGV applications. Thus, the real-world variations must be included in the tests conducted in the AGV applications.

5. CONCLUSION

The review paper discusses methods involved in automated vehicles that optimizes the path planning, energy efficiency, and scheduling. The topics are segregated on the basis of different soft-computing methods including, reinforcement learning, game theory, and optimization methods including A* methods. Although all these methods are important in the context of the AGV, the combination of all these objectives has to be considered. In the future research it is suggested to take up research that would combine path planning, scheduling, and energy optimization as the objective terms to get a better automation in the process which have a human in loop concept included for efficient processing.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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